Ref. Ares(2026)7418655 - 28/07/2026

Empowering bioeconomy projects by deploying Technical, Business, Regulatory and Social assistance services

Project title	Empowering bioeconomy projects by deploying Technical, Business, Regulatory and Social assistance services		
Project acronym	ToBeReaL		
Project number	101181799		
Project start date	01/11/2024	**Duration**	60 months

D4.1 – OPEN REPORT: EMERGING INNOVATIVE TECHNOLOGIES AND FEEDSTOCK AVAILABILITY

Due date	07/31/2025	**Delivery date**	07/22/2025
Work package	WP4		
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Reviewer(s)	Tanja Meyer (BBEPP)		
Type	Report		
Dissemination level	Public (P)		

VERSION AND AMENDMENTS HISTORY

Version	Date (MM/DD/YYYY)	Created	Changes
1	05/02/2025	Jorge García (AINIA)	V1
2	07/22/2025	Tanja Meyer (BBEU)	V2
3	07/26/2026	Jorge García (AINIA)	V3: Executive Summary revised and refocused on key findings, challenges

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			and recommendations; dedicated methodology section incorporated; harmonisation of country profiles in Chapter 1; harmonisation of analytical structure for country assessments in Chapter 6; validation and correction of references, dates and factual information; verification and correction of hyperlinks; inclusion of a consolidated references section.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
AI	Artificial Intelligence
AINIA	Ainia
ALE	Adaptative Laboratory Evolution
ANB	Agentschap Natur & Bos
ARTP	Atmospheric Room-Temperature Plasma
B2BE	Business-to-BioEconomy
B4C	Bioeconomy for Change
BAU	Business-As-Usual
BBEPP	Bio Base Europe Pilot Plant
BBSRC	UK's Biotechnology and Biological Sciences Research Council
BCRS	The Maltese Beverage Container Refund Scheme
BDC	UK's Biorenewables Development Centre
BEC	Bioeconomy Cluster
BFR	Biofuel Region BFR AB
BGE	Biodiversity Genomics Europe
BIC	Biobased Industries Consortium
BioMADE	Bioindustrial Manufacturing and Development Ecosystem
BRCGS	British Retail Consortium Global Standards
BSG	Brewer's Spent Grain
CAGR	Compound Annual Growth Rate
CAP	Common Agriculture Plan
CAPEX	Capital Expenditure
CBD	Cannabidiol
CBE JU	Circular Bio-Based Europe Joint Undertaking
CBP	Consolidated Bioprocessing
CCIS	Chamber of Commerce and Industry of Slovenia – Stajerska Gospodarska Zbornica Firm
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CEAP	Circular Economy Action Plan
CEE	Central and Eastern Europe

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CEN	European Committee for Standardisation
CERTH	Greek Centre for Research and Technology
CHP	Combined Heat and Power
CLUBE	Cluster of Bioeconomy and Environment of Western Macedonia – Cluster Viooikonomias Kai Perivallontos Dytikis Makedonias
CoLABs	Collaborative Laboratories
CPI	UK's Centre for Process Innovation
CREA	Council for Agricultural Research and Economics
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
CSTR	Continuous Stirred Tank Reactors
DEFRA	UK's Department for Environment, Food and Rural Affairs
DESNZ	UK's Department for Energy Security and Net Zero
DIH	Digital Innovation Hub
DM	Dry Matter
DNA	Deoxyribonucleic acid
DSIT	UK's Department for Science, Innovation and Technology
DWC	Dividing-Wall-Column
EAB	Electroactive Bacteria
EFI	European Forest Institute
EIB	European Investment Bank
ENEA	Italian National Agency for New Technologies, Energy and Sustainable Economic Development
ERDF	European Regional Development Fund
ERGA	European Reference Genome Atlas
ETIS	Estonian Research Information System
ETS	Emissions Trading System
EU	European Union
EUDR	European Union Deforestation Regulation
EV ILVO	Eigen Vermogen Van Het Instituut Voor Landbouw – En Visserijonderzoek
FAB FVG	Fondazione Agrifood & Bioeconomy FVG
FAIR	Findable, Accessible, Interoperable and Reusable
FAME	Fatty Acid Methyl Ester
FDCA	2,5-Furandicarboxylic acid

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FDE	Environmental and Sanitary Declaration Forms
FO	Forward Osmosis
FSC	Forest Stewardship Council Certification
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GIS	Geographic Information Systems
GMO	Genetically Modified Organisms
GPS	Global Positioning Systems
GVA	Gross Value Added
HRT	Hydraulic Retention Time
HVO	Hydrotreated Vegetable Oil
IBioIC	UK's Industrial Biotechnology Innovation Centre
ICEADR	Romanian Institute of Agricultural Economics and Rural Development
IFPEN	French Institute of Petroleum – Energy nouvelles
ILUC	Indirect Land-Use Change
IMTA	Integrated Multitrophic Aquaculture
INECP	Bulgarian Integrated National Energy and Climate Plan
INRAE	French National Institute for Agriculture, Food and Energy
IoT	Internet of Things
ISO	The International Organisation for Standardisation
ISPRA	Italian Institute for Environmental Protection and Research
JRC	Joint Research Centre
LCA	Life Cycle Assessment
LIAK	Latvian Industry Development Confederation
LNG	Liquefied Natural Gas
LULUCF	Land-Use, Land-Use Change and Forestry
MAPA	Spanish Ministry of Agriculture, Fisheries and Food
MASE	Italian Ministry for the Environment and Energy Safety
MCAST	The Malta College of Arts, Science & Technology
MD	Membrane Distillation
MEC	Microbial Electrolysis Cell
MLSP	Malta Life Sciences Park
MOFs	Metal-Organic Frameworks

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MSW	Municipal Solid Waste
MT	Metric tonne
NBMs	Nano-enabled Bio-based Materials
NECP	Cypriot National Energy and Climate Plan
NETIS	Hungarian National Environmental Technology Innovation Strategy
NFI	Swedish National Forest Inventory
NGOs	Non-Governmental Organisations
NGS	Next-Generation Sequencing
NNFCC	NNFCC Limited
NPPC	Slovak National Agricultural and Food Center
OFMSW	Organic Fraction of Municipal Solid Waste
OPEX	Operational expenditure
OSRO	Organic Solvent Reverse Osmosis
P(LA-co-3HB)	Poly(lactate-co-3-hydroxybutyrate)
PBA	Polybutylene adipate
PBF	Poly(butylene 2,5-furandicarboxylate)
PBS	Polybutylene succinate
PCL	Polycaprolactone
PDI	Pilot and Demonstration Infrastructures
PEF	Polyethylene Furanoate
PEFC	Programme for the Endorsement of Forest Certification
PET	Polyethylene Terephthalate
PHA	Poly(hydroxyalkanoate)
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate
PLA	Poly(lactic acid)
PNGR	Programma Nazionale per la Gestione dei Rifiuti
PNO ES	PNO Innovation SL
PNO PT	PNO Innovation Unipessoal LDA
PNS	Purple Non-Sulphur
PRTR	Spanish Recovery, Transformation and Resilience Plan
PV	Pervaporation
R&D	Research and Development
R&D&I	Research and Development and Innovation

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R&I	Research and Innovation
RDF	Refuse-Derived Fuel
RE2020	Revised Thermal Regulation
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RED I	Renewable Energy Directive I
RED II	Renewable Energy Directive II
RED III	Renewable Energy Directive III
RES	Renewable Energy Sources
RTFO	Renewable Transport Fuel Obligation
S3	Smart Specialisation Strategy
SAF	Sustainable Aviation Fuel
SCP	Single-Cell Protein
SFE	Supercritical Fluid Extraction
SME	Small and Medium-sized Enterprise
SmF	Submerged Fermentation
SMR	Small Modular Reactor
SRC	Short Rotation Coppice
SRF	Short Rotation Forestry
STEP	Strategic Technologies for Europe Platforms
SusBioMM	UK's Sustainable Bio-based Materials and Manufacture
SWOT	Strengths, Weaknesses, Opportunities, and Threats
TAČR	Technology Agency of the Czech Republic
THC	Tetrahydrocannabinol
TNO	The Netherland's Organisation of Applied Scientific Research
TRL	Technology Readiness Level
TRUST	Transparency, Responsibility, User focus, Sustainability and Technology
TTOs	Technology Transfer Offices
UK	United Kingdom
VAM	Vinyl Acetate Monomer
VFA	Volatile Fatty Acid
VITO	Vlaamse Instelling Voor Technologisch Onderzoek N.V.
VoB	Volume of wood over Bark
WP	Work Package

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EXECUTIVE SUMMARY

The European bioeconomy is increasingly recognised as a strategic pillar for achieving climate neutrality, strengthening industrial competitiveness, enhancing resource security and accelerating the transition towards a circular and sustainable economy. Nonetheless, despite considerable advancement in the development of bio-based technologies during the past decade, numerous promising innovations continue to be constrained by technological, economic, regulatory and market-related barriers that limit their capacity to progress towards large-scale commercial deployment.

This report, developed within the scope of Tasks 4.1 and 4.2 of the ToBeReaL project, provides a comprehensive assessment of emerging technologies, feedstock availability, and the principal technological and socio-economic barriers affecting the development, scale-up, and market uptake of bio-based innovations across Europe. The analysis combines evidence gathered through a literature review, country-level assessments performed by consortium partners, stakeholder consultations, and responses collected through the ToBeReaL questionnaire. To ensure both a European and regional perspective, the assessment was conducted through a collaborative effort involving all project partners, each contributing expertise and evidence from their assigned countries and regions. This territorial approach facilitated the integration of country-specific insights while preserving a coherent cross-European analysis of the challenges and opportunities facing the bioeconomy sector. The allocation of target countries and regions amongst consortium partners is presented in Table 1.

Table 1 – Assignment of Target Regions by ToBeReaL' s partners.

Partner	Countries
1 - PNO ES (Spain)	Spain
2 – ŠGZ / CCIS (Slovenia)	Slovenia, Croatia, Hungary
3 – CLUBE (Greece)	Greece, Cyprus, Bulgaria
4 – BFR (Sweden)	Sweden, Latvia
5 – FAB FVG (Italy)	Italy, Poland
6 – B4C (France)	France, Malta
7 – BEC (Slovakia)	Slovakia, Czechia
8 – AINIA (Spain)	Spain, Estonia
9 – EL ILVO (Belgium)	Romania, Lithuania
10 – VITO (Belgium)	Belgium
11 – PNO PT (Portugal)	Portugal
12 – BBEPP (Belgium)	Belgium
13 – NNFCC (UK)	UK

The results indicate that Europe possesses considerable strengths for the development of a competitive bioeconomy, including a diversified biomass resource base, world-class research infrastructures, strong

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industrial capabilities and a growing ecosystem of innovation-support mechanisms. Significant technological advances have been identified across multiple bio-based value chains, particularly in industrial biotechnology, advanced biorefining, synthetic biology, precision fermentation, carbon capture and utilisation, digitalisation and circular processing approaches. Emerging technologies, including advanced bioreactors, biohydrogen production systems, AI-assisted biomanufacturing, genomics-based innovations and integrated biorefineries, have considerable potential to increase process efficiency, reduce environmental impacts, and expand the portfolio of sustainable bio-based products.

Nevertheless, the analysis also highlights common challenges shared across most European countries. A significant challenge lies in the transition from laboratory and pilot-scale validation to commercial-scale deployment. Many technologies are still at intermediate TRLs (4 – 7). At these levels, there is a high degree of technical uncertainty, significant capital investment requirements and limited access to demonstration infrastructures. This substantially increases financial risk. Consequently, a significant number of innovative solutions face challenges in achieving full market maturity, despite evidencing promising technical performance.

Feedstock availability and biomass mobilisation constitute another critical challenge. Despite the significant production of agricultural residues, forestry by-products, organic waste streams and other renewable biological resources in Europe, the effective mobilisation of these resources is often impeded by fragmented supply chains, logistical limitations, seasonal variability, competing end-users and inconsistent feedstock quality. These factors directly impact process reliability, production economics and long-term investment decisions.

Economic and market-related barriers continue to be equally pertinent. The manufacturing of bio-based products often necessitates higher production costs in comparison to established fossil-based alternatives. Furthermore, numerous emerging value chains have yet to attain the requisite economies of scale necessary for competitive market positioning. The slow pace of commercialisation can be attributed to a number of factors, including limited private investment, restricted access to finance for scale-up activities, insufficient deployment of demonstration infrastructures and the absence of mature business models. Additionally, the level of consumer awareness regarding bio-based products varies considerably throughout Europe, thereby diminishing the potential for demand-pull effects to catalyse market development.

The study also identifies significant regulatory and governance challenges. Several countries still lack dedicated national bioeconomy strategies or coherent policy frameworks capable of aligning innovation, sustainability, industrial development and market uptake objectives. The complexity of regulations, lengthily asynchronous processes for permit issuance, the fragmentation of legislative frameworks, and the ambiguity of future policy developments are often discouraging factors that impede investment and the expeditious implementation of pioneering bio-based solutions. Furthermore, stakeholders repeatedly emphasised the necessity for enhanced harmonisation of sustainability assessment methodologies, standards, certification schemes and end-of-waste criteria.

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From a technological perspective, process efficiency, scalability, downstream processing, technology integration, digital transformation and circular resource management emerge as the most recurrent challenges. The findings demonstrate that future competitiveness will increasingly depend on the successful integration of biotechnology, thermochemical conversion processes, digital technologies, artificial intelligence, advanced process control systems and innovative valorisation pathways within highly integrated biorefinery concepts.

The analysis further reveals that significant regional differences persist throughout Europe. While certain countries benefit from well-established bio-based industrial ecosystems, advanced innovation infrastructures, and comprehensive policy support mechanisms, others continue to face structural barriers linked to limited research capacity, insufficient industrial integration, fragmented innovation ecosystems or restricted access to financing. Nevertheless, common opportunities were identified across all participating countries, particularly in the areas of circular bioeconomy development, biomass valorisation, industrial symbiosis, sustainable feedstock diversification, and digital innovation.

Based on the evidence collected, several priority actions were identified to support the future growth and competitiveness of the European bioeconomy. These include increasing investment in pilot and demonstration infrastructures, strengthening technology transfer mechanisms, improving access to scale-up financing, enhancing collaboration between industry and research organisations, promoting circular valorisation of underutilised biomass streams, accelerating digitalisation and automation, and developing stable, coherent, and long-term policy frameworks. Particular emphasis should be placed on creating favourable conditions for the commercial deployment of emerging bio-based technologies and supporting the development of integrated regional bioeconomy ecosystems.

Overall, the report confirms that Europe possesses the technological capabilities, biomass resources and innovation capacity required to significantly expand its bioeconomy. However, unlocking this potential will require coordinated action across technological, economic, regulatory and societal dimensions. Addressing these barriers through targeted investments, policy support, stakeholder collaboration and accelerated innovation deployment will be essential to transform promising bio-based innovations into commercially successful and sustainable flagship initiatives capable of contributing to the objectives of the European Green Deal and the transition towards a climate-neutral and circular economy.

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1 INTRODUCTION

The present report offers a comprehensive overview of the key technological and socio-economic barriers currently hindering the full potential and market uptake of bioeconomy projects across the EU. This report constitutes a component of Work Package 4 (WP4) of the EU-funded ToBeReal project, which is more broadly concerned with the provision of actionable policy recommendations and the identification of opportunities for public-private partnerships and cross-border collaboration.

D4.1 synthesises the findings from **Task 4.1**, which is centred on the identification of technological impediments that hinder bio-based innovations from becoming flagship initiatives. Led by AINIA and supported by a consortium of expert partners, this task maps current and emerging technologies across a wide TRL scale that are essential for maximising the valorisation of the most relevant EU feedstocks. Particular emphasis is placed on the need for integration of biotechnology, nanotechnology, and digital technologies, and on the challenges related to efficiency, scalability, production costs, and energy consumption. Key insights were gathered through stakeholder interviews and surveys, with a focus on innovation gaps and barriers.

Concurrently, **Task 4.2**, led by SGZ, is addressing the barriers to the uptake of bio-based products on the demand side. This includes an analysis of feedstock availability, end-user and citizen perception, market demand, and broader socio-economic constraints such as competitiveness, profitability, and the lack of robust business models. In addition, we are examining supply-side issues, including production capacity and logistics.

These analyses will serve as a foundational input for the upcoming work in WP5 and WP6. The primary objective of this deliverable is to provide policymakers, industry actors, and other stakeholders with a detailed inventory of the critical factors limiting the progress of the EU bioeconomy. This will support targeted strategies to unlock the sector's full potential in driving Europe's transition to a sustainable, circular economy.

1.1 METHODOLOGY

The identification and assessment of technological and socio-economic barriers affecting the development and upscaling of bio-based projects in Europe was based on a mixed-method approach combining desk research, stakeholder consultation, expert contributions from consortium partners and a dedicated questionnaire developed within the framework of the ToBeReaL project. The methodology was designed to ensure a comprehensive understanding of the current state of the European bioeconomy and to capture both quantitative and qualitative evidence from stakeholder groups.

1.1.1 Literature review and desk research

A systematic review of publicly available information was conducted to identify the main technological developments, feedstock trends, market conditions and barriers affecting bio-based industries across Europe. A comprehensive data set was meticulously compiled from a diverse array

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of sources, including scientific publications, European Commission reports, policy documents, national bioeconomy strategies, project reports, industry publications and relevant initiatives funded under Horizon Europe, Horizon 2020, Circular Bio-Based Europe Joint Undertaking (CBE JU) and other European programmes.

A particular emphasis was placed on the identification of emerging technologies, technology readiness levels (TRLs), feedstock availability, process integration opportunities and technological bottlenecks across several bio-based value chains.

1.1.2 Country-level evidence collection

Country-specific analyses were developed through the active participation of consortium members responsible for different target countries and regions. Each partner collected and validated information regarding the current status of the national bioeconomy, existing barriers, policy frameworks, innovation capacities, biomass availability and market conditions within their assigned territories.

The national data sources included governmental publications, regional strategies, innovation agendas, industrial roadmaps, statistical reports and relevant national stakeholders. This methodological approach facilitated the integration of country-specific perspectives with European-level evidence.

1.1.3 Stakeholder consultation

Consortium partners conducted consultations with relevant stakeholders during the project's initial implementation phase, thereby eliciting their input. The stakeholders in question represented diverse segments of the bioeconomy ecosystem, including:

- Research and technology organisations.
- Universities and academic institutions.
- Industrial companies and SMEs.
- Clusters and innovation ecosystems.
- Public authorities and policymakers.
- Bioeconomy associations and networks.
- Business support organisations and investors.

The consultation activities allowed the consortium to validate findings obtained through the literature review, identify emerging challenges and collect practical insights from organisations directly involved in bio-based innovation and commercialisation.

1.1.4 ToBeReaL questionnaire

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A dedicated questionnaire was developed and distributed amongst stakeholders participating in the bioeconomy ecosystem. The objective of this study was to collect first-hand information regarding technological barriers, innovation needs, entrepreneurship opportunities, circular economy practices, TRLs and perceived obstacles affecting the implementation and scale-up of bio-based projects.

The results of the questionnaire provided further evidence to support the identification of priority barriers, which were subsequently analysed in Chapter 9 and 10 of this report. The findings were used to complement literature-based evidence and expert assessments with stakeholder perceptions and practical experience.

1.1.5 Identification and assessment of barriers

The technological and socio-economic barriers presented in this report were consequently identified through the triangulation of evidence obtained from scientific literature, European and national policy documents, country-specific analyses conducted by consortium partners, stakeholder consultations, responses collected through the ToBeReaL questionnaire and expert knowledge provided by the consortium.

The collected information was analysed in order to identify recurrent challenges affecting the development, demonstration, scale-up and market uptake of bio-based solutions. A particular focus was placed on barriers related to process efficiency, scalability, technology integration, feedstock availability, investment needs, regulatory constraints, market development, circularity and public acceptance.

1.1.6 Limitations

The report reflects the state of knowledge and stakeholder feedback available during the preparation period of Deliverable D4.1. In consideration of the dynamic nature of the bioeconomy sector, it is acknowledged that technological developments, policy frameworks and market conditions may evolve over time. Furthermore, the availability of national information and stakeholder participation varied between countries, which may result in different levels of detail across country profiles.

1.2 Background On Bio-Based Industry Challenges

1.2.1 Overview of the European bioeconomy

The bio-based industry in Europe has evolved significantly, driven by the need for sustainable alternatives to fossil-based resources. It utilises biomass from agricultural residues, forestry by-

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products, and dedicated energy crops to produce biofuels, biochemicals, and biomaterials[1]. Its core aim is to reduce reliance on non-renewable resources and lower the environmental impact of conventional industries, thereby supporting the EU's climate neutrality targets.

Key drivers of this evolution include technological advancements, supportive policies, and rising consumer demand for sustainable products. The industry has progressed from first-generation biofuels to advanced biofuels and diversified into bio-based chemicals and materials. Between 2008 and 2019, its economic contribution grew by 36%, reaching over €814 billion[1].

Today, the bio-based industry pursues broader goals beyond greenhouse gas (GHG) reduction and resource efficiency. It seeks to foster rural development, stimulate innovation across sectors like agriculture, forestry, and biotechnology, and support the EU's Bioeconomy Strategy by improving the use of renewable biological resources and expanding bio-based markets.

Looking forward, the sector is poised to play a central role in the shift toward a circular, sustainable economy. The integration of synthetic biology, industrial biotechnology, and advanced digital tools is expected to boost the performance and scalability of bio-based processes. In particular, recent advancements in lignocellulosic feedstocks are enhancing biomass yields, improving energy traits, and increasing resilience to climate change and pathogens—laying the foundation for a robust and future-proof European bioeconomy[2].

However, the bio-based industry in Europe faces several challenges as it strives to develop a sustainable bioeconomy:

- **Limited biomass availability and competition**: There is substantial competition for biomass resources across sectors, as the transition to a circular bioeconomy demands significant quantities of biomass. This competition extends to various industries, including food, feed, energy, and materials sectors. The increasing demand for biomass in these sectors is driven by decarbonisation efforts for fossil-based carbon and the transition to a circular bioeconomy. The logistics of securing large quantities of biomass feedstocks all year round can be a significant barrier when looking at agroresidues for example, particularly due to seasonal variations in crop yields and the perishable nature of some biomass sources for example from fruit waste. The variability of biomass quality challenges the feasibility of bio-based chemical production, as inconsistent feedstock characteristics can affect process efficiency and product quality. Additionally, biomass is also demanded in other industrial sectors, such as food and feed, energy, construction, and biofuels.

[1]Porc, O., et al., European Bioeconomy in Figures 2008-2019, BIC 2022, European Bioeconomy in Figures 2008 - 2019 | Bio-based Industries Consortium (BIC)

[2]Sulis, D.B., et al., Advances in lignocellulosic feedstocks for bioenergy and bioproducts, Nature Communications 16 (2025) 1244. **https://doi.org/10.1038/s41467-025-56472-y**

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- **Scale-up readiness**: While TRLs are widely used across the European bioeconomy to benchmark the maturity of innovations, many bio-based processes are still in the emerging phase. Typically, these are at TRLs 4-6, where lab-validated concepts must transition through pilot and demonstration stages before reaching commercial viability (TRL 9). Table 2 outlines the TRL scale and its definitions according to the European Commission. While certain bio-based technologies have been successfully deployed in the market, a considerable number continue to encounter challenges related to technical and economic factors that hinder their large-scale implementation. Scaling up emerging bio-based processes requires substantial investment, often ranging from several million to hundreds of millions of euros. In addition, solutions to technical challenges are necessary, such as efficient biomass pre-treatment and the downstream purification of target compounds[3].

Table 2 – Definition of the different Technology Readiness Levels (TRLs)[4].

Technology Readiness Levels	Definitions applied
TRL 1	Basic principles observed
TRL 2	Technology concept formulated
TRL 3	Experimental proof of concept
TRL 4	Technology validated in lab
TRL 5	Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	System prototype demonstration in operational environment
TRL 8	System complete and qualified
TRL 9	Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

In contrast to fossil-based processes, which have benefited from decades of optimisation and existing infrastructure, many bio-based systems require the establishment of dedicated biorefineries, logistics networks and supply chains. A key challenge in this transition is de-risking investment. Investor reluctance often stems from the long timelines, technological uncertainty, and limited short-term returns associated with scaling early-stage bio-based innovations. This hesitation is not necessarily due to a lack of willingness amongst stakeholders in the value chain, but rather to structural financing barriers and risk-aversion

[3]Dias de Souza, N.R., et al., Challenges and opportunities toward a sustainable bio-based chemical sector in Europe, WIREs Energy and Environment 13(4) (2024) e534. https://doi.org/10.1002/wene.534

[4]Technology Readiness Levels | Eligibility | General Conditions | 15. General Annexes | Horizon Europe Work Programme 2026-2027 | European Commission Decision C(2025) 8493 of 11 December 2025 [online].

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typical of capital-intensive sectors. Furthermore, the necessity for interdisciplinary expertise (spanning biotechnology, chemistry, engineering, and digital technologies) adds complexity to the development process. This underscores the importance of cross-sector collaboration and targeted policy support.

- **Economic viability**: The higher production cost of bio-based products compared to their fossil-based counterparts remains a significant barrier. Improved product competitiveness and profitability are crucial drivers for the industry's development[5]. The feasibility of bio-based chemicals production is challenged by several factors, including: the variability of biomass quality, which affects processing efficiency and product consistency, reduced cost-competitiveness as a result of low oil prices, which make petroleum-based alternatives more attractive, and the need for substantial capital investments in new processing facilities and technologies. Additionally, the bio-based industry faces challenges in achieving economies of scale, as production volumes are often lower than those of established conventional processes.
- **Sustainability assessment**: Robust benchmarking of bio-based products against their fossil counterparts is challenging, as most assessments focus primarily on potential GHG mitigation rather than comprehensive sustainability metrics. The sustainability of bio-based products depends on various factors, including biomass availability, conversion processes, use phase, and end-of-life considerations. Life Cycle Assessment (LCA) has emerged as the default tool for evaluating the environmental impact of bio-based products, but it often falls short in capturing the full spectrum of sustainability indicators. A critical assessment of biomass potentials to mitigate sustainability challenges of the EU industrial sector is currently missing. Assessing the socioeconomic and environmental impacts is hindered by the limited knowledge about the industrial-scale performance of production processes of several bio-based chemicals and plastics. This knowledge gap is particularly pronounced for technologies with low TRLs, which struggle to compete with established fossil-based alternatives. The lack of harmonisation and standardisation of sustainability assessment of bio-based chemicals and plastics, including how to scale-up low TRL technologies, how to account for and calculate biogenic carbon flows, and methods to measure associated toxicity and pollution from chemicals and plastics, poses significant challenges[6]. All this has led to inconsistent labelling, contradicting LCAs, which are amongst the consequences of a lack of information related to bio-based materials. To combat these issues, there is a growing need for consensus-building amongst stakeholders, international consistency in approaches, and the development of science-based, flexible, and verifiable assessment methodologies.

[5]Joint Research Centre: Institute for Prospective Technological Studies, Nattrass, L. et al., The EU bio-based industry: Results from a survey, Publications Office, 2016, **https://data.europa.eu/doi/10.2791/806858**

[6]Aligning Life Cycle Assessment methods and bio-based sectors for improved environmental performance | ALIGNED | Project | Fact Sheet | HORIZON | CORDIS | European Commission

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- **Investment and funding**: The availability of funds to invest in production capacity remains a major constraint for the development of the bio-based industry. Substantial investments are necessary to scale-up low TRL technologies to a commercial scale, but given the innovative nature of these technologies, such investments carry high risks and face challenges in obtaining funding due to the requirements for market size, financing, and technical issues. For instance, the European Investment Bank (EIB) provided between €3-8.4 billion to support innovative financing solutions in the agriculture and bioeconomy sector by 2024[7]. Private investors are often reluctant to invest in R&D&I bioeconomy projects because of uncertainties and risks in terms of regulation and policy, technology, market demand as well as feedstock supply issues[8]. This reluctance is exemplified by the fact that only 6% of venture capital investments in Europe go to bioeconomy start-ups[9]. Investing in and building new, modern and innovative biorefineries is a long-term and capital-intensive undertaking. The typical cost of such facilities ranges from €50 million to over €100 million for large-scale facilities.
- **Lack of policies related to investment and demand for bio-based products**: An absence of incentives or efficient policies and a lack of demand-side policy drivers or standards/definitions are hampering the sector's growth. The European bio-based industry faces challenges due to insufficient regulatory support, particularly when compared to fossil-based alternatives. A lack of general measures constraining the use of fossil-based resources (e.g., a comprehensive carbon tax) is viewed as a threat for some product categories, preventing the further development of bio-based technologies. For instance, while the EU Emissions Trading System (ETS) covers certain industries, it does not yet fully account for the potential carbon savings of bio-based products. There is a need for targeted policies and a coherent, long-term policy framework to promote and accelerate the market entry of bio-based innovations and boost necessary investments. This could include measures such as green public procurement policies, tax incentives for bio-based products and mandatory blending quotas for certain bio-based materials in specific applications.
- **Need for Coordinated Public-Private Support in Scaling Bio-Based Innovation**: The industry needs targeted and coherent support for scaling up bio-based innovation, including creating synergies between funding schemes (private, public, national, regional, EU). This challenge is exacerbated by the high capital expenditure (CAPEX) required for facilities and the long timeframes needed for return on investment. Addressing this issue implies not only financial support, but also policy frameworks that encourage long-term investments in bio-based technologies. However, more coordinated efforts are needed to bridge the gap

[7] €3 billion of EIB Group financing announced for farmers and bioeconomy | Newsroom | European Investment Bank

[8] A sustainable bioeconomy for Europe - strengthening the connection between economy, society and the environment: updated bioeconomy strategy | Knowledge for policy

[9] Raising Disruptive Bioeconomy Ventures, Startups and Spin-offs to the top | BioeconomyVentures | Project | Fact Sheet | H2020 | CORDIS | European Commission

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between research and commercialisation, especially the critical phase of scaling up promising technologies.

- **Issues related to citizens or public perception**: Market penetration of bio-based products critically depends on the acceptance and participation of citizens. Poor public perception and limited awareness of industrial biotechnology and bio-based products remain significant challenges[4,5,10]. This lack of understanding often stems from misconceptions about the environmental impact, the production of biomass and the safety of biotechnology processes. Additionally, concerns about greenwashing (where products are marketed as environmentally friendly without sufficient evidence) can undermine consumer trust and hinder market growth. Improving citizens' perception and consumer confidence in bio-based products is crucial for market growth. This can be supported through transparent communication, education initiatives and clear, verifiable labelling schemes. In this context, the European Committee for Standardisation (CEN) has developed several standards and technical reports for bio-based products. These include EN 16785-1 and EN 16785-2, which provide harmonised methodologies for determining bio-based content through radiocarbon analysis, elemental analysis and mass balance approaches, as well as CEN/TR 17341, which provides guidance and examples for reporting sustainability criteria. Complementary implementation initiatives and guidance documents developed by sectoral organisations further facilitate transparency and the reliable communication of bio-based attributes to the market. Together, these harmonised frameworks contribute to greater transparency, comparability and credibility, helping to strengthen consumer trust and reduce the risk of greenwashing within the bio-based sector[11] [12] [13] [14].
- **Regulatory barriers to bio-based development**: The current regulatory framework can be highly restrictive in terms of insurance, often adhering to the principle of "one material, one use, one standard", which can hinder innovation and flexibility in the bio-based sector. This approach limits the potential for multipurpose applications of bio-based materials and can slow down the development of new products. A notable lack of regulations exists that are related to industrial biowaste which need to effectively address end-of-waste criteria. The end-of-waste concept is crucial for transitioning materials from waste status to valuable

[10]Sijtsema, S.J., et al. Consumer perception of bio-based products – an exploratory study in 5 European countries. NJAS: Wageningen Journal of Life Sciences 77(1) (2016) 61-69, **https://doi.org/10.1016/j.njas.2016.03.007**

[11]CSN EN 16785-1: Bio-based products - Bio-based content - Part 1: Determination of the bio-based content using the radiocarbon analysis and elemental analysis

[12]CSN EN 16785-2: Bio-based products - Bio-based content - Part 2: Determination of the bio-based content using the material balance method

[13]TNI CEN/TR 17341: Bio-based products - Examples of reporting on sustainability criteria

[14] NEN (Koninklijk Nederlands Normalisatie-instituut). (2016). *NCS 16785:2016-11. Bio-based content certification scheme*. NEN. https://biobasedcontent.eu/app/uploads/2016/11/NCS-16785-2016-11.pdf

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resources, but the criteria are not yet fully developed for all relevant bio-based streams. The EU Waste Framework Directive specifies that to achieve end-of-waste status, materials must undergo a recovery operation and meet specific criteria, including common use, market demand, fulfilment of technical requirements, and absence of adverse environmental or health impacts. The EU regulatory framework should promote and accelerate the market entry of sustainable innovations and boost necessary investments. This could involve implementing market stimulation measures, developing tools such as standards and labels for better evaluation of bio-based products, and considering mandates or bans to drive environmentally friendly innovation[15].

- **Higher production costs compared to conventional products**: Bio-based products often have higher production costs compared to conventional products, affecting their market competitiveness. This cost disparity is primarily due to economies of scale, with fossil-based industries benefiting from decades of optimisation and infrastructure development. Additionally, there is a limited market for national bio-based products which are perceived to be more expensive than fossil-based products, while advantages and benefits are not well communicated. According to a comparative study focused on bio-based value chains for chemicals, plastics and pharmaceutics[16], the overall costs of the bio-based products in Europe remain significantly higher than those of fossil-based alternatives. On average, bio-based products can carry a perceived price premium of 10 to 50%. This perception gap stems from a lack of consumer awareness regarding the long-term environmental and economic benefits of bio-based alternatives, such as reduced carbon footprint and potential for local job creation. Meanwhile, the low market price and widespread availability of fossil-based products continue to drive purchasing decisions.
- **Market development**: There is a need to develop markets for sustainable and circular bio-based products and processes to reduce dependence on fossil-based feedstock. This development requires a multifaceted approach, including consumer education, policy support, and industry innovation. For instance, the potential for indirect land use change impacts of biofuels (ILUC) effects on food and feed availability and prices creates ethical and environmental concerns[17]. ILUC occurs when the cultivation of crops for biofuels or bio-based products displaces traditional food crops, potentially leading to the conversion of land elsewhere to fill the gap in food production. This phenomenon can result in unintended GHG emissions and biodiversity loss. For this reason, the European Union has implemented

[15] Interreg: North-West Europe BioBase4SME: Needs and challenges of companies in the bioeconomy in NW Europe

[16] Spekreijse, J., et al., Bio-based value chains for chemicals, plastics and pharmaceuticals – A comparison of bio-based and fossil-based value chains, Publications Office, 2021, **https://data.europa.eu/doi/10.2760/712499**.

[17] Directive (EU) 2015/1513 of the European Parliament and of the Council of 9 September 2015, amending Directive (EU) 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.

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measures such as the RED II, which sets sustainability criteria for biofuels and establishes limits on high ILUC-risk feedstocks. The development of advanced biofuels from non-food crops, waste, and residues is being prioritised to mitigate ILUC risks and promote a more sustainable bioeconomy[18].

- **Strategic autonomy**: Growing the market for bio-based products is essential for enhancing Europe's strategic autonomy, as these products are largely sourced, manufactured, used, and recycled within Europe. This approach reduces dependence on fossil-based imports and strengthens the resilience of European supply chains. By fostering the growth of bio-based products, Europe can leverage its domestic resources, stimulate rural development, and create new job opportunities in the bioeconomy and related sectors, which already provide 17.5 million jobs across the Europe post-Brexit[19].
- **Global competition**: Europe faces increasing competition from other regions, particularly the US, China, and India, which are more forward-leaning in recognising and supporting their bioeconomy. The bioeconomy landscape is rapidly evolving, with these nations implementing ambitious strategies to leverage their local industrial, research and renewable resources. For instance, India has recently launched its BioE3 policy, aiming to achieve a US$300 billion by scaling up high-performance manufacturing[20,21]. Similarly, the Chinese '14th Five-Year Plan for Bioeconomy Development (2021-2025) defines a comprehensive roadmap through bioeconomy focusing on strengthening innovation, cultivating bioeconomy industries, and achieving high-quality development[22,23].

To address these challenges and maintain its leadership role, the EU needs to accelerate its efforts in bioeconomy innovation, research and commercialisation. To this end, the EU is taking steps through cooperation initiatives like the EIT Food or CBE JU. The latter will allocate €172 million in 2025 to advance competitive circular bio-based industries across 13 targeted topics[24]. These topics include flagship projects like urban-industrial symbiosis for biowaste valorisation, sustainable macroalgae systems, and the development of bio-based polymers designed to replace hazardous

[18] Directive (EU) 2023/2413 of the European Parliament and of the Council of October 2023, amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.

[19] Ronzon, T., et al. Developments of economic growth and employment in bioeconomy sectors across the EU, Sustainability 12(11) (2020) 4507; **https://doi.org/10.3390/su12114507**

[20] BioE3 Policy: Accelerating Sustainable Biomanufacturing Initiatives and Bioeconomy Growth in Delhi, India

[21] BioE3 (Biotechnology for Economy, Environment and Employment) Policy | Current Affairs | Vision IAS

[22] Zhang, X., et al., The roadmap of bioeconomy in China, Engineering Biology 6(4) (2022) 71-81. **https://doi.org/10.1049/enb2.12026**.

[23] China unveils five-year plan for bioeconomy | National Development and Reform Commission (NDRC) People's Republic of China

[24] Ten years upscaling the bio-based sector and promoting commercialisation | Circular Bio-based Europe Joint Undertaking (CBE JU)

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chemicals. Such initiatives are expected to enhance resource efficiency and foster industrial symbiosis while scaling up innovative technologies to market readiness.

Additionally, the EU is working on implementing market stimulation measures by developing tools like certifications, standards and labels to build consumer trust and ensure product traceability. The EU is also exploring regulatory instruments like mandates and bans to drive environmentally friendly innovation. These efforts aim to improve feedstock use efficiency, overall sustainability, and the competitiveness of the bio-based industry through upcycling and cascading use of biomass produced from side-streams[25]. Furthermore, strategic partnerships between regions and industries are being encouraged to secure a resilient biomass supply chain while fostering local job creation and inclusive economic growth.

1.2.2 Country-specific challenges

1.2.2.1 Belgium[26] [27] [28]

Belgium is divided into three highly autonomous regions: the Flemish Region (Flanders) in the north, the Walloon Region (Wallonia) in the south, and the Brussels-Capital Region in the centre. Due to its federal governance structure, bioeconomy-related policies and initiatives are often developed at regional level. The following overview focuses primarily on the Flemish bioeconomy, which represents one of the most advanced bioeconomy ecosystems in Europe.

Current state of the Belgian bio-based industry

Flanders offers favourable conditions and strong expertise in various aspects of the bioeconomy, providing a solid foundation for further development: The region benefits from a productive and high-value agricultural sector supported by fertile soils, a temperate climate and highly workable arable land that is easy to work. Local farmers and knowledge centres possess strong expertise, and Flanders is home to leading agricultural machinery manufacturers. Additionally, both the chemical sector and the food processing industry are highly developed, contributing to strong technological expertise across industry and research. These sectors have pioneered integrated valorisation models for both fossil-based and bio-based feedstocks, particularly for plant- and animal-derived streams.

[25] Producing novel non-plant biomass feedstocks and bio-based products through upcycling and the cascading use of brewery side-streams | CHEERS | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[26] Werkagenda bioeconomie (2023) – Bioeconomie van ambitie tot actie.(Bioeconomy Work Agenda (2023) – From Ambition to Action) [website Vlaanderen Circulair].

[27] Natuur en Bos | Agentschap voor Natuur en Bos.

[28] B2BE Facilitator - Bio-economie in Vlaanderen.

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Flanders is also recognised as a leader in waste management and circular economy practices. Furthermore, its strategic location in Western Europe, combined with extensive logistics and distribution infrastructure and access to major ports, provides strong international connectivity and facilitates collaboration between industry and research organisations.

Bioeconomy survey in Flanders

Recently, Agentschap Natuur & Bos (ANB) and the Business-to-BioEconomy (B2BE) Facilitator, in collaboration with the European Forest Institute (EFI), conducted an online survey on the bioeconomy in Flanders. The survey was widely distributed to bioeconomy stakeholders and completed by 111 respondents, of whom 56% represented government-related organisations, 21% industry stakeholders and 23% other stakeholder groups. When asked about the benefits of the bioeconomy, respondents identified renewable materials, the transition towards a low-carbon economy and reduced material consumption through increased reuse and recycling as the most important advantages (see Figure 1).

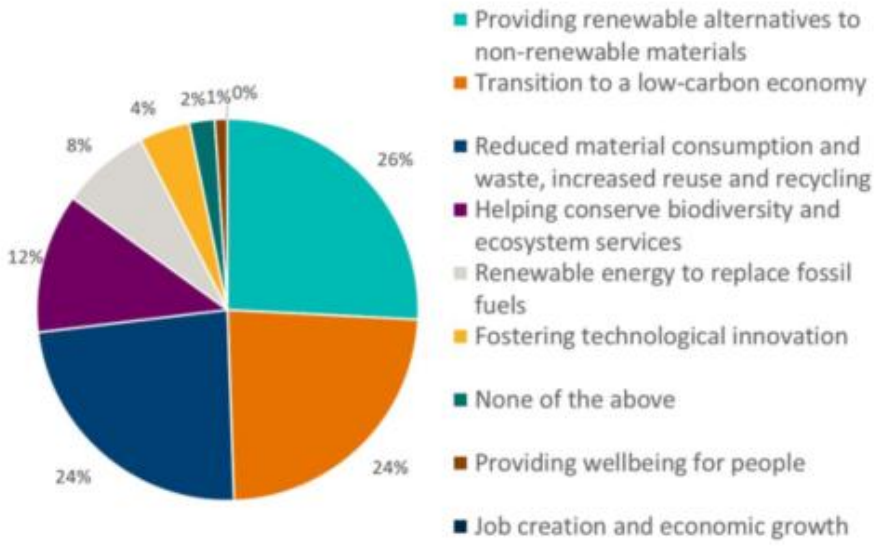


Figure 1 – Benefits of the bioeconomy

(source: Werkagenda bioeconomie (2023))

The survey also explored which sectors are perceived to have the greatest potential for the bioeconomy in Flanders. Green chemistry ranked highest as the sector with the most potential, followed by new advanced materials, bioplastics, and bioenergy (see Figure 2).

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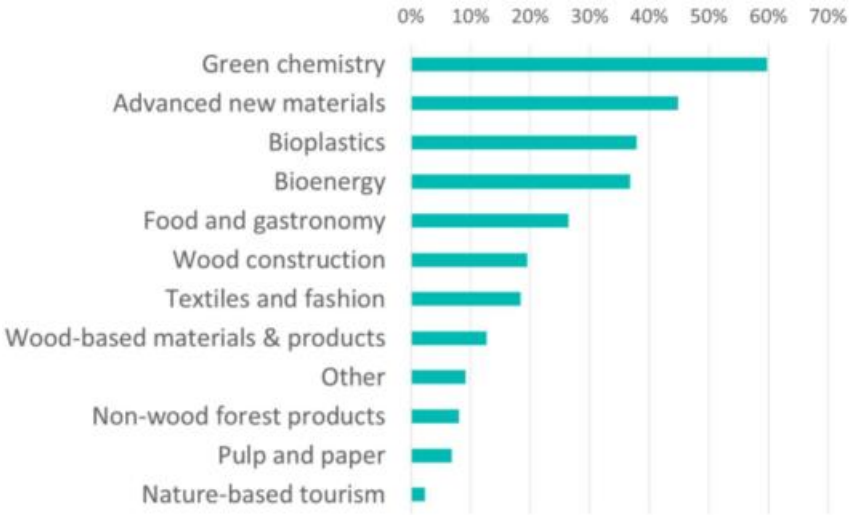


Figure 2 – Sectors with greatest potential for the bioeconomy

(source: Werkagenda bioeconomie (2023))

Main challenges in Flemish bioeconomy

Despite its strengths, several challenges limit the development potential of the Flemish bioeconomy. **Biomass availability and resource constraints** remain amongst the most significant barriers. Flanders faces limited land availability and a relatively scarce domestic biomass supply compared with the size of its economy. High population density, urban expansion, and the continued growth of the built environment place increasing pressure on land use and contribute to the fragmentation of biomass resources, creating logistical challenges for their efficient aggregation and utilisation. Furthermore, the composition of many raw materials, particularly residual and by-product streams, is highly variable, complicating large-scale valorisation and industrial processing.

Another important challenge relates to **competitiveness and market barriers**. Bio-based products and processes must compete with well-established fossil-based alternatives that benefit from decades of technological optimisation, mature supply chains, and economies of scale. This often makes it difficult for innovative bio-based solutions to achieve economic competitiveness and broader market penetration.

The Flemish bioeconomy also faces **environmental and sustainability challenges**. While the bioeconomy can contribute significantly to climate mitigation and environmental sustainability, changing climatic conditions may affect biomass availability and the predictability of agricultural and forestry production. At the same time, bioeconomy development must continuously balance production objectives with biodiversity protection and other ecosystem services. Although bio-based solutions often deliver environmental benefits such as improved soil quality, lower carbon footprints, and climate mitigation, these benefits do not always generate immediate economic returns. In addition, side streams and lower-value by-products require continuous attention, as their valorisation is often essential to the overall viability of bio-based business models. Residual streams may already have existing applications and markets, meaning that the development of new uses must carefully

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avoid market distortions and ensure the creation of genuine economic, environmental, and social added value.

Further challenges arise from **governance, regulatory, and strategic issues**. Agriculture, forestry, and landscape management typically operate over medium- to long-term planning horizons and therefore cannot rapidly adapt to changing market conditions or policy priorities. Similarly, investment decisions in bioeconomy sectors are often based on long timeframes, requiring stable and predictable policy frameworks that are not always available. Existing regulatory barriers, including those related to waste management, nutrient management, and other sectoral regulations, can slow innovation and the deployment of new bio-based solutions. In addition, the distribution of responsibilities across European, federal, and regional governance levels can result in regulatory inconsistencies and create additional complexity for stakeholders. Defining clear long-term strategic priorities is therefore essential, although Flanders remains exposed to broader global developments that may influence future bioeconomy pathways.

Survey results further highlighted **risk perception and stakeholder engagement challenges**. Respondents identified biomass availability as the principal perceived risk for the future development of the Flemish bioeconomy, followed by concerns regarding impacts on ecosystem services and the potential negative effects of biomass imports on developing countries (see Figure 3).

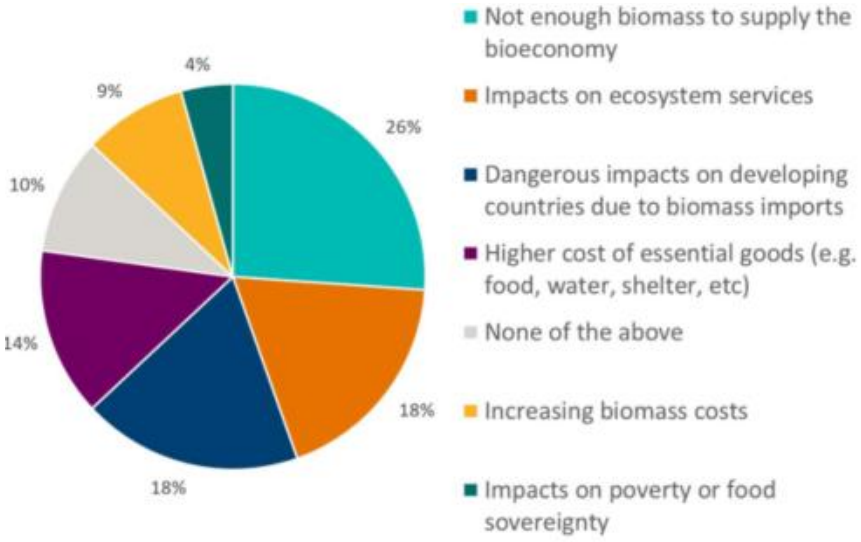


Figure 3 – Risks of the bioeconomy.

(source: Werkagenda bioeconomie (2023))

In addition, stakeholders identified the lack of a supportive legal and policy framework, insufficient cooperation amongst actors across the value chain, and limited financial profitability and market demand for bioeconomy products as some of the main obstacles preventing the sector from reaching its full potential.

Suggested approaches to address challenges in Flemish bioeconomy

There are many opportunities to further develop a sustainable Flemish bioeconomy:

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- **Sustainability goals in industry** are driving companies to align with net-zero targets. The bioeconomy enables the substitution of fossil fuels, chemicals and carbon-intensive materials and new links between agriculture and industry for bio-based resource use.
- **Bioeconomy development** supports the valorisation of low-value streams, nutrient and carbon cycling, and the integration with industrial by-products, such as waste heat and CO_2.
- **Government policy support** is a key trigger for business investment.

The bioeconomy can drive positive change in agriculture, including reduced dependence on synthetic fertilisers, improved soil quality (more organic matter), climate-positive farming practices, reduced nutrient leaching and erosion, valorisation of residual and by-product streams, creation of new markets and partnerships, better profitability and retention of capital within the Flemish economy. Biomass logistics require optimised supply chains and the creation of central hubs. Aggregating diverse streams may create synergies and better match supply to demand. Given limited biomass availability, Flanders should focus on specialised markets and applications where unique bio-based properties provide clear value. This need for specialisation is driven by both resource constraints and technological requirements. By capitalising on these opportunities and addressing the identified barriers, Flanders can further strengthen its position as a leading European bioeconomy region while supporting sustainable industrial development, circular resource use and long-term climate objectives.

1.2.2.2 Bulgaria[29] [30] [31] [32] [33]

Bulgaria, located in Southeastern Europe, has a population of approximately 6.9 million and a land area of 110,994 km², with 38% covered by forests and 46% used for agriculture. The country's bioeconomy is a key economic sector, employing approximately 773,500 people (representing almost one-quarter of the workforce) and generating €4.3 billion in gross domestic product (GDP), which represents one-seventh of the total economy. The Bulgarian bioeconomy is characterised by a predominant focus on primary production, with the agricultural sector, forestry, and food processing collectively accounting for over 75% of bioeconomic value-added. The country is a major producer of cereals (including wheat, maize, and barley), industrial crops (such as sunflower and rapeseed),

[29] Kaneva, K., et al. Executive summary of the strategic concept paper for bioeconomy: Bulgaria (2023) BIOEASTsUP H2020 Project.

[30] Republic of Bulgaria, Ministry of Energy & Ministry of the Environment and Water (2021). Integrated Energy and Climate Plan of the Republic of Bulgaria 2021–2030

[31] Adjarova, L., et al., National Bioeconomy Dossier: Bulgaria. WWF Bulgaria (2020) Bio-Based Industries Joint Undertaking (BBI-JU), Horizon 2020

[32] Kotseva-Tikova, M., Benefitting from the development of the bioeconomy: the case of Bulgaria. Regional Formation and Development Studies, 38(3) (2022) 25-33. **https://doi.org/10.15181/rfds.v38i3.2442**

[33] Bulgarian Industrial Association, Thracian University, & Stakeholders Working Group of Stara Zagora Region. Strategy for Development of the Bioeconomy in Stara Zagora Region (2021). BE-Rural, Horizon 2020

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and essential oils (such as rose and lavender). Furthermore, emerging bio-based industries include herbal phyto-pharmaceuticals, timber products, bioenergy, and bio-based textiles.

Current state of the Bulgarian bio-based industries

Despite its strong biomass resource base, Bulgaria continues to export raw biomass and import bio-based products in large quantities, highlighting the absence of high-value processing industries. The country has 29 biorefineries, the majority of which are engaged in the production of biofuels, but the infrastructure for advanced bio-based material processing (e.g., bioplastics and bio-based chemicals) is underdeveloped. The bioenergy sector is expanding, with 11 biogas plants, two wood-chip-based district heating plants (Sliven and Gabrovo), and multiple facilities utilising wood waste for energy production. Some sectors already demonstrate strong performance, including rose oil production, herbal medicines, timber products and other traditional bio-based activities. In addition, emerging examples of innovative bioeconomy business models can be found throughout the country. For instance, Svilosa AD in Northern Bulgaria specialises in bio-based textiles, while Mondi Stambolijski in South Central Bulgaria processes biowaste into energy, demonstrating the potential of circular bioeconomy approaches. The Integrated National Energy and Climate Plan (INECP) 2021-2030 recognises the role of biomass in Bulgaria's energy transition, particularly through biofuel production, wood-based heating solutions and anaerobic digestion.

Key Challenges in Bulgaria's Bioeconomy

Bulgaria faces several challenges that limit the development of a more advanced and competitive bioeconomy. **Technology and innovation challenges** remain amongst the most significant barriers. Although the country hosts several research institutions with expertise relevant to the bioeconomy, collaboration between academia and industry remains limited, reducing the effectiveness of knowledge transfer and the commercialisation of innovative technologies. In addition, the adoption of digital agriculture and precision farming technologies remains relatively low, constraining improvements in productivity, biomass utilisation, and resource efficiency. Compared with more advanced European bioeconomy countries, Bulgaria also lacks extensive industrial infrastructure for the production of higher-value bio-based products such as bioplastics, bio-based chemicals, and advanced biomaterials.

Another important obstacle concerns **policy and regulatory challenges**. Bulgaria has not yet adopted a dedicated national bioeconomy strategy and instead addresses bioeconomy-related issues through several separate policy frameworks, including the National Development Programme "Bulgaria 2030", the Circular Economy Strategy 2022–2027, and the Rural Development Programme. This fragmented policy landscape can limit coordination across sectors and reduce strategic coherence. Furthermore, the absence of a clearly defined regulatory framework for bio-based products creates uncertainty for investors and may delay commercial-scale deployment of innovative solutions. Small and medium-sized enterprises also face difficulties in accessing financing, while dedicated support mechanisms for bio-based start-ups remain relatively limited.

The country also faces **market and economic challenges** that restrict value creation within the bioeconomy. Despite being a major producer of agricultural and forestry biomass, Bulgaria continues

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to export significant quantities of raw materials, including cereals and wood, while importing higher-value processed bio-based products. This highlights the limited development of domestic processing industries and the resulting loss of economic value. Consumer demand for bio-based products remains relatively low, while higher production costs often reduce the competitiveness of bio-based alternatives compared with fossil-based products. Although sectors such as rose oil, herbal medicines, and wood-based products have achieved strong positions in international markets, emerging industries such as bioplastics and biofertilisers remain underdeveloped.

Further challenges are associated with **environmental sustainability and resource management**. Concerns have been raised regarding the long-term sustainability of forest resource utilisation, with approximately 66% of annual forest growth being harvested. At the same time, a substantial proportion of biomass residues and agricultural by-products remains underutilised because of inefficient collection, logistics, and processing systems. It is estimated that approximately one-third of available biomass resources are lost or wasted before reaching productive uses, reducing overall resource efficiency and limiting opportunities for circular bioeconomy development.

The role of the bioeconomy within Bulgaria's transition towards a climate-neutral economy is also affected by **energy transition challenges**. While the Integrated National Energy and Climate Plan (INECP) 2021–2030 recognises the importance of biomass for energy production, particularly through biofuels and biomass-based heat generation, less emphasis is placed on the development of bio-based materials capable of replacing fossil-based products in sectors such as construction, packaging, and manufacturing. As a result, important opportunities for carbon reduction and industrial decarbonisation remain underexploited. Furthermore, Bulgaria's continued dependence on coal creates additional challenges for the transition towards a more sustainable and diversified bio-based economy.

Suggested approaches to address challenges in Bulgaria's bioeconomy

Strategic policy interventions, innovation support mechanisms and market incentives are necessary to unlock Bulgaria's bioeconomy potential. The development of a dedicated National Bioeconomy Strategy is essential to improve coordination across the agriculture, forestry, energy, and industrial sectors. Such a strategy should prioritise high-value processing industries (e.g., bioplastics, bio-based chemicals, and advanced biofuels) to reduce dependence on raw material exports and increase domestic value creation. Regional bioeconomy hubs, such as the Bioeconomy Cluster in Plovdiv, should be further expanded to facilitate knowledge transfer, stakeholder cooperation and innovation commercialisation. Similarly, research and innovation funding should place greater emphasis on precision agriculture, biomass valorisation technologies and circular economy solutions. Financial incentives for bio-based SMEs and start-ups should be strengthened through green investment grants, tax incentives and dedicated support for bio-based infrastructure development. Public procurement of bio-based products in construction, food packaging and municipal waste management could also stimulate market demand. To support sustainable resource management, stricter forestry regulations should be implemented to prevent overharvesting and ensure the long-term availability of forest resources. The expansion of waste-to-energy initiatives (e.g., anaerobic digestion of agricultural residues) could significantly reduce biomass losses and

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improve resource efficiency. Finally, Bulgaria should strengthen the integration of bioeconomy objectives within climate and energy policies. This includes diversifying bio-based energy applications beyond biomass combustion and increasing support for carbon-negative solutions such as biochar production and carbon sequestration in forest ecosystems as part of broader EU Green Deal commitments. The Bulgarian bioeconomy therefore exhibits considerable potential, yet it remains constrained by policy fragmentation, insufficient innovation capacity and market barriers. The implementation of a coordinated strategy, sustained investment in innovation, stronger support for SMEs and better integration of bioeconomy solutions into climate policies are key measures that could support the development of a more sustainable, competitive, and resilient bio-based economy.

1.2.2.3 Croatia[34] [35] [36] [37] [38] [39] [40] [41]

Croatia possesses significant biomass resources and benefits from a strategic position within the European Union. The country's bioeconomy is strongly linked to agriculture, forestry and biomass-based sectors, which represent important economic activities in many rural regions. Despite these advantages, Croatia is still in a transition phase towards a more advanced and integrated bioeconomy model. While considerable biomass resources are available, challenges related to policy coordination, innovation uptake, industrial development and investment continue to limit the sector's full contribution to sustainable economic development.

Current state of the Croatian bio-based industry

Croatia's bioeconomy is currently dominated by primary biomass production, particularly in the forestry and agricultural sectors. The country remains strongly dependent on the production and export of relatively low-value biomass rather than the development of higher-value bio-based

[34] Croatia 2030: Roadmap for a better future (2020) | National Development Strategy Croatia 2030 | The World Bank

[35] Institute for Development and International Relations (IRMO) aktualno "Bioeconomy in Croatia - do we know where we are going?" (2022) | Institut za razvoj i međunarodne odnose

[36] Radic, T., et al., Defining the concept of "genuine farmer" under the common agricultural policy after 2020. Agriculturae Conspectus Scientificus 86(3) (2021) 265-270. **https://hrcak.srce.hr/file/382386**

[37] Kulisic, B., et al., Positioning The Croatian Linear Bioeconomy Towards Sustainable and Circular Bioeconomy. 2nd International Conference on the Economics of the Decoupling (ICED) (2021) 379-400.

[38] Glavan, D., Bioekonomija: izazovi i potencijali za održivi razvoj ruralnih područja. Master's thesis (2022) University of Zagreb. Repository Faculty of Agriculture University of Zagreb. **https://urn.nsk.hr/urn:nbn:hr:204:906798**

[39] Country Report Croatia 2020 | 2020 European Semester: Assessment of progress on structural reforms, prevention and correction of macroeconomic imbalances, and results of in-depth reviews under Regulation (EU) No 1176/2011 | Communication from the Commission to the European Parliament, the European Council, the Council, the European Central Bank and the Eurogroup

[40] Circular Economy Country Profile – Croatia | ETC CE Report 2022/5 | European Topic Centre - Circualr economy and resource use | European Environmental Agency

[41] Kulisic, B., et al., Positioning the biofuel policy in the bioeconomy of the BioEast macro-region. Biofuels 13(7) (2022) 833-842. **https://doi.org/10.1080/17597269.2021.1984165**

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products and advanced bioprocessing industries. The bioeconomy has been identified as a relevant development area within several national policy frameworks, including the Smart Specialisation Strategy (S3) and the National Development Strategy 2030. In 2020, the Croatian Government initiated the development of a dedicated national bioeconomy strategy, reflecting increasing recognition of the sector's strategic importance. However, the current industrial structure remains characterised by limited value-added processing capacity. The absence of advanced processing facilities restricts the country's ability to fully exploit domestic biomass resources and limits competitiveness in emerging bio-based markets.

Main challenges of the Croatian bio-based industry

Croatia's bioeconomy sector faces several systemic challenges that hinder its full development and integration into the European bioeconomy framework. **Policy and governance challenges** remain amongst the most significant barriers. Although bioeconomy-related objectives are addressed through several national policies, including the Smart Specialisation Strategy (S3) and the National Development Strategy 2030, Croatia still lacks a dedicated and fully implemented national bioeconomy strategy. While the Croatian Government initiated the development of such a strategy in 2020, uncertainty regarding its implementation has limited strategic direction and policy coherence. This fragmented governance landscape creates an unclear framework for businesses, research organisations, and investors, reducing the effectiveness of long-term planning and sector development.

Industrial development and structural weaknesses within key economic sectors represent another important challenge. Croatia is still heavily dependent on the production and export of low-value biomass, particularly from the agricultural and forestry sectors, rather than on the development of higher-value bio-based products and advanced bioprocessing industries. The limited availability of advanced processing facilities restricts the country's ability to fully valorise domestic biomass resources and capture additional economic value. Furthermore, employment in agriculture has declined, with a reported reduction of 57.7% since 2008, contributing to a shrinking workforce in key primary bioeconomy sectors and creating additional challenges for future sector development.

Croatia also faces **regulatory and administrative challenges**. The regulatory environment is often perceived as complex, with permitting and approval procedures creating delays for new investments and bio-based businesses. Such administrative burdens can discourage innovation and constrain the development of emerging bioeconomy sectors. At the same time, the existing regulatory framework does not yet provide sufficient support mechanisms to foster the growth and competitiveness of bio-based industries at either national or international level.

Finally, **investment and financing challenges** continue to affect the sector. Access to finance remains limited, particularly for innovative bioeconomy projects and early-stage companies. The availability of dedicated grant schemes, financial incentives, and specialised funding instruments for bio-based industries remains insufficient, while the high capital investment required for bioprocessing facilities can discourage private-sector participation. The absence of long-term

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strategic funding mechanisms further limits industrial development, innovation uptake, and the commercialisation of bio-based technologies.

Suggested approaches to address challenges in Croatia's bioeconomy

The development and implementation of a dedicated national bioeconomy strategy would provide a clearer framework for coordinating policy actions, attracting investments, and supporting long-term sector development. Improved alignment between national development policies, innovation strategies and bioeconomy objectives could help create a more coherent roadmap for stakeholders. Strengthening value-added biomass processing should be prioritised in order to reduce dependence on low-value raw biomass exports and increase domestic economic benefits. Investments in advanced processing facilities and bioprocessing infrastructure could significantly improve the competitiveness of Croatian bio-based industries. Greater support for research and innovation activities is also required. Enhancing collaboration between academia, research organisations and industry, together with the establishment of bioeconomy clusters and innovation hubs, could facilitate knowledge transfer and accelerate the commercialisation of bio-based technologies and products. Finally, simplifying administrative procedures, improving access to finance, and introducing targeted support mechanisms for bioeconomy projects could encourage private investment and foster the growth of emerging bio-based industries. These measures would support Croatia's integration into the European bioeconomy and help unlock the full potential of its biomass resources.

1.2.2.4 Cyprus[42] [43] [44] [45] [46] [47] [48]

Cyprus, the third largest island in the Mediterranean, has a population of approximately 1.2 million people. The country has a service-oriented economy, with tourism, shipping, and financial services contributing significantly to GDP. Although agriculture's contribution to the economy is relatively modest, it remains important for rural development, local food security and environmental

[42] Panoutsou, C., et al., Biomass supply in EU27 from 2010 to 2030. Energy Policy 37(12) (2009) 5675-5686. **https://doi.org/10.1016/j.enpol.2009.08.032**

[43] Kythreotou, N., et al., An assessment of the biomass potential of Cyprus for energy production. Energy 47(1) (2012) 253-261 **https://doi.org/10.1016/j.energy.2012.09.023**

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[45] Searle, S.Y., and Malins, C.J., Waste and residue availability for advanced biofuel production in EU Member States. Biomass and Bioenergy 89 (2016) 2-10. **https://doi.org/10.1016/j.biombioe.2016.01.008**

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[47] Republic of Cyprus. Cyprus' draft integrated National Energy and Climate Plan for 2021-2030 | Ministry of Energy, Commerce and Industry | STIP Compass

[48] Shaping the future bioeconomy across sectoral, governmental and geographical levels | ShapingBio | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

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sustainability. Cyprus' geographical location and climatic conditions present inherent natural constraints related to land availability and water resources, which directly influence the country's biomass production potential and the development of bioeconomy activities. Cyprus does not currently have a fully dedicated national bioeconomy strategy. However, several policy initiatives relevant to the bioeconomy have been implemented, including the Cyprus Action Plan for the Transition to a Circular Economy (2021-2027) and the National Energy and Climate Plan (NECP) (2020). These initiatives address issues related to waste valorisation, biomass utilisation for energy production and the promotion of circular economy approaches in sectors such as agriculture, aquaculture, and waste management. The dominant bio-based sectors in Cyprus include agriculture (providing employment for approximately 14,090 people), food and beverage processing (with similar number of employees to the agriculture sector), bio-based chemicals and plastics, waste management, aquaculture, and bioenergy. Although forestry remains a relatively small sector, sustainable forest management initiatives have contributed to increasing its value-added potential. Other relevant bio-based industries include wood products and biopharmaceuticals.

Current state of the bio-based industry in Cyprus

The bioeconomy in Cyprus remains at an early stage of development, with notable progress seen in waste management and bioenergy. Several initiatives have been launched to promote circularity and biomass valorisation. These include WASP TOOL project, which supports local authorities in implementing waste prevention strategies, and the UNLOCK initiative, which explores the conversion of waste streams from meat production into bio-based materials. In addition, the VALUEMAG project is researching the use of microalgae and aquatic biomass as feedstocks for future bio-based value chains. The private sector also includes companies active in biopharmaceuticals and bio-based packaging materials. However, the country still lacks large-scale biorefineries and advanced biomaterial production facilities. As a result, Cyprus remains largely dependent on imports for bio-based chemicals and bioplastics, highlighting the need to strengthen domestic production capacities and industrial value chains. The NECP recognises biomass and biogas as important components of the renewable energy mix. Current biogas production potential is estimated to range between 114 and 697 million m3, largely derived from livestock manure and food industry residues. Nevertheless, a more structured and coordinated approach to bioenergy development is still required.

Main Challenges for the Bioeconomy in Cyprus

Despite its potential, the bioeconomy in Cyprus faces several important constraints that limit its development and industrial expansion. **Biomass availability and resource mobilisation challenges** are amongst the most significant. The country's geographical conditions, characterised by limited arable land and scarce water resources, inherently restrict biomass production potential. At the same time, substantial quantities of agricultural residues from citrus orchards, olive groves, vineyards, and fruit production remain underutilised, with a significant proportion still being landfilled or burned on-site despite restrictions on open burning. Cyprus also generates considerable volumes of biodegradable waste (estimated at approximately 9.2 million tonnes annually) from municipal

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waste streams, food processing activities, and livestock farming. However, the absence of integrated collection, treatment, and valorisation systems limits the efficient utilisation of these resources.

Another important area concerns **bioenergy and infrastructure challenges**. Although biomass and biogas are recognised within the NECP, Cyprus has not yet established a fully integrated approach to bioenergy development and circular bioeconomy deployment. The expansion of bioenergy technologies is constrained by fragmented regulations, substantial capital investment requirements, and a limited range of economic incentives capable of supporting wider market uptake.

The country also faces **policy and governance challenges**. Cyprus does not currently have a dedicated national bioeconomy strategy, resulting in fragmented policy efforts and limited coordination between sectors and stakeholders. While initiatives such as the Circular Economy Action Plan, the Plastic Bag Levy and the THALIA Cohesion Policy Programme support relevant sustainability objectives, they do not provide a comprehensive framework for bioeconomy development. In addition, financial support for bioeconomy-related research, innovation, and industrial deployment remains relatively limited.

Further barriers are linked to **industrial development and market competitiveness challenges**. Bio-based industries in Cyprus operate under conditions characterised by relatively high production costs, limited economies of scale, and dependence on imported raw materials. As a result, the country continues to import significant quantities of bio-based products, including bioplastics and biofuels, due to insufficient domestic production capacity. Although some sectors, such as aquaculture, have experienced growth under dedicated national development plans, additional investments are required to strengthen local value chains, develop sustainable feed alternatives, and increase their contribution to the bioeconomy.

Finally, Cyprus faces **policy integration and strategic alignment challenges**. While the NECP recognises the contribution of biomass and waste-to-energy solutions to the energy transition, bioeconomy objectives are not yet fully embedded within broader economic and industrial development policies. Stronger integration between circular economy initiatives, renewable energy strategies, industrial policies, and innovation programmes would help improve resource efficiency, support industrial development, reduce emissions, and create new market opportunities for bio-based products and services.

Suggested approaches to address challenges in Cyprus' bioeconomy

The development of a dedicated national bioeconomy strategy would provide a coherent framework for policy coordination, stakeholder engagement and investment attraction. Such a strategy should be aligned with both the Circular Economy Action Plan and the NECP to ensure a coordinated approach to biomass utilisation, renewable energy production and sustainable industrial development. Investment in biomass valorisation infrastructure is essential. Priority areas include the expansion of anaerobic digestion facilities, the deployment of decentralised bioenergy systems and the improvement of waste collection, sorting and processing infrastructure. Lessons learned from successful waste prevention and resource efficiency initiatives could support these efforts. Moreover, financial support mechanisms should also be strengthened to facilitate research,

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innovation and commercialisation activities. Existing programmes such as THALIA 2021-2027 could incorporate dedicated funding instruments targeting bioeconomy projects and bio-based industrial development. Enhanced collaboration between academia, research organisation and industry will be also crucial to accelerate the development and deployment of innovative solutions in areas such as bio-based materials, sustainable agriculture, aquaculture and biopharmaceuticals. Finally, greater public awareness and consumer acceptance of bio-based products should be promoted through education campaigns, sustainability labelling schemes and green public procurement policies with the objective of stimulating demand for sustainable alternatives and support market growth. By implementing these actions, Cyprus could build upon its existing strengths in waste management, aquaculture and renewable energy while addressing key barriers related to biomass mobilisation, policy fragmentation and industrial capacity, thereby accelerating its transition towards a more sustainable and competitive bioeconomy.

1.2.2.5 Czechia[49] [50] [51] [52] [53] [54] [55]

The Czech Republic, located in Central Europe, is known for its robust industrial tradition, a resilient agricultural sector, and strong research and innovation capabilities. The country benefits from a well-developed infrastructure and a high level of technological innovation, particularly in manufacturing, food processing, forestry and environmental technologies.

The Czech Republic has been steadily developing its bioeconomy through policies focused on sustainable resource management, innovation, and research-driven solutions. Although the country does not yet have a dedicated national bioeconomy strategy, it has established an important policy framework through the "Concept of Bioeconomy in the Czech Republic" (2019–2024). This initiative aims to improve the efficiency of bio-based sectors, promote synergies amongst stakeholders and support effective public investment in research and innovation.

Key activities outlined include:

[49] Bioeconomy Platform of the Czech Republic | Czech University of Life Sciences Prague

[50] Concept of Bioeconomy in the Czech Republic 2019-2024 | The Ministry of Agriculture of the Czech Republic

[51] Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe | BioINSouth | Project | Fact Sheet | HORIZON | CORDIS | European Commission

[52] Kubánková, M., and Nedelník, J., BIOEAST HUB CZ. Executive Summary of the Strategic Concept Paper for Bioeconomy: Czech Republic (2023) BIOEASTsUP H2020 Project

[53] Closing-the-loop-on-wood: Circular Bioeconomy Opportunities in the Value Chain for Forest Products and Wood in Czechia | Institute of Circular Economy (INCIEN) | European Circular Economy Stakeholder Platform

[54] Czech Republic - Central and Eastern European Initiative for Knowledge-based Agriculture, Forestry and Aquaculture in the Bioeconomy | BIOEAST

[55] BOOSTing the bioeconomy transformation FOR (4) the BIOEAST region | BOOST4BIOEAST | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

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- **National Coordination**: Establishing interdepartmental working groups and steering committees to oversee bioeconomy initiatives is essential for effective coordination and management.
- **International Collaboration**: Engaging Visegrad Group countries and participating in international expert groups is key to advancing bioeconomy development.
- **Technological Advancement**: Participating in European research projects is complemented by a commitment to facilitating the transfer of research outcomes to stakeholders.

The Ministry of Agriculture considers the bioeconomy a key instrument for promoting sustainable management of natural resources, sustainable agriculture, forestry, water management, aquaculture, food production and the strengthening of primary producers within bio-based value chains.

Current state of the bio-based industry in Czechia

Several initiatives have contributed to the development of the Czech bioeconomy ecosystem. A significant milestone has been the establishment of the BIOEAST HUB CZ, which promotes collaboration amongst research organisations, policymakers, industry representatives and other stakeholders. In addition, projects such as BIOEASTsUP and Boost4BIOEAST have supported the development of strategic bioeconomy actions and strengthened regional cooperation.

The adoption of the "Strategic Framework of the Circular Economy of the Czech Republic 2040" further demonstrates the country's commitment to integrating bioeconomy and circular economy principles within broader sustainability policies. Czech participation in European research and innovation programmes has also contributed to technological advancement and knowledge transfer in bio-based sectors.

The Czech Republic benefits from a strong research and innovation ecosystem, supported by specialised institutions and research centres focused on bioeconomy, low-carbon development, and sustainable resource utilisation. These strengths position the country as an important emerging actor in the transition towards a sustainable bio-based economy.

Main challenges in Czechia's bioeconomy

Despite the progress achieved in recent years, several challenges continue to hinder the full development of the Czech bioeconomy. **Research and innovation capacity challenges** remain particularly important. Although the Czech Republic benefits from a strong research and innovation ecosystem and hosts specialised institutions working on bioeconomy and low-carbon development, continuous investment is needed to maintain and upgrade research infrastructures, strengthen scientific excellence, and support the development of innovative solutions for the sustainable use of biological resources. Ensuring that research capabilities keep pace with emerging technological opportunities will be essential for maintaining competitiveness within the European bioeconomy landscape.

Another key area concerns **investment and commercialisation challenges**. While a solid research base exists, additional financial support is needed to facilitate the transition from research results to

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market-ready products and services. The scale-up of innovative bio-based technologies and business models often requires significant investments, and further efforts are needed to strengthen financing mechanisms capable of supporting commercial deployment and industrial uptake.

The Czech Republic also faces **public awareness and stakeholder engagement challenges**. Increasing public understanding of the bioeconomy and its environmental, economic, and societal benefits remains important for strengthening consumer acceptance of bio-based products and encouraging broader participation in the transition towards a sustainable bio-based economy. Greater awareness can also contribute to stronger support for innovation, sustainable consumption patterns, and bioeconomy-related policy initiatives.

In addition, **regulatory and policy framework challenges** continue to influence the pace of bioeconomy development. Policymakers must balance the need to encourage innovation and investment with the need to maintain high environmental standards and ensure sustainable resource use. Establishing regulatory conditions that support innovation while avoiding unnecessary administrative burdens will be important to facilitate the development and deployment of new bio-based technologies and business models

Suggested approaches to address challenges in Czechia's bioeconomy

Further development of the Czech bioeconomy requires sustained investment in research and innovation infrastructures, strengthened mechanisms for technology transfer and commercialisation, and enhanced collaboration between academia, industry and public authorities. The further development and consolidation of the existing bioeconomy policy framework, aligned with circular economy objectives, could provide greater policy coherence and facilitate long-term investment. In parallel, increased public engagement and awareness-raising activities would support market acceptance of bio-based products and services, helping to accelerate the transition towards a sustainable and competitive bioeconomy.

1.2.2.6 Estonia[56] [57] [58] [59] [60] [61] [62]

[56] Estonia: Statistics | Global Insights | GlobalEDGE.

[57] Mapping Estonia's bio-based potential | Country-Report-Estonia-2020 | Bio-based Industries Consortium (BIC)

[58] Estonia 2023 Energy Policy Review | International Energy Agency

[59] Bioeconomy / Timber — Invest in Estonia

[60] Viira, A.H., et al., Executive summary of the strategic concept paper for bioeconomy: Estonia (2023) BIOEASTsUP H2020 Project

[61] Klimaministeerium & Regionaal-Ja Põllumajandusministeerium - Estonian Circular Bioeconomy Roadmap 2030 (ringbiomajanduse teekaart)

[62] Tetere, V., and Peerlings. J., Measuring the forest-based bioeconomy in Estonia, Latvia, Lithuania, and Finland. Scandinavian Journal of Forest Research 39(5) (2024) 226-231. **https://doi.org/10.1080/02827581.2024.2362216** .

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Estonia is a Northern European country located on the eastern coast of the Baltic Sea. With an area of 45,228 km^2 and a population of approximately 1.34 million people, its flat landscape (with an average elevation of 50 meters above sea level), abundant lakes (over 1,500) and bogs create a diverse environment shaped by a maritime climate of wet winters and cool summers, which influences agricultural practices and natural resource management. Estonia's bioeconomy is characterised by its strong forestry and agriculture sectors. Forests cover approximately 47-51% of Estonia's land area, contributing 7.22% to GDP through the forest-based bioeconomy, while agriculture occupies 20-22% of the territory, with a focus on cereals (barley and oats), oilseeds, and biomass production for renewable energy. The fisheries and aquaculture sectors, supported by Estonia's extensive coastline of 3,794 kilometres, also make a substantial economic contribution. The bioeconomy is a significant economic sector in Estonia, providing s substantial share of employment and making an important contribution to national GDP. It spans a wide range of sectors, including agriculture, forestry, fisheries, aquaculture, food processing, and parts of the chemical, biotechnology and energy industries. Emerging and interconnected bio-based sectors, including bioenergy, biochemicals and bio-based textiles, are also continuing to develop.

Current state of the bio-based industry in Estonia

Despite its strong biomass resource base, Estonia remains primarily a net exporter of raw biomass and an importer of high-value bio-based products, reflecting a gap in domestic value-added processing capabilities. Currently, Estonia has several operational biorefineries producing biofuels, mainly biodiesel and biogas derived from wood waste. However, there is limited infrastructure for advanced bio-based materials, including bioplastics and lignocellulosic biochemicals. The country's strategic focus on the circular bioeconomy aims to combine sustainability, economic and social development, and added value from natural resources. Estonia also possesses significant untapped biomass resources, with approximately 85,000 tonnes/year of manure and 450,000 tonnes/year of wood residues remaining underutilised. Although important progress has been made in the development of the bioeconomy, the sector continues to face challenges related to technological development, policy coordination, market integration and resource management.

Estonia-specific challenges

Despite its strong biomass resource base and growing commitment to the circular bioeconomy, Estonia faces several challenges that limit the development of higher-value bio-based industries. **Research, innovation, and technology deployment challenges** represent one of the main obstacles. Although the country benefits from a solid research and development base, including institutions such as the Estonian University of Life Sciences, collaboration between academia and industry is not always sufficient to ensure effective knowledge transfer and the commercialisation of innovative solutions. The uptake of digital agriculture and precision farming technologies is progressing but remains at a relatively early stage, limiting improvements in resource efficiency and circularity. Furthermore, Estonia lacks large-scale industrial facilities for the production of advanced bio-based materials, bioplastics, and bio-based chemicals, reducing opportunities to generate higher added value from domestic biomass resources.

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Another important constraint concerns **policy and governance challenges**. Bioeconomy-related actions are currently distributed across several ministries and policy domains, resulting in a fragmented governance framework. The absence of a fully integrated approach to bioeconomy development creates uncertainty for investors and can slow the market uptake of innovative bio-based products and technologies. In addition, financing opportunities for innovation projects remain insufficient for many SMEs, while targeted support mechanisms for bio-based start-ups are still relatively limited.

The country also faces **market and industrial development challenges**. Exports of raw materials, particularly timber and cereals, continue to exceed domestic processing activities, limiting the value generated within national bio-based value chains. Although consumer awareness and interest in bio-based products are gradually increasing, Estonia's domestic market remains relatively small. As a result, many bio-based products face difficulties achieving sufficient scale and competitiveness. While established sectors such as timber products and dairy perform strongly, emerging industries including bioplastics and biofertilisers have yet to achieve a significant market presence.

Further barriers are linked to **resource management and environmental sustainability challenges**. Forestry remains a cornerstone of the Estonian bioeconomy, but discussions continue regarding sustainable harvesting levels, long-term resource availability, and the valorisation of forestry residues. In addition, biomass losses during collection, storage, and processing reduce circularity and prevent the full utilisation of available biological resources. Significant quantities of manure and wood residues remain underutilised, highlighting opportunities for improved resource management and biomass valorisation.

The transition towards a climate-neutral economy also presents **energy transition challenges**. Estonia's National Energy and Climate Plan recognises the importance of biomass for renewable energy production through biofuels, anaerobic digestion, and wood-based heating systems. However, comparatively less attention has been directed towards the development of bio-based materials capable of replacing fossil-derived products in sectors such as construction, packaging, and manufacturing. This limits the contribution that the bioeconomy could make to industrial decarbonisation. In addition, Estonia's historical reliance on oil shale for energy production continues to present a significant challenge for the transition towards a low-carbon and more diversified bio-based economy.

Proposed opportunities and approaches to address challenges in Estonian bioeconomy

Several opportunities exist to strengthen Estonia's bioeconomy and address the challenges identified. Firstly, stronger collaboration between academia and industry could improve knowledge transfer and accelerate the commercialisation of high-value bio-based solutions (e.g., biochemicals, advanced biomaterials, novel biofuels and innovations in bioreactors). Secondly, the development of an integrated national bioeconomy roadmap, supported by clear standards and incentives for bio-based products, could provide greater policy coherence and stimulate market growth. Thirdly, improving access to financing and venture capital for bio-based industries, especially in rural areas, would support innovation, business development and local job creation. Fourthly, the promotion of

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circular bioeconomy approaches for the valorisation of agricultural residues, municipal biowaste, and forestry by-products could further enhance sustainability, resource efficiency and economic resilience. Finally, reducing dependence on oil shale and accelerating the transition towards renewable bioenergy and carbon-neutral bio-based products will be essential for achieving the objectives of the European Green Deal and national climate targets. The Estonian bioeconomy has significant potential but remains constrained by policy fragmentation, weaknesses in knowledge transfer and innovation deployment, and persistent market barriers. Implementing a coordinated strategy, investing in innovation, supporting SMEs and integrating bioeconomy solutions into climate policies will be key to building a more sustainable, competitive, and resilient bio-based economy.

1.2.2.7 France[63] [64] [65] [66] [67] [68]

France is one of Europe's leading bioeconomy countries, benefiting from extensive agricultural resources, a strong industrial base, advanced research capabilities, and a supportive policy framework. The country has played a pioneering role in the development of bio-based products and industrial biotechnology, supported by a diversified biomass resource base and a well-established network of research institutions, industrial clusters, and innovation platforms. The French bioeconomy has evolved significantly since the early 2000s, driven by increasing fossil fuel prices, growing environmental concerns, and regulatory pressures aimed at replacing substances with high environmental impacts. More recently, the ecological transition agenda and regulations such as RE2020 have reinforced the role of bio-based products and materials as key instruments for reducing dependence on fossil resources, supporting industrial competitiveness, and contributing to climate objectives.

Current state of the French bio-based industry

France has developed a mature and diversified bioeconomy ecosystem supported by national strategies, public funding programmes, industrial collaborations, and regional initiatives. Since 2018–2019, interest in bio-based products has accelerated, with many stakeholders shifting from

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[64] Anaerobic FermenTation & EsteRification of BIOmass for producing fine CHEmicals | AFTERBIOCHEM | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[65] high Performing and Safe Solvent Derived From Cellulosic Feedstocks | ReSolute | 887674 | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[66] Bioeconomy for Change en partenariat avec La Région GrandEast, Focus on the Bazancourt-Pomacle Biorefinery. (2023, June 15). Official Bioeconomy Portal of the Grand Est Region

[67] CO-creating the next generation platform of PILOT and demo infrastructures, unlocking faster innovation and EU bioeconomy growth | COPILOT | 101157279 | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[68] A network of bioeconomy open access pilot and multipurpose demo facilities | Pilots4U | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

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direct fossil substitutes ("drop-in" products) towards higher-value applications that better exploit the unique properties of biomass. This strategic orientation has opened opportunities in sectors such as specialty chemicals, cosmetics, nutraceuticals, advanced materials, and sustainable ingredients. Public support has played an important role in the development of the sector. The French environmental agency ADEME has supported bio-based innovation through programmes such as AGRICE (a long-standing initiative established in 1994 to promote the development of non-food uses of agricultural resources, including bio-based chemicals, materials and energy applications), while broader initiatives such as France 2030 have mobilised significant investments to strengthen the country's industrial and technological capabilities in strategic sectors, including the bioeconomy. France also benefits from a strong industrial base, including several flagship biorefinery projects. The Bazancourt-Pomacle biorefinery, developed through cooperation between agricultural cooperatives and industrial actors, is internationally recognised as a model of industrial symbiosis, integrating multiple value chains around agricultural feedstocks. More recently, facilities such as AFYREN NEOXY in Saint-Avold have demonstrated the commercial viability of circular biorefinery concepts, producing bio-based chemicals and fertilisers from sugar beet by-products within a zero-waste framework. Regional ecosystems play a particularly important role in the development of the French bioeconomy. The Grand Est region has positioned itself as a major bioeconomy hub, hosting leading research infrastructures, industrial projects, and bioeconomy clusters. Flagship initiatives such as AFTERBIOCHEM and ReSolute illustrate the region's capacity to develop innovative bio-based intermediates and solvents from agricultural and cellulosic feedstocks. Similarly, the Hauts-de-France region benefits from strong agricultural production and a well-developed industrial ecology ecosystem that supports bio-based chemical industries. Overall, France combines strong biomass availability, industrial know-how, research excellence, and public support mechanisms, making it one of the most advanced bioeconomy ecosystems in Europe.

Key Challenges in France's Bioeconomy

Despite its strong position within the European bioeconomy, France faces several challenges that may limit future growth and industrial deployment. **Business, investment and value-chain challenges** are still significant, particularly regarding the scale-up and commercialisation of innovative technologies. Many companies continue to face difficulties in securing investment for industrial deployment, while reductions in public funding have increased financing pressures. High production costs for bio-based products, combined with competition from lower-cost fossil-based alternatives, can affect profitability and market penetration. In addition, fragmented value chains, logistical challenges, limited cooperation amongst stakeholders, and constraints in biomass availability—especially second-generation sugars—can hinder the development of integrated bio-based industries. Competition between food, feed, energy, and industrial uses of biomass further increases pressure on available resources.

Technical challenges continue to affect industrial deployment and innovation. One of the main difficulties relates to the scale-up phase, where biological processes and microorganisms may behave differently under industrial conditions than they do at laboratory scale. This contributes to relatively high failure rates during technology transfer and commercialisation. Climate change also

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introduces additional risks by affecting the availability and productivity of biomass feedstocks such as flax and other agricultural resources.

Regulatory challenges remain an important concern for bioeconomy stakeholders. Lengthy administrative procedures, including processes such as Novel Food approvals, can delay market entry and increase costs. Uncertainty regarding the future evolution of French and European regulations, particularly in areas such as biofuels and sustainability requirements, may also affect investment decisions. Furthermore, the absence of harmonised standards in certain sectors, including construction materials and cosmetics, creates barriers to market development. The complexity of the legal framework, which spans agricultural, energy, industrial, and chemical legislation, can further complicate project implementation.

Market uptake and consumer acceptance challenges also influence the growth of bio-based industries. Public awareness of bio-based products remains relatively limited, and these products are sometimes perceived as less effective than conventional alternatives. In addition, consumers may be reluctant to pay premium prices for more sustainable products, limiting market uptake and slowing the expansion of bio-based markets.

Finally, **environmental assessment challenges** continue to generate debate within the sector. Different methodologies for life-cycle assessment (LCA), carbon accounting, end-of-life modelling, environmental declarations, and the use of mass-balance approaches can produce differing results and interpretations. The lack of harmonisation in these methodologies can make it more difficult to communicate and demonstrate the environmental benefits of bio-based products.

Proposed approaches to address challenges in France's bioeconomy

To strengthen the competitiveness and long-term sustainability of the French bioeconomy, greater emphasis should be placed on the development of high-value bio-based products capable of competing through performance and functionality rather than solely on cost. Sectors such as cosmetics, nutraceuticals, specialty chemicals, and advanced ingredients offer significant opportunities to exploit the unique characteristics of biomass while reducing direct competition with fossil-based products. Improving access to public and private financing will remain essential for supporting industrial scale-up and reducing the risks associated with the commercial deployment of innovative technologies. Stronger involvement of regional clusters, industrial partnerships, and European initiatives could help facilitate investment and accelerate the transition from pilot-scale development to full commercial production. Further efforts should focus on accelerating technology scale-up through improved access to pilot and demonstration infrastructures. Open-access facilities and collaborative platforms, such as those promoted through initiatives including COPILOT and Pilots4U, can help reduce technological risks, accelerate validation processes, and improve the success rate of industrial deployment. From a regulatory perspective, clearer and more stable policy frameworks, together with stronger incentives for the uptake of bio-based products, would help stimulate investment and support market development. The development of harmonised standards and certification frameworks across key sectors would further strengthen market confidence and facilitate commercialisation. Increasing consumer awareness of the environmental, health, and

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sustainability benefits associated with bio-based products will also be important to stimulate market demand. Finally, further work on the harmonisation of life-cycle assessment methodologies and environmental performance metrics would improve the ability of stakeholders to demonstrate the benefits of bio-based solutions and strengthen their position within increasingly sustainability-driven markets. By building on its strong industrial base, established biorefinery infrastructure, research excellence, and supportive innovation ecosystem, France is well positioned to consolidate its leadership within the European bioeconomy and accelerate the transition towards a more sustainable and competitive bio-based economy.

1.2.2.8 Greece [69] [70] [71] [72] [73] [74] [75] [76] [77] [78]

Greece, a Mediterranean country in Southeastern Europe, has a diverse landscape and a strong agricultural heritage, making it well-suited for bioeconomy development. The country possesses abundant biomass resources from agriculture, forestry, and fisheries, along with significant biodiversity that can support the production of bio-based products and bioenergy. The Greek bioeconomy contributes an estimated €27 billion in turnover and employs around 500,000 people, primarily in agriculture, food production and renewable energy. Key sectors include agriculture and forestry, marine resources, circular economy practices, bio-based industries (including bioplastics, biofuels and biotechnology) and green tourism linked to biodiversity conservation. Although, Greece faces economic and environmental challenges, including limited infrastructure for bio-based industries, fragmented policy implementation, and slow adoption of innovative bioeconomic

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solutions, the sector is increasingly recognised as a driver of sustainability, regional development and economic diversification.

Current state of the Greek bio-based industry

The Greek bio-based sector is still developing, with increasing activity in biomass utilisation, bioenergy, sustainable agriculture and biotechnology. Despite significant natural resources, the lack of a dedicated national bioeconomy strategy and fragmented sectoral policies continue to constrain its expansion. Nevertheless, ongoing initiatives, regional strategies and investments are positioning Greece as an emerging player in the European bioeconomy. Greece has implemented several policies that support its growth. These include the National Strategy for Circular Economy (2018), the National Renewable Energy Action Plan, and sector-specific frameworks related to forestry, agriculture, and waste management.

- **Bioenergy and Biomass Utilisation**: Greece operates 25 biogas plants and 12 biodiesel plants, producing approximately 130,000 m3 of biodiesel, mainly from sunflower and rapeseed feedstocks. The bioenergy sector has significant development potential, particularly in Western Macedonia, which is undergoing a post-lignite transition. Biomass, biofuels and green hydrogen projects are being developed to replace fossil-based energy sources, supported by the Just Transition Plan. The district heating networks in Kozani and Ptolemaida are notable examples of integrating biomass and waste-to-energy solutions into regional energy systems.
- **Agri-Food Industry and Waste Valorisation**: Agriculture is a major driver of the Greek bioeconomy, with 26% of manufacturing enterprises engaged in agri-food processing. Central Greece is becoming a centre for food waste valorisation initiatives. For example, the Agrovision Winery in Chalkidiki has implemented the reuse of wine industry by-products for disinfectant production, demonstrating circular bioeconomy principles. Similarly, the Regional Association of Solid Waste Management Agencies of Central Macedonia has implemented a Christmas tree shredding programme that converts word residues into biomass pellets and organic compost.
- **Forestry and Wood-Based Bioeconomy**: Although forests cover more than 30% of Greece's land area, the forestry sector contributes only 0.04% to GDP, indicating substantial untapped potential. Western Macedonia is actively exploring sustainable wood production and biomaterials for construction while investing in biorefinery concepts that convert forest residues into bio-based chemicals and fuels. However, fragmented land ownership and outdated forestry practices continue to restrict large-scale industrial development.
- **Biotechnology and Bio-Based Materials**: Biotechnology is an emerging sector supported by research organisations such as CERTH and NTUA. Bio-based products, including bioplastics and green chemicals, are under development, although they have not yet reached market-scale production. The BIOSKOH project in Western Macedonia represents one of the most advanced examples of biorefinery development in Greece, demonstrating the conversion of lignocellulosic feedstocks into high-value bio-based products.

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- **Blue Bioeconomy and Aquaculture**: Greece has the highest value of aquaculture output in the European Union, contributing approximately €844 million annually. Innovations in marine biomass utilisation and sustainable fish farming are increasing the sector's bioeconomy potential. However, waste valorisation within aquaculture remains relatively limited, with few large-scale initiatives focused on the conversion of fishery by-products into bio-based products.
- **Circular Bioeconomy and Smart Specialisation**: Several S3 platforms support bioeconomy development in Greece through innovation, sustainable resource management and enhanced regional competitiveness. Central Macedonia has established itself as a hub for digital agriculture, high-tech farming and food traceability systems, supported by universities, research institutions and industrial clusters. Region priorities include artificial intelligence (AI)-driven food supply-chain optimisation, sustainable crop management, bio-based fertilisers, smart irrigation systems and waste valorisation from food processing industries. Western Macedonia has adopted bioeconomy development as a key pillar of its Just Transition Plan. The region is increasingly focused on biomass, biofuels and sustainable forestry as alternatives to fossil fuel-based economic activities. The Cluster of Bioeconomy and Environment of Western Macedonia (CluBE) plays a pivotal role in promoting cooperation between industry, researchers and policymakers. Both regions recognise the importance of knowledge transfer, skills development and entrepreneurship. Programmes supporting start-ups and SMEs in bio-based value chains, bioplastics production and sustainable construction materials are expanding, while regional bioeconomy hubs, smart specialisation initiatives and digital platforms support industrial symbiosis and innovation.

Challenges in the Greek Bioeconomy

Greece faces several challenges that continue to constrain the development of a more integrated and competitive bioeconomy. **Technological and infrastructure challenges** remain amongst the most significant barriers. Biorefinery capacity is still limited, with many bio-based activities operating at pilot or small-commercial scale, particularly in areas such as bioplastics, biofuels, and green chemistry. Investment in biotechnology and bioprocess engineering remains insufficient to support large-scale industrial deployment, while the limited availability of advanced processing facilities restricts the valorisation of agricultural, forestry, and industrial residues. Although Greece generates substantial quantities of biomass and organic waste, a significant share remains underutilised, highlighting the need for more efficient collection, processing, and valorisation systems. In addition, skills shortages in specialised technical areas continue to affect the growth of emerging bio-based industries.

Another important constraint relates to **policy and governance challenges**. Although several national and regional policies support elements of the bioeconomy, Greece still lacks a dedicated national bioeconomy strategy capable of providing a coherent framework across agriculture, energy, industry, waste management, and circular economy policies. This fragmented policy landscape can reduce coordination amongst stakeholders and create uncertainty regarding long-term priorities. Furthermore, complex regulatory procedures and lengthy permitting processes may discourage

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investment, particularly for innovative SMEs and start-ups seeking to develop new bio-based products and technologies.

The sector also faces **economic and investment challenges**. Access to private capital remains relatively limited, and many bioeconomy initiatives depend heavily on European funding programmes and public support mechanisms. Higher production costs often reduce the competitiveness of bio-based products compared with fossil-based alternatives, while the limited scale of domestic bio-based industries can make it difficult to attract large investors. Although bioeconomy projects linked to waste valorisation, renewable energy, and biomass utilisation have gained momentum in some regions, broader mobilisation of private-sector investment will be necessary to support long-term growth and industrial deployment.

Further barriers are associated with **education, awareness, and skills challenges**. Public understanding of the bioeconomy and its potential benefits remains uneven, particularly in rural areas where bioeconomy activities could contribute significantly to local development. Research has shown that many farmers already apply practices consistent with circular bioeconomy principles without necessarily recognising them as such. Limited access to specialised training, advisory services, and professional development opportunities further restricts the adoption of innovative practices and technologies. Strengthening the alignment between educational programmes and industry needs will therefore be important for developing the skills required by the sector.

Finally, Greece faces several **cross-cutting sustainability and market integration challenges**. The incorporation of circular economy principles into bio-based value chains remains inconsistent despite significant opportunities for agricultural residue valorisation, composting, bio-based materials, and waste-to-energy solutions. Similarly, the deployment of smart agriculture technologies and digital tools has the potential to improve resource efficiency and productivity, but adoption remains uneven across regions and sectors. Strengthening links between circular economy initiatives, renewable energy deployment, industrial development, and regional innovation policies will be essential to maximise the contribution of the bioeconomy to Greece's sustainable development objectives.

Suggested Approaches to Strengthen the Greek Bioeconomy

To accelerate the development of Greece's bioeconomy, the following actions are recommended:

- Develop a national bioeconomy strategy to integrate sectoral policies and create a coherent roadmap for investment and innovation.
- Strengthen public-private partnerships to bridge the gap between research institutions and industry, fostering knowledge transfer and commercialisation of bio-based technologies.
- Enhance investment incentives through targeted funding mechanisms, tax breaks, and innovation grants for bio-based start-ups and SMEs.
- Expand circular bioeconomy projects in Western Macedonia and Central Greece, focusing on waste-to-energy solutions, bioplastics, and green chemicals.

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- Improve workforce training and education by introducing specialised curricula in biotechnology, bioengineering, and sustainable production in collaboration with universities and technical schools.
- Promote regional specialisation in bioeconomy by leveraging Western Macedonia's biomass potential and Central Greece's forestry resources to develop competitive bio-based industries.

1.2.2.9 Hungary[79] [80] [81] [82] [83]

Hungary, as a Central and Eastern European (CEE) country, has considerable potential for developing a bioeconomy due to its rich agricultural resources and growing interest in sustainability. The country possesses significant biomass resources and a strong agricultural base, creating favourable conditions for the development of bio-based industries and circular bioeconomy initiatives. However, despite this potential, Hungary faces a number of challenges that limit the effective implementation of a circular and bio-based economy. These challenges arise from policy fragmentation, insufficient support for research and innovation, limited integration across sectors and structural economic constraints.

Current state of the Hungarian bio-based industry

Hungary's bioeconomy potential is largely based on its agricultural biomass resources and related bio-based activities. Several national policy documents address bioeconomy-related objectives, including the National Clean Development Strategy, the S3 and the National Environmental Technology Innovation Strategy (NETIS). Hungary also benefits from a strong academic and scientific base that could support the development of bioeconomy-related technologies and innovations.

Nevertheless, the current innovation ecosystem remains insufficiently connected to industrial actors, limiting the commercial deployment of research outputs. Even though the country has significant biomass resources, the use of these resources is not as good as it could be because of limited industrial demand, insufficient market incentives, and a lack of advanced processing infrastructure. Consequently, a substantial portion of biomass is exported as raw material rather than being processed domestically into higher-value bio-based products. The development of circular

[79] Ministry of Rural Development. National Environmental Technology Innovation Strategy 2011-2020 | NETIS | Budapest, Hungary

[80] Hungarian Ministry of Agriculture, Department for Agricultural Research and Agri-Environmental Management, Executive Summary Of The Strategic Concept Paper For Bioeconomy: Hungary | 2023 | BIOEASTsUP H2020 project

[81] Mapping Hungary's bio-based potential | Country-Report-Hungary-2023 | Bio-based Industries Consortium (BIC)

[82] Juhász, R., and Steinwender, C., Industrial policy and the great divergence (2023) w31736. National Bureau of Economic Research.

[83] Hungarian Ministry of National Development. National Energy Strategy 2030

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bioeconomy solutions is further constrained by limited biorefinery capacity and a shortage of advanced bioprocessing facilities capable of converting biomass into innovative bio-based products.

Main challenges for Hungary's bio-based industry

Hungary's bioeconomy development is shaped by a combination of institutional, economic, technological, and human-capital challenges that limit the country's ability to fully exploit its substantial biomass resources and scientific potential. **Policy and governance challenges** stem primarily from the fragmented nature of the current policy framework. Although several national strategies address bioeconomy-related objectives, including the National Clean Development Strategy, the S3 and the NETIS, these instruments are not sufficiently integrated. The absence of a comprehensive national bioeconomy strategy reduces policy coherence, limits synergies across sectors, and weakens the overall effectiveness of implementation efforts.

A further constraint relates to **research, innovation, and technology-transfer challenges**. Hungary possesses strong academic and scientific capabilities, yet investment in bioeconomy-related research and innovation remains relatively modest compared with several Western European countries. The innovation ecosystem is characterised by limited collaboration between research organisations and industry, constraining the commercialisation of research outcomes. In addition, insufficient long-term investment and the limited availability of dedicated funding mechanisms create barriers to the development, scaling, and market deployment of innovative bio-based technologies.

The sector also faces **industrial integration and market development challenges**. Connections between agriculture, forestry, and bio-based industries remain relatively weak, limiting the creation of integrated value chains. Although Hungary is rich in agricultural biomass resources, domestic utilisation remains below its potential because of limited industrial demand and insufficient market incentives. As a result, a substantial share of biomass is exported as raw material rather than being transformed domestically into higher-value bio-based products, reducing opportunities for value creation and industrial diversification.

Investment and economic challenges further affect the competitiveness of the sector. High production costs, competition from imported bio-based products, and limited access to finance continue to constrain business development. Small and medium-sized enterprises often encounter difficulties when seeking capital, specialised technical expertise, and growth financing. Moreover, the banking sector has traditionally taken a cautious approach towards green and bio-based investments, reducing the availability of financial support for start-ups, scale-ups, and innovative industrial projects.

Another important area concerns **biomass utilisation and circularity challenges**. While Hungary benefits from abundant biomass resources, inefficiencies in collection, logistics, and processing systems result in avoidable resource losses. The limited availability of biorefineries and advanced bioprocessing infrastructure further restricts the conversion of agricultural and forestry biomass into higher-value products. Consequently, opportunities to strengthen circularity, improve resource efficiency, and increase domestic value creation remain underexploited.

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Finally, **skills and workforce challenges** may affect the long-term growth of the sector. The transition towards a modern bioeconomy requires specialised expertise in fields such as biotechnology, bioengineering, bioprocessing, and circular economy management. However, Hungary faces shortages of qualified professionals in several of these areas, limiting the capacity of companies and research organisations to develop, operate, and scale innovative bio-based solutions. Strengthening education, training, and skills development will therefore be essential to support the future competitiveness of the Hungarian bioeconomy

Suggested approaches to address challenges in Hungarian bioeconomy

Addressing the identified challenges will require coordinated action from policymakers, industry stakeholders, research organisations and educational institutions. The development of a comprehensive national bioeconomy strategy could strengthen policy coherence and improve coordination between existing national initiatives. Greater integration between agriculture, forestry, industry and research actors would help maximise the value of Hungary's biomass resources and support the creation of stronger bio-based value chains. Increasing investment in research, development and innovation, together with improved collaboration between academia and industry, would facilitate the commercialisation of bio-based technologies and accelerate market uptake. Enhanced financial support mechanisms, including incentives for SMEs, start-ups and green investments, could also stimulate private-sector participation. Further investment in biorefineries, advanced bioprocessing facilities and circular resource management infrastructure would help improve biomass utilisation and reduce resource losses. At the same time, strengthening education and training programmes in bioeconomy-related disciplines would contribute to closing existing skills gaps and supporting long-term sector growth. Hungary's bioeconomy shows considerable promise, but its successful development will depend on overcoming policy fragmentation, weak industry integration, insufficient R&D support, economic constraints and workforce shortages. A coordinated approach that promotes innovation, investment, circularity and skills development will be essential to unlock the fully potential of the Hungarian bioeconomy.

1.2.2.10 Italy[84] [85] [86]

The Italian bioeconomy comprises primary production sectors such as agriculture, forestry, fisheries and aquaculture, together with processing industries including wood processing, paper production, biorefineries, biotechnology and marine-based industries. The sector currently generates

[84] Bioeconomy in Italy | BIT | 2017.

[85] Bioeconomy in Italy | BIT II | The Italian Updated strategy on Bioeconomy

[86] Grupo di Coordinamento Nazionale per la Bioeconomia (GCNB) – Piano d'Azzione aggiornato (2025-2027) per l'implementazione della Strategia Italiana per la Bioeconomia BIT II | Comitato Nazionale per la Biosicurezza, le Biotecnologie e le Scienze della Vita

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approximately €250 billion in annual turnover and employs around 1.7 million people, making Italy one of the leading bioeconomy players in Europe.

In 2017, Italy adopted the 'Italian Strategy for the Bioeconomy', promoted by the Presidency of the Council of Ministers. The strategy defines the bioeconomy as the sustainable production of renewable biological resources and the transformation of these resources and related waste streams into food, feed, bio-based products and bioenergy.

The strategy provides a shared vision for addressing environmental, economic, and social challenges while creating opportunities for sustainable growth and international cooperation. It is closely aligned with the National Strategy for Smart Specialisation and the National Strategy for Sustainable Development, supporting the integration of sustainability objectives with economic development and therefore ensuring the 'reconciliation' between environmental sustainability and economic growth.

Current state of the Italian bio-based industry

Italy has established one of the most advanced bioeconomy policy frameworks in Europe. The Italian Bioeconomy Strategy and its updated version (BIT II) promote the transition towards a sustainable and circular bioeconomy through the efficient use of biological resources, innovation and industrial development.

The strategy prioritises the transition from sector-based approaches to integrated system approaches, the creation of value from biodiversity and circularity, the shift towards a more sustainable economy; and the acceleration of innovation uptake. It also promotes Italy's role as a reference point for bioeconomy development in the Mediterranean region.

The Italian bioeconomy already represents a significant economic sector, supported by strong capabilities in agriculture, food production, biotechnology, biorefineries, forestry and marine resources. The strategy aims to further increase turnover and employment by approximately 20% by 2030.

Main challenges in the Italian bioeconomy

The Italian bioeconomy benefits from a mature policy framework, strong industrial capabilities, and diversified biomass resources. Nevertheless, several challenges continue to affect its long-term competitiveness and sustainability across different bio-based sectors. **Agricultural competitiveness and rural development challenges** are particularly relevant, as many farms continue to face limited profitability due to their small average size, low revenues, price volatility, and increasing international competition. These issues are compounded by rural depopulation, insufficient logistical services, and weak integration within agricultural value chains. Environmental pressures, including soil degradation, water scarcity, and pollution, further affect the resilience of the sector, while limited technological innovation and insufficient knowledge transfer constrain productivity improvements and the adoption of more sustainable practices.

Closely linked to these issues are **value-chain integration and circularity challenges**. In several sectors, particularly the agri-food industry, connections between primary producers and downstream

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industries remain relatively weak. Significant quantities of by-products and waste are generated each year, yet their valorisation is often constrained by fragmented value chains, limited resource efficiency, and regulatory conditions that do not always facilitate the qualification and management of by-products. Strengthening industrial symbiosis and improving the utilisation of biological residues therefore remain important priorities.

Italy also faces **forestry and biomass resource management challenges**. Although forest resources constitute a significant asset, parts of the sector continue to experience underutilisation and abandonment, limiting the economic value generated from forestry activities while contributing to biodiversity loss and increasing vulnerability to climate-related pressures. Additional constraints include incomplete national forest statistics, insufficient forest management and valorisation strategies, dependence on imported raw materials and low-value products, as well as risks associated with illegally or unsustainably sourced timber. The sector is also affected by limited training and capacity-building in modern forest management practices.

In the maritime domain, **blue bioeconomy and marine sustainability challenges** continue to influence the development of fisheries, aquaculture, and marine bio-based industries. Unsustainable fishing practices, environmental pressures linked to aquaculture, pollution, invasive species, and climate change impacts all affect resource availability and ecosystem health. At the same time, the fishing sector faces economic pressures, increasing dependence on imported fish products, complex administrative procedures, limited diversification of aquaculture species, insufficient certification schemes, and growing competition for coastal resources from tourism, urbanisation, and recreational activities. The limited implementation of marine spatial planning further complicates the sustainable use of marine resources.

The development of advanced bio-based industries is also affected by **industrial competitiveness and market development challenges**. The availability of sustainable and cost-competitive biomass remains uneven, while domestic markets for bio-based products are still relatively small compared with conventional alternatives. Companies must also contend with high capital investment requirements and significant financial risks when scaling industrial facilities. In addition, difficulties in quantifying and communicating the environmental and social benefits of bio-based products can reduce market uptake. Concerns have also been raised regarding products that do not fully comply with labelling and certification requirements, creating distortions within the market.

Finally, **regulatory and investment challenges** continue to affect several bioeconomy sectors. Stakeholders have identified regulatory gaps relating to industrial biowaste management, end-of-waste criteria, and the broader framework governing bio-based products. In some cases, sector-specific incentive schemes may also create unintended distortions along value chains. Ensuring greater regulatory clarity, stability, and coherence will be important to support innovation, attract investment, and facilitate the large-scale deployment of bio-based solutions.

Suggested approaches to overcome these Italian challenges

Addressing these challenges requires stronger integration between primary production sectors and downstream bio-based industries, together with increased investment in research, innovation and

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industrial-scale biorefinery infrastructures. Greater emphasis should be placed on the valorisation of agricultural, forestry, marine and industrial residues through circular economy approaches. Further progress will depend on the development of stable regulatory frameworks for bio-based products and secondary raw materials, enhanced farmer training and technology transfer activities, wider adoption of digital and sustainable production practices, and increased market uptake of bio-based products. These actions would contribute substantially to achieving the objectives of the Italian Bioeconomy Strategy and reinforcing Italy's position as one of Europe's leading bioeconomy ecosystems.

1.2.2.11 Latvia[87] [88] [89]

Latvia is in the northeastern corner of Europe. It has a population of 1.9 million and a land area of 64,573 km², of which 51% is covered by forests and 30.5% is agricultural land. The country possesses a strong bioresource base and significant potential for bioeconomy development. The forestry sector is a major contributor to Latvia's bioeconomy, focusing on sustainable forest management and the development of innovative wood products. At the same time, the agricultural sector is being modernised through the integration of biotechnologies, plant breeding, crop diversification and sustainable horticultural practices.

The role of traditional bioeconomy sectors is particularly significant in Latvia. In 2015, the manufacturing sector employed approximately 128,000 people, representing around two-thirds of total manufacturing employment and 14% of total national employment. In addition, approximately 108,000 private forest owners who receive irregular income from forests and more than 30,000 farmers producing crops for their own consumption contribute to the broader bioeconomy ecosystem.

Current state of the bio-based industry in Latvia

The traditional bioeconomy sectors constitute an important component of Latvia's economy. In 2015, agriculture, forestry, fisheries, the food industry and woodworking contributed 54% of the added value generated by all manufacturing sectors. The total added value of these traditional bioeconomy sectors amounted to €1.99 billion. In 2023, Latvia's total GDP reached €43.91 billion. Despite a reduction in the area dedicated to farming, agriculture remains the leading bio-based primary sector, generating a Gross Value Added (GVA) of €503 million. Forestry follows with a GVA of €393 million, while fishing and aquaculture contribute €34 million.

Latvia also has considerable potential for biomass production from agricultural, animal, and fish-processing by-products. Animal by-products account for approximately 6% of the total biogas

[87] Mapping Latvia's bio-based potential | Country-Report-Latvia-2020 | Bio-based Industries Consortium (BIC)

[88] Latvia.eu (2025) Key facts about Latvia

[89] LIBRA Latvian Bioeconomy Strategy 2030, (2018) Retrieved from https://www.zm.gov.lv/lv/media/1023/download?attachment

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production in the country. The country is increasingly focusing on the application of biotechnologies to produce bio-based chemicals, pharmaceuticals, bioplastics and other innovative bioproducts from biomass and biomass by-products. Latvia's rapidly advancing biorefinery ecosystem is centred on biotechnology-based solutions that support the transition towards a sustainable bioeconomy. This ecosystem emphasises the conversion of biomass, the production of higher-value bio-based products, collaboration amongst 22 participating entities, economic growth, sustainability objectives, and the attraction of strategic investments.

Main challenges in Latvian bioeconomy

Latvia's bioeconomy already includes several well-established businesses operating in sectors such as forestry, agriculture, and biomass processing. However, **value creation and biomass utilisation challenges** continue to affect the sector's ability to fully capture the economic potential of domestic biological resources. Existing biomass utilisation patterns do not always prioritise the generation of higher value-added products or the most efficient socio-economic use of land and biomass. In some cases, established market structures and business models may favour the continuation of existing practices, which can slow the emergence of new value chains, innovative biomass applications, and more advanced bio-based industries. As competition for biological resources increases globally, the transition towards higher-value uses of biomass may also create tensions with incumbent actors.

Another important area concerns **research, innovation, and investment challenges**. The development of an innovation-driven bioeconomy requires significantly higher levels of investment in research and development, particularly from the private sector. Current investment levels remain below those needed to accelerate the development of new technologies, products, and business models capable of strengthening Latvia’s position in international bioeconomy markets. As a result, the pace of technological innovation and industrial transformation remains slower than desired.

The country also faces **technology transfer and commercialisation challenges**. Existing mechanisms supporting the transfer of knowledge and technologies from research organisations to industry remain fragmented and relatively slow. Limited interaction between research institutions, innovation actors, and businesses constrains the commercialisation of scientific results and reduces the impact of research investments. This situation affects productivity growth and limits the development and export of higher value-added bio-based products.

In addition, **intersectoral cooperation and value-chain integration challenges** continue to influence bioeconomy development. Stronger collaboration between agriculture, forestry, fisheries, biotechnology companies, research organisations, and industrial actors is needed to unlock synergies and support more integrated bio-based value chains. The current level of cooperation is not always sufficient to maximise opportunities for resource efficiency, innovation, knowledge exchange, and the creation of new bioeconomy markets. Strengthening these connections will be important for enhancing competitiveness and increasing the value generated from Latvia's biological resources.

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Suggested approaches to address challenges in Latvian bioeconomy

To fully capitalise on Latvia's bioeconomy potential, efforts should focus on increasing the value generated from domestic biological resources and strengthening innovation-driven development. Greater investment in research and development, particularly from the private sector, could accelerate the development of advanced bio-based products and enhance international competitiveness. Strengthening technology transfer systems and innovation support mechanisms would facilitate the commercialisation of research outcomes and support the growth of high-value bioeconomy activities. Further development of the biotechnology and biorefinery ecosystem could enable more efficient utilisation of agricultural, forestry, animal, and fish-processing by-products, creating new opportunities for bio-based chemicals, pharmaceuticals, bioplastics, and other innovative products. In addition, stronger cooperation between agriculture, forestry, fisheries, research organisations, and industry stakeholders would help establish integrated value chains, improve resource efficiency, and support the transition towards a more competitive and sustainable bioeconomy. By building on its substantial forest resources, agricultural base, growing biotechnology sector, and emerging biorefinery ecosystem, Latvia is well positioned to increase the economic value generated from biological resources while advancing the objectives of its Bioeconomy Strategy 2030.

1.2.2.12 Lithuania[90] [91] [92] [93] [94] [95] [96] [97]

Lithuania, located in the Baltic region of Northern Europe, has a population of approximately 2.8 million and a land area of 65,300 km², with around 33% covered by forests and 45% used for agriculture. The country's bioeconomy plays a vital role in its economy, particularly in rural areas, contributing significantly to employment and economic output. The bioeconomy sectors, including agriculture, forestry, fisheries and food processing, account for a significant share of Lithuania's

[90] Vitunskienė, V., and Aleksandravičienė. A., Executive summary of the strategic concept paper for bioeconomy: Lithuania (2023) BIOEASTsUP H2020 Project

[91] BOOSTing the bioeconomy transformation FOR (4) the BIOEAST region | BOOST4BIOEAST | 101133398 | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[92] Vaisilaitė, J., Overview of state of play on bioeconomy in Lithuania. Workshop "Facilitating development of bioeconomy policy – needs and gaps" (2019) Ministry of Agriculture.

[93] Aleksandravičienė, A., et al., The strategic concept for the Lithuanian bioeconomy: insights for niche bioenergy sectors (2023) **https://doi.org/10.12688/openreseurope.16085.2**

[94] Circular Economy Country Profile – Lithuania | ETC-CE Report 2022/5 | European Topic Centre - Circular economy and resource use | European Environmental Agency

[95] Lithuania – Common Agricultural Policy (CAP) Strategic Plan - European Commission

[96] MITA – Final conference of the project "Roadmap for Lithuania's industrial transition to a circular economy (2021). Online version: https://youtu.be/oXuD6qnYfEQ?si=esxWPDGvbXuy4HI8

[97] Lietuva 2030 - Bendrasis planas | Comprehensive Plan of the Territory of the Republic of Lithuania (Summary in English)

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GDP. The country is a major producer of cereals (wheat, rye, and barley), industrial crops (rapeseed and flax), and dairy products. Additionally, the forestry sector is well-developed, with timber and wood-based industries contributing significantly to bioeconomic value-added. Lithuania has been actively promoting its bioeconomy as a means of integrating the sustainable production and conversion of biomass into valuable products such as food, feed, bio-based products and bioenergy. The bioeconomy is expected to contribute simultaneously to economic growth, environmental sustainability and reduced dependence on fossil resources. Lithuania's geographical characteristics are comparable to those of Denmark, with both agriculture and forests representing key land-use systems. However, due to historical development pathways, agriculture has traditionally played a particularly important role in Lithuania's economy.

Current state of the bio-based industry in Lithuania

Despite its strong biomass production capacity, Lithuania remains largely focused on primary production and biomass exports, with limited development of high-value bio-based industries. The country possesses considerable potential for biorefinery development and bio-based manufacturing, but investment in advanced bio-based materials, including bioplastics and bio-based chemicals, remains relatively limited. The bioenergy sector is expanding rapidly, with numerous biogas plants and wood-based energy facilities contributing to Lithuania's renewable energy objectives.

Agriculture remains a key driver of Lithuania's economy, with approximately 45% of the country's territory dedicated to agricultural activities. The primary sector, comprising agriculture, forestry, and fisheries, contributes 3.6% of Lithuania's total GVA. Despite demographic challenges, 56.2% of the population resides in rural areas, representing one of the highest proportions within the European Union.

The bioeconomy encompasses a broad range of sectors, including biological resource production, food production, biogas, and biofuels. Lithuania possesses substantial biomass resources and significant biorefining potential. The food industry remains highly dynamic, while biorefining companies are also increasingly active. Most biorefineries are currently concentrated in the northern regions of the country. Additionally, the market is witnessing the emergence of new start-ups, although established corporations are no longer as dominant as they were previously. Lithuania's bioeconomy is supported by an abundant resource base. Emerging feedstocks of interest include wheat, barley, rye, rapeseed, dairy-derived resources, forestry biomass, willow, and miscanthus. Agricultural biomass remains dominant, while forest biomass accounts for approximately one quarter of the biomass generated by agriculture. Moreover, Lithuania is also actively participating in international bioeconomy initiatives. Its involvement in BIOEAST and related projects facilitates knowledge exchange, regional collaboration, and policy development. The BOOST4BIOEAST project, launched in 2024, seeks to promote a circular bioeconomy through innovation and collaboration while creating high-value employment opportunities in rural areas.

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Policy Framework and Institutional Landscape

As of 2023, Lithuania does not have a dedicated national bioeconomy strategy or action plan, although efforts are underway to develop one. Various national policies and strategic documents indirectly support bioeconomy development:

- **Roadmap for Lithuania's industrial transition to a circular economy**, which promotes resource efficiency and the use of renewable resources.
- **Lithuanian Common Agriculture Policy (CAP) Strategic Plan (2022)**, which emphasises the production of high-value-added biomass-based products and innovation in agriculture and rural development.
- **Comprehensive Plan of the Territory of the Republic of Lithuania (2021)**, which includes strategic priorities related to sustainable economy, resource efficiency and renewable energy deployment.

A major recent development was the establishment of the Lithuanian Bioeconomy Hub on 26 September 2024. The hub aims to facilitate dialogue amongst ministries, scientific institutions, businesses and society. Its objectives include strengthening policy coherence, improving science-policy interactions, fostering public-private partnerships and developing a holistic vision for Lithuania's bioeconomy. Political interest in the bioeconomy is increasing and initiatives such as BOOST4BIOEAST are contributing to the development of action plans and strategic frameworks.

Synergies and Transformation Pathways

Enhancing synergies amongst agriculture, forestry, fisheries, industry and research sectors is increasingly recognised as essential for Lithuania's sustainable development. Greater collaboration across sectors is expected to improve resource efficiency, foster innovation and facilitate the creation of higher-value products and services. These transformation pathways are considered central to the future development of Lithuania's circular bioeconomy.

Key challenges in Lithuanian bioeconomy

Lithuania is entering a new phase of bioeconomy development characterised by growing political interest, increasing stakeholder engagement, and the emergence of new coordination mechanisms such as the Lithuanian Bioeconomy Hub. However, several structural challenges continue to limit the country's ability to fully exploit its biomass resources and expand higher-value bio-based industries.

Strategic and policy challenges remain a key area of concern. Although several national plans and policy instruments support elements of the bioeconomy, Lithuania still lacks a dedicated national bioeconomy strategy and action plan. The absence of a comprehensive framework has a number of consequences, including limited policy coordination, reduced efficiency of resource allocation, and difficulty in establishing long-term priorities across sectors and institutions.

A second challenge relates to **biomass valorisation and industrial development**. Lithuania possesses abundant agricultural and forestry resources but continues to rely heavily on the export of raw biomass rather than its conversion into higher-value products within the country. As a result,

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significant opportunities for value creation, industrial diversification, and circular resource use remain underexploited. The limited utilisation of biological waste streams further constrains resource efficiency and reduces the economic benefits that could be generated from available biomass resources.

The transition towards a more advanced bioeconomy is also influenced by **research, innovation, and technology transfer challenges**. Financial constraints limited private-sector participation in research and development, and insufficient cooperation between research organisations and industry reduce the capacity to develop and commercialise innovative bio-based products and technologies. The relatively slow development of technology transfer mechanisms further limits the translation of scientific knowledge into market applications.

Closely linked to these issues are **infrastructure and investment challenges**. The expansion of industrial-scale bioeconomy activities requires greater investment in biorefineries, advanced manufacturing facilities, and biomass-processing technologies. High production costs, limited production capacity, weak private investment, and difficulties in securing financing for large-scale projects continue to constrain the growth of advanced bio-based sectors. While Lithuania is actively seeking to attract foreign investment and improve the business environment, further investment will be required to unlock its full biorefining and industrial potential.

Another important area concerns **cross-sectoral cooperation and value-chain integration challenges**. Stronger collaboration amongst agriculture, forestry, fisheries, industry, policymakers, and research organisations is widely recognised as essential for improving resource efficiency, accelerating innovation, and creating integrated bio-based value chains. Current levels of cooperation do not always allow the full exploitation of synergies across sectors, limiting opportunities for knowledge exchange and market development.

Finally, **social and cultural challenges** continue to influence bioeconomy development. Studies have identified declining levels of interpersonal trust, particularly amongst older generations, as a factor affecting cooperation, entrepreneurship, innovation activities, and investment in research and development. Strengthening stakeholder engagement, fostering collaboration, and building a stronger innovation culture will therefore be important elements in the long-term development of Lithuania's bioeconomy.

Suggested approaches to address challenges in Lithuanian bioeconomy

Lithuania is currently at a pivotal stage in the development of its bioeconomy. To strengthen sustainability, competitiveness and value creation, several actions should be prioritised. The development and implementation of a dedicated national bioeconomy strategy would provide a coherent framework for coordinating policies, directing investments and supporting long-term sector growth. Greater emphasis should be placed on the production of high-value-added bio-based products instead of exporting raw biomass. This would increase domestic value creation and improve the competitiveness of Lithuanian bioeconomy sectors. Cross-sectoral collaboration should be strengthened through initiatives such as the Lithuanian Bioeconomy Hub and international platforms such as BIOEAST and BOOST4BIOEAST. Enhanced cooperation amongst ministries, businesses,

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scientific institutions and civil society could accelerate innovation and facilitate more effective resource utilisation. Increased investment in research, development, technology transfer and industrial-scale infrastructure will be essential for overcoming existing bottlenecks. Particular attention should be given to biomass valorisation technologies, advanced biorefineries, bio-based chemicals, bioplastics and circular bioeconomy solutions. Finally, efforts to improve stakeholder engagement, build trust, attract private investment and support entrepreneurship will contribute to creating a more innovative and resilient bioeconomy ecosystem. The establishment of the aforementioned Lithuanian Bioeconomy Hub, together with the country's active participation in related initiatives, could provide a solid foundation for all these developments. Addressing current challenges through coordinated policies, stronger collaboration and innovation-driven investments will be key to unlocking the full potential of Lithuania´s bioeconomy.

1.2.2.13 Malta[98] [99] [100] [101] [102]

Malta's bioeconomy is in its early stages of development, with progress being made primarily in sectors such as fisheries and aquaculture, agriculture, and waste management. Due to its limited land mass, scarce natural resources, and dependence on imports, Malta's bioeconomy faces particular structural constraints. However, the country also presents important opportunities through the sustainable use of marine resources, waste valorisation, and circular economy initiatives. The Maltese government has demonstrated a growing commitment to sustainable development objectives, aligning national efforts with the European Union Bioeconomy Strategy and broader circular economy goals.

Current state of the bio-based industry in Malta

Despite its small size, Malta has established several initiatives that contribute to the development of a bio-based economy. One of the most notable projects is the SEALIVE project, which addresses plastic pollution through the development of eight innovative bio-based products designed to reduce dependence on fossil-based feedstocks. These products include fishing nets, fishing crates, oyster

[98] K. Dolge, et al., A comparative analysis of bioeconomy development in European Union Countries. Environmental Management 71 (2023) 215-233. https://doi.org/10.1007/s00267-022-01751-3

[99] T. Ronzon, and R. M'Barek, Socioeconomic indicators to monitor the EU's bioeconomy in transition. Sustainability 10(6) (2018) 1745. https://doi.org/10.3390/su10061745

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mesh bags, mulching film, rigid food packaging, flexible food packaging, deep-frozen food films and cutlery. The project seeks to promote sustainable end-of-life solutions while addressing plastic pollution both on land and at sea. The University of Malta plays an important role in the national bioeconomy ecosystem, particularly through activities related to blue biotechnology and the valorisation of fish waste. Located close to the University of Malta, the Malta Life Sciences Park (MLSP) serves as a strategic hub for life sciences and red biotechnology activities. The facility supports both start-ups and established enterprises by providing laboratory infrastructure, business services and innovation support. In addition, EcoStack Innovations contributes to biodiversity conservation and sustainable agriculture through research activities, publications and collaborative projects focused on environmental sustainability. Current bioeconomy activities are concentrated mainly in fisheries and aquaculture, agriculture, biotechnology, blue bioeconomy applications and waste management initiatives, with growing emphasis on circular economy approaches and resource efficiency.

Analysis of Malta-Specific Challenges

Malta's bioeconomy development is strongly influenced by the country's geographical characteristics and resource limitations. **Resource availability and infrastructure challenges** represent one of the main barriers to the expansion of bio-based industries. The island's limited land area and restricted agricultural capacity constrain domestic biomass production, creating a high dependence on imported feedstocks and raw materials. These constraints are further amplified by climate-related pressures, particularly water scarcity and drought conditions, which affect agricultural productivity and biomass availability. In addition, Malta lacks specialised research infrastructure, pilot facilities, and industrial-scale demonstration capacities dedicated to bio-based industries, limiting opportunities for technology development and scale-up.

The development of the sector is also affected by **market and business challenges**. The small size of the domestic market restricts economies of scale and can limit the commercial viability of bio-based products and services. Bioeconomy ventures, particularly start-ups and SMEs, often encounter difficulties in securing adequate financing and attracting private investment. Market uptake is further constrained by relatively low consumer awareness of bio-based products, reducing demand and creating additional barriers to business growth.

Another important area concerns **policy and regulatory challenges**. While Malta aligns with European bioeconomy and circular economy objectives, the country does not currently have a dedicated national bioeconomy strategy. As a result, bioeconomy-related actions are addressed through broader sustainability and circular economy initiatives rather than within a coordinated framework. Regulatory gaps related to biowaste valorisation, certification systems, and the development of bio-based products can create uncertainty for investors and slow the expansion of emerging bio-based sectors.

The sector also faces **social and skills-related challenges**. Public participation in bioeconomy initiatives and sustainable consumption practices remains relatively limited, reducing societal engagement with emerging bio-based solutions. At the same time, the availability of specialised

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education, training programmes, and technical skills related to the bioeconomy remains insufficient to fully support sector growth. Cultural preferences and established consumption habits may also slow the adoption of innovative bio-based alternatives and circular business models.

Suggested approaches to address challenges in Malta

Strengthening Malta's bioeconomy will require a coordinated approach that takes into account the country's unique geographical and resource constraints while building on its strengths in marine resources, biotechnology, research, and circular economy initiatives. The development of a dedicated national bioeconomy strategy could provide a clearer framework for policy coordination, stakeholder engagement, investment attraction, and long-term sector development. Such a framework would help improve coherence across bioeconomy-related activities, including biowaste management, circular economy initiatives, blue biotechnology, and sustainable resource utilisation. Further progress will depend on strengthening research, innovation, and industrial capacities. Investment in specialised research infrastructure, pilot facilities, and innovation support mechanisms could facilitate the development and scale-up of bio-based technologies, while stronger collaboration between universities, research centres, industry, and public authorities would accelerate knowledge transfer and commercialisation. Particular attention could be placed on areas where Malta has comparative advantages, including marine biotechnology, sustainable aquaculture, algae-based value chains, and the valorisation of marine and fisheries residues. Addressing resource constraints will also be essential. Promoting water-efficient agricultural practices, improving resource management, and enhancing biomass valorisation technologies could help increase the availability and efficient use of domestic biological resources. In parallel, the expansion of circular economy approaches and biowaste valorisation initiatives could reduce dependence on imported feedstocks while creating additional sources of value from currently underutilised resources. Market development and business growth could be supported through improved access to finance, dedicated funding instruments for bioeconomy SMEs and start-ups, and greater participation in European research and innovation programmes. Given the limited size of the domestic market, export-oriented strategies and the development of niche, high-value bio-based products may offer important opportunities for growth and international competitiveness. Finally, increasing public awareness of bio-based products and sustainable consumption patterns, together with the development of specialised education and vocational training programmes, would support the creation of a stronger bioeconomy ecosystem. Building the skills needed for emerging bio-based industries and fostering greater societal engagement in sustainability initiatives will be important for ensuring the long-term resilience and competitiveness of Malta's bioeconomy. By combining these efforts with its growing capabilities in biotechnology, marine resources, and circular economy innovation, Malta can further develop a sustainable and resource-efficient bioeconomy despite its structural limitations.

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1.2.2.14 Poland[103] [104] [105]

Poland has significant potential for the development of the bioeconomy and bio-based industries due to the large availability of unused, underutilised and residual biomass that could be transformed into value-added products and services. This potential is closely linked to the country's strong agricultural, food-processing and forestry sectors, which provide an abundant resource base for the development of a circular rural bioeconomy. The country also benefits from a highly qualified scientific community, particularly in agricultural and biological sciences, as well as biochemistry, genetics and molecular biology. These strengths provide favourable conditions for future bioeconomy development and innovation.

Current state of the Polish bio-based industry

The bioeconomy and related topics are addressed through several national policy initiatives, including the Strategy for the Development of the Country 2020 and the Roadmap of a Transition to a Circular Economy. In addition, a dedicated national bioeconomy strategy is currently being developed. One of the key objectives of the future Polish Bioeconomy Strategy and Action Plan is to strengthen the framework conditions required to support a sustainable transition towards a climate-neutral future and to increase the value generated from locally available bioresources. According to the European Innovation Scoreboard 2024, Poland is classified as an Emerging Innovator, achieving a performance level equivalent to 65.9% of the EU average. This performance is significantly above the average for Emerging Innovators (48%) and is improving at a rate more than double the EU average (+10%). The current public expenditure on research and development remains relatively low. In 2024, public R&D expenditure represented 0.53% of GDP, corresponding to 62.3% of the EU average. Venture capital expenditure has remained largely stagnant since 2017 and has declined by 1.2%. In contrast, business R&D expenditure continues to increase, with Poland ranking first amongst Emerging Innovators in this category.

Poland also benefits from substantial feedstock availability originating from agriculture, the food industry, and forestry. Together with its scientific capacity, this creates favourable conditions for the future development of bio-based value chains and bioeconomy-related innovation.

Main challenges in Poland's bioeconomy

Poland has a strong biomass resource base, a growing innovation ecosystem, and significant scientific capabilities. However, several structural challenges continue to affect the development of

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a more integrated and competitive bioeconomy. **Strategic and policy challenges** arise from the fact that, although bioeconomy-related issues are addressed through several national policy frameworks and work is underway to develop a dedicated Bioeconomy Strategy and Action Plan, a comprehensive framework coordinating all relevant policy areas has not yet been fully implemented. This limits policy coherence and makes it more difficult to align stakeholders around common objectives and long-term priorities.

Another important challenge concerns **agricultural productivity and biomass utilisation**. The average productivity of the agricultural sector remains below that of many European countries, partly because of agrarian fragmentation, lower soil quality in some regions, and shorter growing seasons. These factors affect the efficiency with which biomass resources can be produced and mobilised, despite the country's substantial feedstock availability.

Further barriers are linked to **research, innovation, and technology-transfer challenges**. Poland possesses a strong scientific base in fields relevant to the bioeconomy, yet collaboration between research institutions and bio-based industries remains limited, particularly in the agricultural sector. This restricts the uptake of innovation and slows the development and commercialisation of new bio-based products, services, and technologies. Public investment in research and innovation also remains below the European average, while venture capital activity has shown limited growth in recent years.

The sector is also affected by **value-chain integration and business ecosystem challenges**. Stronger connections are needed between biomass producers, industrial processors, technology providers, distributors, and commercial actors. Given the cross-sectoral nature of the bioeconomy, effective collaboration across agriculture, forestry, food processing, manufacturing, and service sectors is essential. However, these linkages are not yet fully developed, reducing opportunities for innovation, value creation, and market expansion.

Closely related to this issue are **cluster development and business support challenges**. The limited availability of specialised bioeconomy clusters, innovation hubs, and business support organisations constrains networking, technology transfer, and cooperation amongst stakeholders. The absence of well-developed support structures makes it more difficult to establish integrated value chains and accelerate the development of bio-based industries.

Finally, **sustainability assessment and monitoring challenges** continue to affect decision-making within the sector. According to expert assessments, knowledge regarding the sustainability performance of bioeconomy activities remains insufficient, particularly in relation to carbon footprints, circularity, and resource efficiency. This limits the ability of stakeholders to evaluate environmental impacts, identify improvement opportunities, and demonstrate the benefits of bio-based solutions.

Suggested approaches to address challenges in Poland's bioeconomy

To unlock Poland's bioeconomy potential and accelerate the transition towards a circular bioeconomy, the following actions are recommended:

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- Finalise and implement a comprehensive national bioeconomy strategy that provides a coherent framework for policy coordination, investment, and stakeholder engagement.
- Strengthen cooperation between academia and industry to improve knowledge transfer, accelerate innovation uptake, and support the commercialisation of bio-based products and technologies.
- Increase public and private investment in research, development, and innovation, particularly in areas related to biomass valorisation and advanced bio-based manufacturing.
- Support the establishment and expansion of bioeconomy clusters and specialised business support organisations to facilitate networking, technology transfer, and cross-sectoral collaboration.
- Improve integration across value chains by strengthening connections between biomass suppliers, industrial processors, distributors, and end-users.
- Promote sustainability assessment tools and monitoring systems to improve knowledge regarding carbon footprints, circularity, and resource efficiency within bioeconomy sectors.
- Enhance agricultural productivity through innovation, modernisation, and improved resource management practices while making better use of available biomass resources.
- Build a favourable national bioeconomy ecosystem capable of leveraging Poland's abundant feedstock resources, strong scientific expertise, and growing innovation capacity.

By addressing these challenges and building on its considerable biomass resources, scientific capabilities, and innovation potential, Poland is well positioned to strengthen its bioeconomy and increase the value generated from domestic biological resources while supporting sustainability and climate-neutral development objectives.

1.2.2.15 Portugal[106] [107] [108] [109] [110] [111]

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Portugal has around 10.6 million inhabitants (2024) and a diverse territory, embracing mainland Europe and the Atlantic islands of the Azores and Madeira. It covers 92,212 km² of land and possesses an Exclusive Economic Zone (EEZ) of approximately 1.7 million km², the third largest in the European Union. This extensive land and sea domain provides abundant biological resources, including forests, which cover approximately 36% of the national territory, as well as significant fisheries, aquaculture, and agricultural resources. The Portuguese economy benefits from well-established agriculture, forestry, fisheries, and agri-food sectors, complemented by an emerging biotechnology industry. These natural assets provide a strong foundation for the development of a bioeconomy based on forestry, biomass, agricultural products, marine resources, and bio-based innovation.

Current state of the Portuguese bio-based industry

Portugal has established an important policy foundation for bioeconomy development through the National Strategy for the Sustainable Bioeconomy, initially developed with a horizon to 2025 and subsequently extended to 2030. The strategy focuses primarily on primary production sectors, including agriculture, forestry, and fisheries, with the objective of valorising domestic biological resources, reducing dependence on non-renewable resources, and contributing to carbon neutrality goals. To support implementation, Portugal has launched the Action Plan for a Sustainable Bioeconomy (Horizon 2025), complemented by initiatives such as the Blue Bioeconomy Roadmap and the Carbon Neutrality Roadmap 2050, ensuring alignment between bioeconomy development and national climate objectives. Policy implementation is coordinated by key public institutions, including the Ministry of Environment, the Planning Office, and the Portuguese Environment Agency, and is further supported through regional smart specialisation strategies. The country possesses substantial biomass resources and significant potential for the development of bio-based industries. Forest residues alone are estimated at approximately 2 million tonnes annually, while the extensive marine domain offers considerable opportunities for the blue bioeconomy, including sustainable fisheries, aquaculture, algae production, and marine biotechnology. Several initiatives are supporting the development of innovation infrastructure. One notable example is the Blue Demo Network, promoted by the Blue Bio Alliance, which aims to strengthen demonstration and testing capabilities for blue bioeconomy technologies. Nevertheless, the overall industrial ecosystem remains characterised by a limited number of large-scale bio-based processing facilities and a relatively low level of commercial deployment of bio-based innovations.

Main challenges in Portugal's bioeconomy

The development of Portugal's bioeconomy is increasingly supported by dedicated strategies, emerging innovation infrastructures, and significant terrestrial and marine resources. Nonetheless, several barriers continue to affect industrial scale-up, value-chain development, and market implementation. Portugal faces significant challenges in developing its bio-based industry:

- **Policy and governance coordination gaps**: Bioeconomy-related responsibilities remain distributed across multiple ministries and policy frameworks. This fragmented governance structure has resulted in limited coordination between sectors and regions, creating

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inconsistencies in policy implementation and reducing the overall effectiveness of support mechanisms. Although the National Strategy for the Sustainable Bioeconomy has improved the policy landscape, stakeholders continue to identify the need for stronger coordination and a more integrated governance framework.

- **Industrial infrastructure limitations:** One of the principal barriers to bioeconomy development is the shortage of pilot-scale, demonstration, and scale-up facilities. Portugal currently lacks integrated biorefineries and dedicated demonstration infrastructures capable of validating and scaling innovative bio-based technologies. As a result, many innovations remain at laboratory scale or require access to facilities outside the country, slowing technology development and commercialisation. This challenge is particularly relevant in emerging sectors such as marine biomass processing and advanced bio-based materials.
- **Regulatory complexity and permitting hurdles:** Complex regulatory requirements and lengthy permitting procedures continue to affect the development of bio-based industries. Companies must navigate multiple regulatory frameworks and approval processes involving different authorities, increasing administrative burdens and project development timelines. Environmental licensing and other permitting requirements can be particularly time-consuming, creating uncertainty for investors and slowing the implementation of bioeconomy projects.
- **Investment, financing and commercialisation bottlenecks:** Portugal possesses strong scientific and research capabilities in areas such as biotechnology, marine sciences, and bio-based innovation. However, the translation of research results into commercially viable products and industrial activities remains limited. Collaboration between universities, research organisations, technology transfer entities, and industry is not always sufficient to support the effective commercialisation of research outcomes. The limited availability of specialised innovation support structures, incubators, accelerators, and technology transfer mechanisms further constrains bio-based entrepreneurship and the market uptake of innovative solutions. At the same time, access to finance remains a significant barrier for bioeconomy projects and businesses. Bio-based ventures are often perceived as high-risk investments, resulting in limited private-sector participation and a strong dependence on public funding schemes and European programmes. High operating costs, together with insufficient financial incentives, further hinder industrial scale-up and reduce the competitiveness of bio-based solutions compared with established fossil-based alternatives.
- **Biomass feedstock mobilisation and supply chain challenges:** Although Portugal has abundant biomass resources, the effective mobilisation of feedstocks remains challenging. Agricultural and forestry resources are often generated by fragmented producers, complicating collection, aggregation, and logistics. A significant proportion of available forest residues remains underutilised or is directed towards low-value applications because of insufficient collection systems, transport infrastructure, and processing capacity. Similar challenges affect the utilisation of marine biomass resources, which remain largely untapped despite their considerable potential. Weak coordination along value chains and limited

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information regarding biomass availability further constrain the development of new bio-based industries and circular bioeconomy models.

Suggested approaches to address challenges in Portugal's bioeconomy

Portugal's extensive terrestrial and marine biological resources provide a strong foundation for the development of a competitive and sustainable bioeconomy. Building on this potential will require stronger coordination across policy domains and closer integration between existing bioeconomy, circular economy, climate, and innovation frameworks. Enhanced governance mechanisms could improve coherence amongst national and regional initiatives while facilitating collaboration between public authorities, research organisations, industry, and civil society. Further progress will depend on strengthening innovation and industrial scale-up capacities. Expanding pilot plants, demonstration facilities, integrated biorefineries, and specialised centres for marine biomass processing would help bridge the gap between research and commercial deployment. These investments could be complemented by stronger technology-transfer mechanisms, closer cooperation between universities and industry, and the development of innovation ecosystems involving clusters, incubators, accelerators, and specialised support organisations. Improving access to finance will also be important for accelerating industrial development. Dedicated funding instruments, investment incentives, and risk-sharing mechanisms could encourage greater private-sector participation while supporting the scale-up of innovative bio-based technologies. At the same time, simplifying administrative procedures and streamlining permitting requirements would reduce barriers for project developers and improve investment certainty. The mobilisation of biomass resources represents another strategic priority. Investments in collection, storage, transport, and processing infrastructure could facilitate the valorisation of agricultural, forestry, and marine biomass streams while improving coordination across value chains. Particular attention could be directed towards increasing the utilisation of currently underexploited forest residues and advancing the sustainable development of marine bioresources, where Portugal benefits from a distinctive competitive advantage within Europe. Finally, increasing stakeholder engagement and public awareness of the environmental, social, and economic benefits of the bioeconomy would help strengthen market uptake and societal support for bio-based solutions. By combining stronger governance, improved innovation capacities, greater investment, and more effective resource mobilisation, Portugal would be well positioned to expand its bio-based industries and reinforce its role as a leading bioeconomy actor in both the Atlantic and European contexts.

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1.2.2.16 Romania[112] [113] [114] [115]

Romania, located in Southeastern Europe, has a land area of 238,397 km² and a population of approximately 19 million, with 54% living in urban areas. The country possesses around 13 million hectares of agricultural land and 6.5 million hectares of forests, making the bioeconomy a strategically important sector. Agriculture, food processing, and forestry constitute the main bioeconomy sectors. Romania is one of Europe's leading producers of cereals, particularly wheat, maize, and sunflower, while its forestry sector provides important resources for timber and bioenergy production. Organic farming has also expanded significantly in recent years, with certified organic land exceeding 5% of total agricultural land. The country's extensive biological resources provide a strong foundation for bioeconomy development and position Romania as an important contributor to the European bioeconomy.

Current state of the Romania's bio-based industry

Romania possesses substantial bioeconomic resources, particularly in agriculture and forestry, although its bioeconomy remains less developed than those of many Western European countries. The Ministry of Agriculture and Rural Development is currently responsible for coordinating bioeconomy-related policies, working alongside institutions such as the Institute of Agricultural Economics and Rural Development (ICEADR) to promote sustainable rural development. However, Romania does not yet have a dedicated national bioeconomy strategy or a universally accepted national definition of the bioeconomy.

The main sectors contributing to the Romanian bioeconomy include agriculture, forestry, food processing and bioenergy. Romania has extensive agricultural resources, with strong production of cereals such as wheat, maize, and barley, as well as oilseeds including sunflower and rapeseed. Organic farming continues to expand and offers opportunities for higher-value agri-food production. With more than 6.5 million hectares of forest, the forestry sector is also a major contributor to the national bioeconomy. Forest resources support timber production, wood-processing industries, and biomass-based energy generation. In a similar vein, the agri-food sector plays a significant role in the Romanian economy. However, much of the industry remains focused on relatively low-technology production processes, limiting competitiveness in higher-value market segments. In addition, the bioenergy sector is developing rapidly, with several biogas plants and facilities utilising

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[115] Balan, E.M., and Zeldea, C.G., Bioeconomy in Romania: investigating farmers' knowledge. Sustainability 15(10) (2023) 7883. **https://doi.org/10.3390/su15107883**

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agricultural and forestry residues for energy production. Nevertheless, advanced biofuels, bio-based chemicals, and other high-value bio-based industries remain at an early stage of development. Despite its resource base, Romania continues to be a net exporter of raw biomass rather than processed bio-based products, indicating significant opportunities for increased domestic value creation through further industrial development.

Main challenges in Romanian bioeconomy

Romania's bioeconomy benefits from an extensive agricultural and forestry resource base, yet several structural challenges continue to limit the development of higher-value bio-based industries. **Strategic and governance challenges** are a result of the absence of a dedicated national bioeconomy strategy and the lack of a shared national framework capable of coordinating policies, investments, and stakeholders across sectors. Although bioeconomy-related activities are addressed through various policy initiatives, the absence of a common vision reduces policy coherence and limits the effectiveness of implementation efforts.

A further challenge concerns **industrial development and value creation**. Romania continues to prioritise primary production and the export of raw biomass, notably from the agricultural and forestry sectors. As a result, a significant proportion of the economic value associated with biological resources is retained outside the country through downstream processing and manufacturing activities. This restricts the development of competitive domestic value chains and reduces opportunities to expand higher-value bio-based industries.

The transition towards a more knowledge-intensive bioeconomy is also affected by **research, innovation, and technology development challenges**. Investment in research, development and innovation remains relatively modest, constraining the development and commercialisation of new technologies, products and services. The limited availability of funding opportunities and innovation support mechanisms has a negative impact on the ability of the Romanian bio-based sectors to compete in emerging international markets and to adopt advanced bioeconomy solutions.

Furthermore, **industrial infrastructure challenges** are intimately linked to these issues. The availability of advanced biorefineries, industrial-scale processing facilities, and manufacturing capacities for bio-based products remains limited. This restricts the country's ability to transform biological resources into higher-value products and participate more actively in emerging bio-based value chains. The expansion of industrial infrastructure will therefore be an important factor in increasing domestic value creation and strengthening competitiveness.

Finally, the sector continues to face challenges in the areas of **resource management and environmental sustainability**, which impact its long-term development. Concerns related to unsustainable forestry practices, including illegal logging, have a detrimental effect on the sustainable management of forest resources and can compromise the credibility of bio-based value chains. Furthermore, deficiencies in waste management systems constrain the recovery and utilisation of biological residues, thereby diminishing prospects for cultivating more circular and resource-efficient bioeconomy models.

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Suggested approaches to address challenges in Romania's bioeconomy

Romania's extensive biological resources provide a strong foundation for the development of a more competitive and value-added bioeconomy. Progress will depend on the establishment of a dedicated national bioeconomy strategy capable of improving policy coordination, aligning stakeholders, and providing a long-term vision for sector development. Greater investment in advanced biorefineries, bio-based manufacturing facilities, and industrial processing infrastructure could strengthen domestic value creation and reduce dependence on exports of raw biomass. At the same time, enhanced support for research, development, and innovation would facilitate the commercialisation of new technologies and accelerate the uptake of advanced bioeconomy solutions. Stronger collaboration between agriculture, forestry, industry, research organisations, and public authorities could support the creation of integrated bio-based value chains and improve resource efficiency. Further efforts should also focus on sustainable resource management, including improved forestry governance and the wider adoption of circular economy practices that promote the utilisation of biological residues and by-products. By combining stronger policy coordination, increased innovation capacity, industrial modernisation, and sustainable resource management, Romania could significantly expand the economic value generated from its biological resources while contributing to national and European sustainability objectives.

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1.2.2.17 Slovakia[116] [117] [118] [119] [120] [121] [122] [123] [124] [125] [126] [127]

Slovakia is a landlocked Central European country with a population of approximately 5.4 million. Its natural landscape is characterised by extensive forests, agricultural land, and water resources, providing a strong foundation for bioeconomy development. The Slovak bioeconomy is closely linked to agriculture, forestry, food production, and the sustainable use of biological resources. In recent years, increasing attention has been given to sustainability, circular economy principles, and the development of innovative bio-based industries. The country possesses significant natural assets, including fertile agricultural land, extensive forest resources, and a well-established agri-food sector, creating favourable conditions for future bioeconomy growth.

Current state of the Slovakia's bio-based industry

The bioeconomy in Slovakia remains at a developing stage, although important progress has been made through European initiatives, research activities, and innovation programmes. In 2019, the Ministry of Agriculture and Rural Development of the Slovak Republic initiated the development of a national bioeconomy strategy. The process currently involves the collection and analysis of data from relevant bioeconomy sectors and includes contributions from universities, research centres, clusters, public institutions, and industry representatives. Public consultations are also planned as

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part of the preparation process. Several strategic policy documents support bioeconomy-related development, including:

- Research and Innovation Strategy for Smart Specialisation of the Slovak Republic (2013).
- Strategy of the Economic Policy until 2030 (2018).
- Updated Strategy on Biodiversity Protection until 2020 (2013).
- Greener Slovakia – Environmental Policy Strategy until 2030 (2019).
- Proposal for an Integrated National Energy and Climate Plan (2018).

The principal public institutions involved in bioeconomy development include:

- Ministry of Agriculture and Rural Development of the Slovak Republic.
- Ministry of Economy of the Slovak Republic.
- Ministry of Environment of the Slovak Republic.
- Ministry of Education, Science, Research and Sport of the Slovak Republic.
- Bioeconomy Cluster and other innovation-oriented organisations.

The Slovak bioeconomy currently focuses on three main areas:

- **Sustainable agriculture and food production**, including resource efficiency, organic farming, regenerative agriculture, and food waste reduction.
- **Forestry and wood-based industries**, promoting sustainable forest management and biomass utilisation.
- **Biotechnology and bio-based industries**, including emerging activities related to bioplastics, biofuels, and innovative biomaterials.

Biomass is Slovakia's most important renewable energy source, accounting for approximately 70.4% of primary renewable energy production. Forests cover approximately 41% of the country's territory, providing substantial potential for biomass-based energy and materials, although this potential has not yet been fully utilised. Agriculture contributes approximately 1.4% to national GDP, while agricultural land represents 48.4% of Slovakia's territory. Despite the availability of resources, significant potential remains untapped due to the continued export of raw materials such as wheat and roundwood, while higher-value processed products are often imported. International companies have begun investing in the Slovak bio-based sector. A noteworthy example is Evonik's manufacturing facility for rhamnolipid biosurfactants, representing an important milestone in the development of sustainable industrial biotechnology within the country. Additionally, the Slovak Bioeconomy Cluster, established in 2015, plays an important role in fostering partnerships throughout agri-food and bio-based value chains and supporting the growth of the bioeconomy ecosystem.

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Main challenges in Slovak bioeconomy

Slovakia has established important foundations for bioeconomy development through sectoral policies, innovation initiatives, and the ongoing preparation of a national bioeconomy strategy. However, several challenges persist that hinder the sector's capacity to enhance the value of its biological resources and expedite the shift towards a more integrated bioeconomy.

Strategic and governance challenges still represent a significant issue. Although work on a national bioeconomy strategy has been underway since 2019, Slovakia has not yet adopted a comprehensive framework capable of fully coordinating bioeconomy-related policies and stakeholders. Existing activities are distributed across multiple strategies and programmes, while the absence of a formal national bioeconomy definition further complicates policy alignment and the development of a shared vision across sectors.

The country also faces **agricultural competitiveness and resource utilisation challenges**. Agriculture is still being impacted by structural and environmental pressures, including the effects of climate change, evolving production conditions, foreign ownership of agricultural land, and relatively low self-sufficiency in some essential food products. These factors have a detrimental effect on productivity and reduce the sector's ability to generate higher-value bio-based products from domestic biomass resources. At the same time, considerable quantities of agricultural and forestry resources continue to leave the country as raw materials, limiting domestic value creation.

Further constraints are linked to challenges in **research, innovation, and investment**. While Slovakia benefits from an active research community and growing interest in bioeconomy-related innovation, investment in research and development remains insufficient to support rapid technological deployment and commercialisation. Collaboration between research organisations, industry, advisors, and primary producers is not always strong enough to facilitate effective knowledge transfer. SMEs and start-ups in the bio-based sector also encounter difficulties in securing financing for innovation, industrial scale-up, and market expansion, which limits the growth of emerging bio-based industries.

The development of the sector is additionally influenced by challenges relating to **market and consumer acceptance**. In the business world, bio-based products frequently encounter challenges in competing with well-established fossil-based alternatives. These challenges stem from higher production costs and a relatively limited market demand. While Slovak consumers generally display a favourable attitude towards renewable materials, this acceptance is primarily associated with traditional products such as wood, glass, and paper. It is important to note that awareness of newer bio-based materials, industrial biotechnology applications and innovative bioeconomy solutions remains comparatively limited, which is slowing market uptake and investment.

Suggested approaches to address challenges in Slovakia's bioeconomy

Slovakia's abundant forest resources, agricultural base, and growing innovation ecosystem provide a strong foundation for the development of a competitive and sustainable bioeconomy. A key priority should be the finalisation and implementation of the national bioeconomy strategy, supported by a common national definition and a governance framework capable of improving coordination across

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ministries, sectors, and stakeholders. Such a framework would help align existing policy instruments, strengthen strategic planning, and provide greater visibility for investment opportunities. Further progress will depend on increased investment in research, development, and innovation, together with stronger collaboration between universities, research organisations, advisors, industry stakeholders, and primary producers. Improving knowledge transfer mechanisms and supporting the commercialisation of innovative technologies could accelerate the development of higher-value bio-based products and services while strengthening the competitiveness of domestic industries. Expanding access to finance for bio-based SMEs, start-ups, and industrial projects will also be important. Dedicated support mechanisms, innovation funding schemes, and stronger cooperation within clusters and innovation networks could facilitate business development and industrial scale-up. At the same time, efforts should focus on increasing the domestic processing of biomass resources and reducing dependence on exports of unprocessed agricultural and forestry materials, thereby generating greater value within national bio-based value chains. Supporting sustainable agricultural and forestry practices, improving resource efficiency, and promoting circular bioeconomy solutions will be equally important for long-term resilience. In parallel, awareness-raising activities and demonstration initiatives could help increase acceptance of innovative bio-based products and strengthen market demand. By combining stronger governance, increased innovation capacity, greater investment, and improved value-chain integration, Slovakia can build on its natural resources and emerging industrial capabilities to accelerate the transition towards a more sustainable and competitive bioeconomy.

1.2.2.18 Slovenia[128] [129] [130] [131]

Slovenia possesses significant potential for bioeconomy development due to its abundant natural resources, strong research and innovation capacities, and strategic location within Central Europe. The country's bioeconomy is closely linked to forestry, agriculture, and emerging bio-based industries, providing a solid foundation for sustainable growth and circular resource utilisation. Slovenia also benefits from well-developed research and innovation capabilities that support the development of advanced bio-based solutions. While these strengths provide favourable conditions for bioeconomy development, several structural and market-related factors continue to influence the pace of industrial deployment and value creation.

[128] Juvancic, L., et al., Executive summary of the strategic concept paper for bioeconomy: Slovenia (2023) BIOEASTsUP H2020 Project

[129] CCIS – Association of Chemical Industries of Slovenia, National Bioeconomy Dossier: Slovenia (2020) | Central European Leaders of Bioeconomy Network | CELEBIO

[130] Juvancic, L., et al., Strategic concept paper for Bioeconomy in Slovenia: from a patchwork of good practices to an integrated, sustainable and robust bioeconomy system. Open Resource Europe 3 (2023) 167 **https://doi.org/10.12688/openreseurope.16181.1**

[131] Virant, G., et al., Country Report: Slovenia (2020) | Central European Leaders of Bioeconomy Network | CELEBIO

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Current state of the Slovenian bio-based industry

Slovenia has developed a thriving bioeconomy ecosystem, supported by natural resources, research institutions, and a range of bio-based initiatives. The country has demonstrated increasing interest in integrating circular economy principles, digital technologies, and sustainable material production into its economic development model. The forestry and agricultural sectors are the primary providers of biomass resources for bioeconomy activities. However, the supply chains for biomass are still very fragmented, which reflects the dispersed structure of land ownership and production systems. While these sectors generate significant biomass resources, their integration into higher-value industrial value chains remains limited. The country also possesses capabilities in bio-based processing and bioconversion technologies. However, many existing facilities continue to operate at pilot or demonstration scale rather than at full commercial scale. Consequently, the implementation of advanced bio-based technologies in industry continues to be restricted, and the creation of higher-value bio-based products is progressing more slowly than in leading European bioeconomy countries. Slovenia is proactively exploring opportunities related to circular bioeconomy models, sustainable materials, digitalisation, and bio-based innovation. These areas represent significant opportunities for future growth, provided that existing structural and investment barriers can be addressed.

Main challenges in Slovenia's bioeconomy

Slovenia benefits from abundant biological resources, strong research capabilities, and growing interest in circular bioeconomy approaches. However, several structural, technological, financial, and governance-related barriers continue to limit the transition from a resource-based bioeconomy towards higher-value industrial bio-based production. One of the most significant challenges facing Slovenia's bioeconomy is the **fragmented structure of biomass production**, particularly within the forestry and agricultural sectors. The dispersion of landholdings has a detrimental effect on the efficient aggregation and mobilisation of biomass resources, resulting in increased logistics and transportation costs throughout the value chain. This negatively impacts the economic viability of bio-based production and hinders the development of industrial-scale applications. Furthermore, the limited availability of large-scale biomass processing hubs has a restrictive effect on opportunities for converting domestic biological resources into higher-value bio-based products.

The **bioconversion and biorefining sectors are underdeveloped**, with many facilities operating primarily at pilot scale rather than commercial scale. This lack of industrial maturity creates important scalability challenges and reduces the ability of Slovenian companies to compete internationally. The limited investment in the modernisation of infrastructure further restricts the adoption of more efficient and higher-yield processing technologies. Consequently, the commercial deployment of innovative bio-based solutions is progressing more slowly than anticipated.

Access to finance remains a significant challenge for bioeconomy businesses, particularly SMEs seeking to scale innovative technologies and business models. **Investment in bio-based ventures is often viewed as a high-risk strategy** due to the extended development timelines, uncertain market conditions and protracted return-on-investment periods involved. Securing private

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financing can therefore be challenging, especially for projects requiring substantial upfront investment. The limited availability of targeted financial incentives, grants and support mechanisms further constrain the growth of bio-based industries and innovation activities.

Regulatory and market complexity continues to impact the competitiveness of Slovenia's bioeconomy sector. Lengthy approval procedures, administrative burdens, and complex sustainability certification requirements create obstacles for companies seeking to commercialise bio-based products. These factors increase costs, delay market entry, and reduce the attractiveness of investment in new bio-based ventures. As a consequence, innovative products and processes often face difficulties reaching commercial markets in a timely manner.

Although Slovenia benefits from strong research institutions and considerable expertise in bioeconomy-related fields, collaboration between research organisations, industry, and policymakers remains insufficiently developed. The **absence of a comprehensive policy framework and the need for stronger innovation networks** can hinder the efficiency of knowledge transfer, technology adoption, and commercialisation activities. This restricts the translation of research excellence into industrial competitiveness and market-ready bio-based solutions.

Suggested approaches to address challenges in Slovenia's bioeconomy

To strengthen the competitiveness and resilience of its bioeconomy, Slovenia should focus on improving coordination across bioeconomy-related policies and establishing a more integrated governance framework capable of supporting long-term sector development. Stronger collaboration between research organisations, universities, industry, and policymakers would facilitate knowledge transfer, accelerate innovation uptake, and improve the commercialisation of bio-based technologies. Particular attention should be given to improving biomass mobilisation and supply-chain efficiency through the development of aggregation systems and regional processing hubs capable of supporting larger-scale industrial operations. At the same time, increased investment in bioconversion technologies, biorefineries, and advanced bio-based manufacturing infrastructure would help overcome current scalability limitations and strengthen the country's capacity to generate higher-value bio-based products. Additionally, addressing financial barriers will also be essential. Expanding access to targeted funding instruments, innovation grants, and investment incentives could encourage greater participation from SMEs and private investors, while reducing the risks associated with scaling bio-based ventures. In parallel, simplifying regulatory procedures and streamlining sustainability certification processes would facilitate market entry and improve the business environment for innovative bio-based companies. Finally, greater integration of digital technologies and circular economy principles throughout bio-based value chains could enhance resource efficiency, support sustainable material production, and improve overall competitiveness. By combining its strong research capabilities, abundant biological resources, and growing interest in circular economy approaches, Slovenia would be well positioned to accelerate the transition towards a more integrated, innovative, and sustainable bioeconomy.

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1.2.2.19 Spain[132] [133] [134] [135] [136] [137]

Spain is the largest country in Southern Europe, covering more than 504,000 km², and has a population of 48.6 million inhabitants (2024). Its diverse climatic conditions, ecosystems, and landscapes support extensive agricultural, forestry, and marine resources, positioning the country as one of the main contributors to the European bioeconomy. Spain benefits from a diversified economy with strong agricultural, agri-food, forestry, fisheries, aquaculture, and biotechnology sectors. Together, these sectors provide a solid foundation for the development of bio-based value chains and the transition towards a more sustainable and circular economy. The country's abundant biological resources, coupled with a well-established research and innovation ecosystem, create significant opportunities for the development of advanced bio-based products, industrial biotechnology applications, and circular bioeconomy initiatives.

Current state of the Spain's bio-based industry

Spain has actively promoted the bioeconomy through the Spanish Bioeconomy Strategy, launched in 2015 with the aim of generating added value from biological resources while supporting sustainability and climate objectives. The strategy focuses on agriculture, livestock, fisheries, aquaculture, food processing, forestry, industrial bioproducts, biomass-based bioenergy, and services associated with rural areas. According to the Joint Research Centre, Spain's bioeconomy generated a turnover of approximately €229.9 billion in 2020, representing around 10% of the EU-27 total. The sector generated approximately €68.5 billion in added value, also accounting for around 10% of the EU total, and supported approximately 1.41 million jobs, corresponding to 8% of EU bioeconomy employment. At regional level, several Autonomous Communities have developed dedicated circular bioeconomy strategies or action plans. Regions such as Andalusia, Castilla y León, Catalonia, and the Basque Country have established specific bioeconomy frameworks, while other regions are currently developing strategic initiatives adapted to local biomass resources and industrial priorities. Spain also participates actively in national and European innovation initiatives. Support mechanisms include funding schemes for operational groups, projects financed through the Recovery, Transformation and Resilience Plan (PRTR), and programmes coordinated by the

[132] Instituto Nacional de Estadística | INE| Press Release: Annual Population Census. 1 January 2024. Preliminary Results.

[133] Ministerio de Agricultura, Pesca y Alimentación | Bioeconomía

[134] Estrategia Española de Bioeconomía Horizonte 2030 | Ministerio de Economía y Competitividad | Secretaria de Estado de Investigación, Desarrollo e Innovación

[135] Asociación Española de Bioempresas | AseBio | Financing, a solid ecosystem, and regulation: key challenges for Spain to drive the Bioeconomy forward

[136] Plan complementario de agroalimentación | Agroalnext | Plan de Recuperación, Transformación y Resiliencia (PRTR) .

[137] Programa StartBEC By AINIA | Programa de acompañamiento tecnológico cofinanciado por el Ministerio de Agricultura, Pesca y Alimentación orientado a empresas emergentes en Bioeconomía .

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Ministry for Ecological Transition and Demographic Challenge, the Ministry of Science, Innovation and Universities, and the Ministry of Agriculture, Fisheries and Food (MAPA). Notable initiatives include the Start-Bec programme, developed by MAPA in collaboration with AINIA, which provides technological support to emerging bioeconomy enterprises. In addition, the Agroalnext programme has carried out a comprehensive assessment of biomass availability at provincial level, helping to improve knowledge of biomass resources and their potential uses across multiple Spanish regions. Despite these initiatives, Spain's bioeconomy remains below its full potential and faces several structural challenges that limit the deployment of advanced bio-based industries and the large-scale implementation of circular bioeconomy models.

Main challenges in Spanish bioeconomy

Spain has established one of the most comprehensive bioeconomy frameworks in Southern Europe, supported by abundant biological resources, strong regional ecosystems, and a diversified research and innovation landscape. Nevertheless, several structural and market-related barriers continue to affect the development and large-scale deployment of advanced bio-based industries. **Regulatory and policy fragmentation** remains one of the main barriers, as coordination between national and regional administrations is often inconsistent, resulting in fragmented policies and uneven support across Autonomous Communities. Although Spain adopted a national Bioeconomy Strategy in 2015, its implementation has been slower than expected and the strategy has not been substantially updated to reflect recent technological and market developments. Furthermore, sector-specific regulations, particularly in areas such as biotechnology, waste management, renewable energy, emissions, and water resources, may create uncertainty and complicate project implementation, especially at the regional level.

Innovation, financing and commercialisation challenges also continue to constrain bioeconomy development. Spain benefits from a strong research and innovation system, including universities, technology centres, and specialised bioeconomy actors. However, collaboration between research organisations, industry, and technology-transfer entities remains insufficiently integrated, limiting the commercialisation of innovative technologies and research results. At the same time, many bio-based projects require substantial investment in research, demonstration, scale-up, and market deployment before reaching commercial maturity. Access to adequate financing remains particularly challenging for innovative SMEs and start-ups, reducing their ability to scale promising technologies and compete with established fossil-based industries. These factors continue to slow the transition from pilot-scale development to industrial implementation.

In addition, **administrative and permitting bottlenecks** frequently delay the development of new bio-based industrial projects. Lengthy and sometimes unpredictable approval procedures can discourage investment and increase project risks. Stakeholders have repeatedly highlighted the need for more streamlined administrative processes and innovative tools, such as regulatory sandboxes, capable of supporting the testing and deployment of novel bioeconomy solutions.

Spain also faces **sectoral imbalances in bioeconomy development**. Existing incentives and support mechanisms have traditionally focused on bioenergy and biofuels, while other strategic

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sectors, including advanced bio-based materials, bioplastics, industrial biotechnology, and biochemicals, remain comparatively underdeveloped. At the same time, although the agri-food sector is one of the country's major strengths, significant opportunities remain to improve circularity and increase the valorisation of agricultural and food-processing by-products.

At the market level, **competitiveness challenges** continue to affect the expansion of bio-based products. Many bio-based alternatives struggle to compete with established fossil-based products because of higher production costs and insufficient market incentives. In some cases, trade-related and regulatory barriers at both national and European levels can further affect the competitiveness of Spanish bio-based industries and limit their capacity to access new markets.

Important disparities also exist in terms of **regional development and territorial cohesion**. While regions such as Navarra and Catalonia have developed strong innovation ecosystems and have become leaders in bioeconomy-related activities, other territories continue to face limitations associated with infrastructure, investment capacity, and institutional support. Given the recognised role of the bioeconomy in rural development and job creation, a more balanced territorial deployment of bioeconomy initiatives remains necessary.

Finally, **public awareness and education challenges** continue to affect the sector. Public understanding of the economic, environmental, and social benefits associated with the bioeconomy remains relatively limited, reducing both consumer engagement and broader societal support. Strengthening awareness-raising activities, education programmes, and skills development initiatives will therefore be essential to create the human capital and social acceptance required for long-term bioeconomy growth.

Suggested approaches to address challenges in Spanish bioeconomy

To fully capitalise on its substantial resource base and innovation capabilities, Spain should prioritise the revision and effective implementation of its national bioeconomy strategy, while strengthening coordination between national and regional administrations. A more coherent governance framework would help align policies, reduce fragmentation, and improve the effectiveness of support measures across the country. Greater investment is also needed to support the transition from research and demonstration activities to commercial-scale deployment. Expanding access to financing, particularly for SMEs and innovative bio-based enterprises, would facilitate industrial scale-up and accelerate market entry. At the same time, strengthening cooperation amongst research organisations, technology centres, industry, and public authorities would improve knowledge transfer and foster the commercialisation of innovative technologies. Moreover, administrative procedures and permitting processes should be streamlined to reduce uncertainty and improve the investment environment for bio-based projects. The introduction of more flexible regulatory mechanisms, including pilot frameworks and regulatory sandboxes, could further support innovation and technology adoption. Spain should also promote a more balanced development of the bioeconomy by increasing support for sectors beyond bioenergy, including bioplastics, biochemicals, industrial biotechnology, and advanced bio-based materials. Particular attention should be given to the valorisation of agricultural, forestry, fisheries, and food-processing residues, thereby strengthening

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circular economy practices and increasing the value generated from domestic biological resources. Finally, improving public awareness, enhancing education and training programmes, and supporting bioeconomy development in less advanced regions would contribute to a more inclusive and competitive bioeconomy. Building on its strong resource base, regional diversity, research capacity, and industrial strengths, Spain is well positioned to expand its role as one of the leading bioeconomy actors within the European Union.

1.2.2.20 Sweden[138] [139] [140] [141] [142] [143]

Sweden has a population of approximately 10.6 million inhabitants (2024) and a land area of around 410,000 km². Forests cover approximately 68% of the national territory, while agricultural land accounts for around 7%. Despite the large territorial extent, most of the population is concentrated in urban areas, with around 90% living in cities or smaller localities. Sweden possesses one of the most developed bioeconomies in Europe, built upon abundant forest resources, well-established biomass supply chains, strong industrial capabilities, and advanced research and innovation ecosystems. The forest sector has historically been the backbone of the Swedish bioeconomy and continues to play a central role alongside agriculture, fisheries, bioenergy, and emerging bio-based industries. The country's long-standing commitment to sustainable resource management, combined with strong environmental policies and industrial innovation, has positioned Sweden as an important agent in Europe's green transition and bioeconomy development.

Current state of the Swedish bio-based industry

The Swedish bioeconomy is estimated to generate a value equivalent to approximately 6% of national GDP and provides employment for around 330,000 people. Although forestry remains the dominant sector, other bioeconomy activities have expanded steadily, including agriculture, aquatic resources, industrial residual streams, biotechnology, and renewable energy production. The forest bioeconomy has deep historical roots, dating back to the late nineteenth century. Today, approximately 50% of Swedish forests are owned by private individuals, 25% by industry, and 15% by the state. Well-established supply chains and long-term forest management practices have

[138] Andersson, K., Bioenergy the Swedish experience. Svebio. (2015) Retrieved from https://www.svebio.se/wp-content/uploads/2017/06/Bioenergy_Swedish_experice_3rded_web.pdf

[139] Borén, E. et al., Biobased economy in Northern Sweden. A bioeconomy blueprint, prepared in the frame of the BioModels4Regions project (2025).

[140] Bioinnovation. The Bioeconomy. (2025) https://www.bioinnovation.se/en/om-bioekonomi-begrepp-och-fakta/

[141] Fridman, J., and Danell, K., Sveriges Skogar under 100 år. Riksskogstaxeringen 1923-2023 (2023). ISBN 978 91 7844 539 4.

[142] Statistics Sweden 2025. Retrieved from https://www.scb.se/en/

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enabled the sustainable utilisation of forest resources for multiple industrial applications. The implementation of the National Forest Inventory since 1923 has contributed to sustainable forest management. As a result, the standing forest stock has increased by more than 100% over the last century, reaching approximately 3.6 billion m³. The Swedish bioeconomy has also played an important role in the country's energy transition. Since the late 1970s, bioenergy has progressively replaced fossil fuels in district heating systems, industrial energy use, and electricity generation. Policy instruments such as the carbon tax introduced in 1991 and participation in the EU Emissions Trading System have contributed to significant reductions in greenhouse gas emissions while supporting the development of bioenergy and biofuels. In 2023, Sweden presented a new Bioeconomy Strategy, which is currently under consultation and aims to provide a comprehensive framework for future bioeconomy development within a fossil-free society.

Sweden-specific challenges

As Sweden seeks to expand its bioeconomy while meeting ambitious climate and biodiversity objectives, a number of challenges are becoming increasingly important for the long-term development of the sector. **Regulatory challenges** are amongst the most significant concerns, particularly within the forest-based bioeconomy. Stakeholders frequently highlight the complexity of the evolving regulatory landscape and the potential impacts of both national and European legislation on biomass utilisation and industrial development. The implementation of policies associated with the Fit for 55 package, the EU Deforestation Regulation, and the Nature Restoration framework has generated concerns regarding future access to biomass resources, investment certainty, and the long-term competitiveness of forest-based industries. A central point of debate relates to differing perspectives on forests, with EU policies increasingly emphasising forests as carbon sinks, while Sweden traditionally views forests as a renewable resource base capable of substituting fossil-based materials and products.

Industrial scale-up, innovation and investment challenges also remain important. Although technologies for processing and upgrading forest biomass are generally available, scaling innovative biorefinery concepts from pilot and demonstration stages to full industrial deployment remains difficult. The transition from research and development to commercial operations requires substantial investments, long development periods, and complex industrial partnerships. Regulatory uncertainty and the high capital requirements associated with industrial facilities can further affect investor confidence and limit the deployment of new bio-based technologies.

The country also faces **market structure and competitiveness challenges**. Established industrial actors continue to dominate certain segments of the bioeconomy, creating barriers for emerging companies and innovative business models. In some cases, existing standards, practices, and value chains may slow the introduction of new bio-based products and technologies. At the same time, bio-based products often face difficulties competing with fossil-based alternatives because of cost differences and market conditions that favour established industries.

Administrative and permitting challenges continue to affect the pace of industrial development. Lengthy and sometimes unpredictable environmental permitting procedures have been identified as

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significant barriers to investment and the implementation of projects associated with the green transition. Recognising these shortcomings, the Swedish government initiated a review of environmental permitting procedures in 2023 to identify opportunities for improvement.

Finally, **governance, stakeholder engagement and societal acceptance challenges** persist despite Sweden's advanced position in the bioeconomy. The future development of Sweden's bioeconomy will depend not only on technological and industrial progress but also on the ability to balance diverse societal expectations regarding the use of biological resources. Forests are expected to simultaneously provide raw materials for industry, renewable biomass for energy and bio-based products, carbon sequestration, biodiversity conservation, water regulation, recreational opportunities, and cultural services. These multiple and sometimes competing objectives can create tensions amongst stakeholders, including forestry companies, industrial actors, environmental organisations, local communities, policymakers, and the Sami people, whose traditional livelihoods depend on access to land and natural resources. In addition, differing interpretations of the bioeconomy concept and its role in achieving sustainability objectives can complicate decision-making and policy implementation. Strengthening dialogue, stakeholder engagement, and public understanding of the bioeconomy will therefore be important for building consensus and supporting the long-term development of a sustainable and competitive bioeconomy.

Suggested approaches to address challenges in Sweden's bioeconomy

As Sweden advances towards a fossil-free economy, maintaining its leadership position within the European bioeconomy will require balancing industrial development, climate objectives, biodiversity protection, and sustainable resource management. Greater dialogue between national and European policymakers could help ensure that regulatory frameworks support both sustainable forest management and the continued development of bio-based industries. Further efforts should focus on accelerating the scale-up of innovative bio-based technologies through increased support for demonstration projects, industrial biorefineries, and commercial deployment initiatives. Strengthening collaboration between research institutions, industrial actors, and public authorities would facilitate technology transfer and reduce barriers to market uptake. Improving investment conditions and reducing regulatory uncertainty would help attract long-term capital for bio-based industries. Continued reforms aimed at streamlining environmental permitting procedures could further support industrial development while maintaining high environmental standards. Sweden should also promote a more diversified bioeconomy by encouraging innovation beyond traditional forestry and bioenergy sectors, including advanced biomaterials, industrial biotechnology, bio-based chemicals, and circular bioeconomy solutions. At the same time, integrated approaches to land-use planning and stakeholder engagement will be increasingly important to balance economic development, biodiversity protection, climate objectives, and social considerations. Finally, strengthening communication, education, and public engagement around the role of the bioeconomy could help build a broader societal understanding of its contribution to a fossil-free and sustainable economy. By combining its abundant natural resources, strong industrial base, advanced research capabilities, and long experience in sustainable resource management, Sweden is well positioned to remain one of Europe's leading bioeconomy nations.

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1.2.2.21 UK[144] [145] [146] [147] [148] [149] [150] [151]

The United Kingdom possesses significant strengths in life sciences, biotechnology, engineering biology, and innovation-driven entrepreneurship, providing a strong foundation for the development of a competitive bioeconomy. The country benefits from world-leading universities, advanced research infrastructure, a dynamic start-up ecosystem, and extensive collaboration between academia, industry, and public institutions. Engineering biology has become a central pillar of the UK's bioeconomy strategy and has been identified as a critical technology for future economic growth. This commitment is reflected in the National Vision for Engineering Biology, which aims to position the UK as a global leader in sustainable biomanufacturing, industrial biotechnology, and bio-based innovation. The UK bioeconomy is characterised by its strong focus on science-based innovation, commercialisation, and market-driven solutions, with applications spanning agriculture, food production, chemicals, healthcare, advanced materials, and energy systems.

Current state of the UK's bio-based industry

The UK bioeconomy represents the integration of bioscience, biotechnology, and renewable biological resources across multiple economic sectors. According to previous government assessments, the bioeconomy contributed approximately £220 billion in GVA and supported around 5.2 million jobs in 2014. Direct bioeconomy activities in sectors such as agriculture, food production, and industrial biotechnology generated approximately £56 billion in GVA and supported nearly 981,000 jobs. Upstream activities contributed a further £35.5 billion, while downstream utilisation of bio-based products generated approximately £108.3 billion, demonstrating the extensive economic impact of bioeconomy-related value chains. The UK has historically sought to expand the bioeconomy through government-industry collaboration aimed at developing sustainable solutions

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[146] BEIS Growing the Bioeconomy (withdrawn) Available at: https://assets.publishing.service.gov.uk/media/61a60c91d3bf7f055b2934cf/181205_BEIS_Growing_the_Bioeconomy__Web_SP_.pdf

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[148] DESNZ: Project contract PS22436 - Economic and climate benefits to the UK of an increased use of bio-based chemicals (RAF097/2223) 2024, unpublished

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for the agri-food, chemical, health, and energy sectors. Significant opportunities have also been identified in the production of bio-based chemicals, which could contribute substantially to future economic growth while reducing greenhouse gas emissions. A distinctive feature of the UK approach is its emphasis on cross-sectoral integration and innovation-led growth. Research infrastructure, including biorefinery centres, innovation networks, and demonstration facilities, plays a key role in supporting technology development and reducing commercialisation risks. Public-private partnerships remain central to bridging the gap between academic research and industrial deployment. Although the UK Bioeconomy Strategy (2018) aimed to position the country as a global leader in bio-based solutions by 2030, it was subsequently replaced by the Innovation Strategy (2021), resulting in a more decentralised governance model. Today, bioeconomy development is strongly supported by regional innovation clusters, research institutions, industrial partnerships, and targeted programmes focused on engineering biology and sustainable manufacturing.

The regulatory landscape is evolving to support competitiveness and international market access. Current efforts focus on enhancing alignment with major international markets, including the European Union and the United States, while preserving flexibility in areas where the UK seeks to develop competitive advantages, such as precision breeding technologies and engineering biology. Stakeholders have also advocated for stronger regulatory harmonisation, mutual recognition arrangements, and standards development to facilitate the commercialisation of bio-based products and improve international market access.

The UK benefits from a relatively mature financing ecosystem for biotechnology and bioeconomy-related innovation. Public support is provided through organisations such as Innovate UK, research councils, and sector-specific funding programmes. Private investment has remained strong, particularly within biotechnology. Venture capital investment in UK biotech companies reached significant levels in recent years, with the country maintaining its position as one of Europe's leading destinations for biotechnology investment. The financing environment supports companies across multiple stages of development, from early-stage innovation to commercial scale-up. Nonetheless, challenges remain, particularly regarding seed-stage financing, long-term support for industrial-scale deployment, and maintaining competitiveness in relation to other major bioeconomy regions such as the EU and the United States.

Main challenges in British bioeconomy

As the UK seeks to strengthen its position as a global leader in engineering biology and sustainable biomanufacturing, several challenges continue to influence the commercialisation, scale-up, and competitiveness of bio-based industries. **Policy cohesion and governance challenges** remain amongst the most significant barriers. Following the replacement of the 2018 Bioeconomy Strategy by the 2021 Innovation Strategy, bioeconomy governance has become more decentralised. Responsibilities are distributed across multiple departments and agencies with differing priorities, including environmental protection, industrial innovation, and energy policy. This fragmentation can result in policy inconsistencies, competing objectives, and inefficient allocation of resources across bioeconomy sectors.

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The UK also faces **regulatory coordination challenges**. Regulatory oversight is distributed across multiple organisations, including the Food Standards Agency (FSA), the Health and Safety Executive (HSE), and the Department for Environment, Food and Rural Affairs (DEFRA). While efforts are underway to improve regulatory alignment with international markets, businesses continue to encounter complexity and uncertainty when navigating regulatory requirements, particularly SMEs operating in emerging bio-based sectors.

Another major obstacle concerns **commercialisation, scale-up and industrial deployment challenges**. Although the UK possesses world-leading research capabilities and has invested heavily in bioeconomy-related research and innovation, many technologies remain at relatively preliminary stages of commercial development. Transitioning innovations from laboratory and pilot scale to industrial production continues to be a major challenge. Additional investment is required to expand demonstration facilities, biomanufacturing capacity, and industrial-scale biorefineries capable of supporting the large-scale production of bio-based products. Without sufficient scale-up infrastructure, many promising technologies face difficulties progressing beyond pilot or demonstration stages, limiting their commercial and economic impact.

The sector also faces **investment and financing challenges**. Despite strong venture capital activity and growing investor confidence in biotechnology, some areas continue to experience difficulties in securing long-term financing. Reduced grant funding and declining participation in domestic seed-stage investment can create barriers for early-stage companies seeking to commercialise innovative technologies.

In addition, **market development and international competitiveness challenges** continue to limit growth. Demand for bio-based products remains constrained in some sectors by price competitiveness, limited market incentives, and the absence of strong demand-pull mechanisms. Without sufficient market signals, innovative products may struggle to achieve the scale necessary for widespread adoption. At the same time, the UK faces increasing competition from the European Union, the United States, and other regions investing heavily in biotechnology, engineering biology, sustainable manufacturing, and industrial bioeconomy development. Maintaining international competitiveness will require continued innovation, supportive regulatory frameworks, strong domestic markets, and effective coordination between public and private stakeholders.

Suggested approaches to address challenges in the UK's bioeconomy

To maintain its position as a global leader in biotechnology, engineering biology, and sustainable biomanufacturing, the UK will need to strengthen policy coordination, accelerate commercialisation pathways, and support the industrial deployment of innovative bio-based Solutions. Stronger cross-departmental coordination could reduce policy fragmentation, improve resource allocation, and provide greater clarity for investors and businesses operating across bioeconomy value chains. Further efforts should focus on accelerating the commercialisation of research and innovation by supporting the transition from lab-scale research to pilot, demonstration, and industrial-scale deployment. Expanding access to shared biomanufacturing facilities, biorefineries, and other scale-

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up infrastructure would help reduce investment risks and improve the market readiness of emerging technologies.

Maintaining strong public and private investment will also be essential. Continued support for research and innovation programmes, combined with targeted financing mechanisms for scale-up activities, could improve the ability of SMEs and innovative companies to bring new bio-based products to market. At the same time, stronger collaboration between academia, industry, investors, and government agencies would help maximise the value generated from the UK's research excellence. Furthermore, the development of clearer market incentives could further stimulate demand for bio-based products. Measures such as minimum bio-based content requirements, public procurement initiatives, fiscal incentives, and harmonised standards could improve market uptake while increasing confidence amongst producers and consumers.

Finally, continued work on international regulatory alignment and standards harmonisation would strengthen the UK's position within global bioeconomy value chains. By combining its strengths in engineering biology, biotechnology research, innovation infrastructure, and industrial collaboration, the UK is well positioned to remain a leading international actor in the transition towards a sustainable and high-value bioeconomy.

1.3 Importance Of Technology Integration And Process Efficiency

The bio-based industry in Europe is of critical importance in the context of the continent's transition towards a sustainable and circular economy. As the European Union intensifies its efforts to achieve climate neutrality and reduce dependence on fossil resources, the role of bio-based industries becomes increasingly significant. The integration of advanced technologies and the pursuit of process efficiency are of paramount importance in this regard. These elements serve not only as enablers of innovation but also as cornerstones of industrial competitiveness and environmental stewardship within the sector[152].

Technological integration within the bio-based industry involves a broad spectrum of innovations that collectively enhance productivity, quality, and sustainability. The bio-based industry is a multidisciplinary field encompassing agriculture, forestry, fisheries, and industrial biotechnology, all of which benefit from advances in science and engineering. These innovations underpin the transformation of biomass into value-added products such as biofuels, bioplastics, and biochemicals, making technology integration indispensable to the success of the entire value chain[153].

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In the contemporary European context, technology functions as a catalyst for unlocking the potential of underutilised and complex biomass sources. Through advancements in enzymatic hydrolysis, fermentation, and catalytic conversion, industries are now able to extract and convert valuable compounds from lignocellulosic and non-food biomass with greater precision and yield[154] [155]. These capabilities are crucial for improving the economic feasibility of bio-based production, particularly as the industry navigates fluctuating resource availability and market volatility. Moreover, technological innovation has facilitated the evolution of biorefineries, which emulate the versatility of petroleum refineries but operate on renewable feedstocks. These integrated biorefineries possess the capacity to process diverse biomass inputs into a wide array of bio-based products, thereby enabling a more flexible and diversified product portfolio. The integration of technology enables bio-based industries to adapt to changing demand and market trends while making better use of available resources.

Digitalisation, another key facet of technological integration, has emerged as a powerful tool in enhancing operational efficiency and transparency across the bio-based industry[156]. Real-time monitoring and data-driven optimisation of production processes leads to significant reductions in waste, energy consumption and resource input[157]. Precision agriculture and smart forestry techniques, enabled by remote sensing, geographic information systems (GIS), and machine learning, contribute to the sustainable sourcing of biomass by improving yield prediction and input management[158]. The application of artificial intelligence (AI) and big data analytics within laboratory and industrial settings has accelerated the discovery of novel bio-based compounds and optimised biotechnological processes[159]. The utilisation of computational modelling and simulation, incorporating the concept of digital twins, facilitates the acquisition of valuable insights into process dynamics and enables proactive decision-making[160]. These technologies assist bio-based

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companies in optimising their operations, anticipating maintenance needs, and enhancing overall process control.

Concurrently, the implementation of blockchain and associated traceability technologies has enhanced the integrity of bio-based supply chains. In the bioeconomy, transparency and traceability are critical attributes, since sustainability claims must be verifiable to build consumer trust and support market development by eliminating fraud and tempering[161] [162]. These technologies contribute to greater confidence amongst stakeholders and end users by ensuring the provenance and sustainability of biomass and bio-based products[163]. Furthermore, the integration of these technologies is vital in enhancing the compatibility of bio-based products with existing industrial infrastructures. Technological advances have enabled the development of drop-in bio-based alternatives that can replace fossil-based inputs without requiring significant changes in equipment or processes. This compatibility facilitates market acceptance and accelerates the spread of bio-based solutions in traditional sectors such as construction, packaging, automotive and textiles[164] [165] [166].

Process efficiency is a key consideration in all stages of the bio-based value chain, from feedstock handling and pretreatment to conversion, purification and downstream processing. Improvements in these areas can lead to significant cost reductions, higher product yields and improved scalability. Efficient processes minimise resource use and emissions, while increasing throughput and product consistency. In a world where resources are limited and the sustainable availability of biomass is

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finite; efficiency gains are not only desirable but essential for long-term viability[167] [168] [169]. To this end, process intensification techniques, such as continuous processing and integrated unit operations, are pivotal to achieving these objectives. By reducing the number of processing steps and simplifying operations, industries can achieve more compact and energy-efficient systems.

Energy efficiency is a particularly salient aspect of process optimisation. The production of bio-based products, especially those derived from complex biomass, can be energy intensive. Consequently, innovations that reduce thermal and electrical energy requirements are critical to improving overall environmental performance[170]. Waste heat recovery systems, energy-efficient reactors and process integration strategies are all means by which the carbon footprint of bio-based production can be reduced[171] [172]. Likewise, another area where process optimisation can have a significant impact is water efficiency. A substantial proportion of bio-based processes are dependent on water for various critical functions, including reactions, cooling, and cleaning. The development of technological solutions that either reduce water consumption or enable water recycling is therefore of paramount importance[173]. Such solutions not only result in a reduction of operating costs but also serve to minimise the environmental impact of production facilities. This is particularly salient in regions where water scarcity is a prevalent issue or where regulatory restrictions on industrial water usage are in place[174] [175].

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Waste minimisation and valorisation serve as a prime example of the symbiotic relationship between technological innovation and operational efficiency. The process of converting process residues and by-products into valuable co-products, such as bioenergy, animal feed or soil amendments, improves overall resource efficiency and contributes to a circular economy. This approach enhances operational performance and supports broader environmental and economic objectives[176] [177] [178].

The competitive positioning of Europe's bio-based industries demonstrates the importance of integrating technologies and improving efficiency[179]. As global interest in sustainable materials and green technologies increases, the ability to innovate and optimise is a strategic advantage. European companies that lead in these areas will be better placed to capture emerging market opportunities, attract investment and form international partnerships[180]. Furthermore, enhancing process efficiency and leveraging technological advancements support quality assurance and regulatory compliance. The consistency of product specifications, the ability to trace products, and compliance with sustainability standards are becoming increasingly important in both domestic and international markets. Technologies that enable precise control of inputs and outputs enhance a company's ability to meet these expectations, thereby strengthening its credibility in the marketplace[181] [182] [183].

The role of R&D institutions and innovation poles in Europe is of crucial importance in advancing the technological frontier of the bioeconomy. The effective collaboration between academia, industry and research centres is instrumental in facilitating knowledge transfer and the co-creation of

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solutions that are tailored to real-world challenges[184] [185]. The pivotal function of pilot plants and demonstration facilities in the commercialisation of laboratory discoveries is instrumental in ensuring the translation of research into practical, marketable solutions[186] [187].

In conclusion, it is evident that technology integration and the pursuit of process efficiency are fundamental to the current and future success of the European bio-based industry. These elements enable the sector to improve resource use, enhance environmental performance and maintain a competitive edge in an evolving global economy. By advancing these dimensions, the European bioeconomy can continue to grow in both size and impact, reinforcing its central role in the continent's sustainable development agenda. This will be analysed in detail in Section 5.

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2 CURRENT STATE OF BIO-BASED PROCESSES

2.1 BIOCONVERSION TECHNOLOGIES

Bio-based processes have emerged as a promising alternative to traditional chemical and industrial processes, offering potential solutions to environmental challenges and resource depletion. The bioeconomy is intrinsically based on bio-based processes, which are essential in converting the potential of renewable biological resources, including plants, microorganisms, and enzymes, into a diverse range of tangible goods and services, including biochemicals, biomaterials, bioplastics, pharmaceuticals, and biofuels, amongst others. The motivation for the development of bio-based processes has been driven by the need for formulating sustainable alternatives to fossil-based production methods and the growing awareness of environmental issues.

The evolution of bio-based processes has undergone a considerable leap forward in recent decades, largely due to the significant advances developed in biotechnology, genetic engineering, and process engineering. These advances have enabled the development of more efficient and versatile bio-based processes, with applications ranging from biofuel production to the synthesis of pharmaceuticals and specialty chemicals.

The primary objectives of bio-based processes are to reduce the environmental impact of industrial activities, decrease dependence on non-renewable resources, and create more sustainable production methods. By using renewable feedstocks and biological catalysts (or biocatalysts), these processes aim to minimise waste generation, reduce energy consumption, and lower GHG compared to conventional chemical processes.

Key areas of focus in bio-based processes include bioconversion technologies, which involve the transformation of biomass or other organic materials into valuable products through biological means. These technologies cover fermentation, enzymatic conversion, and microbial processes and facilitate the establishment and development of bio-based processes, enabling the transformation of natural resources into sustainable products.

Bioconversion, otherwise designated as biotransformation, plays a key role in the development of the bioeconomy, offering sustainable methods to transform organic materials (such as biomass, agricultural waste, or industrial byproducts) into valuable products or energy sources by means of biological processes or agents, including certain microorganisms and enzymes. Despite being generally less productive than chemical synthetic reactions, it is also vital to acknowledge the pivotal role that bioconversion processes, such as microbial fermentation, enzymatic processes, or anaerobic digestion, play in reducing Europe's reliance on fossil fuels and expediting the transition

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towards a green and circular economy[188]. This transition offers environmental benefits as well as significant economic and social advantages, including the creation of new markets and employment opportunities, particularly in innovative sectors and rural and coastal areas where the production of biological resources is concentrated. The EU's ambitious zero pollution and climate neutrality goals by 2050, in line with the European Green Deal and the newly developed Industrial Clean Deal, can be achieved through the potential or circular bio-based innovative solutions, driven by efficient bioconversion methods.

The current state of bioconversion technologies is characterised by rapid advancements in genetic engineering, metabolic engineering, and synthetic biology, which have expanded the range of possible transformations and improved process efficiencies. The maturity of bioconversion technologies varies significantly as is reflected in their TRLs. Conventional biomass producing, such as biorefineries based on sugar, starch, oil, and pulp mill processes, has reached TRLs between 8 and 9, indicating full commercial application. However, many advanced biorefinery concepts aimed at producing chemicals and materials are at lower TRLs, requiring further research and development before commercialisation. Some emerging technologies are still in early stages of development such as single platform biorefineries for conversing lignocellulosic wastes to environmentally biofuels[189] or other bio-based products such as ectoine or medium-chain fatty acids[190] [191].

Several bioconversion technologies have achieved commercial success, being identified as established technologies:

2.1.1 Enzymatic hydrolysis

Enzymatic hydrolysis is a critical biochemical process in the valorisation of lignocellulosic biomass, in which complex carbohydrates are decomposed into fermentable sugars through the action of specific enzymes, including cellulases, hemicellulases and ligninases. These enzymes demonstrate optimal functionality within a relatively narrow temperature range of 45-55 ºC and a broad pH range

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[191]Ng, H.S., et al., Production and recovery of ectoine, Processes 11(2) (2023) 339. https://doi.org/10.3390/pr11020339

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of 4.8-5.5. Notably, their efficacy can be improved following biomass pretreatment, reducing recalcitrance and enhancing substrate accessibility by disrupting the lignin-cellulose matrix[192] [193].

This process is a pivotal phase in the production of second-generation biofuels (e.g., bioethanol) and biochemicals (e.g., lactic acid, succinic acid, and oligosaccharides), as will be evidenced later in this report. Common feedstocks are utilised in this process, including wheat straw, corn stover, miscanthus, forestry by-products, and agro-industrial wastes such as sugar beet pulp and distillers dried grains[194].

Nevertheless, there are still technical and economic challenges to overcome. The elevated expense of commercial enzymes constitutes a substantial impediment to large-scale implementation, thus accounting for a considerable proportion of total production costs[195]. Furthermore, the inhibition of enzymes by lignin-derived compounds, in addition to substrate variety, have been demonstrated to result in a reduction in conversion yields[196]. Studies employing exergy analysis have indicated that enzymatic hydrolysis can be energetically viable, achieving efficiencies of about 70%, although it should be noted that certain processes continue to exhibit significant irreversibility[197].

Recent advancements in enzyme cocktails, such as combinations of *Arpergillus sp.*, *Trichoderma reesei* and *Penicillium citrinum*, and production strains, have exhibited hydrolytic efficiencies of up to 93% for industrial cellulose pulp[198]. Additionally, there is an increasing focus on improved

[192]Vargas, F., et al., Agricultural residue valorization using a hydrothermal process for second generation bioethanol and oligosaccharides production, Bioresource Technology 191 (2015) 263-270. https://doi.org/10.1016/j.biortech.2015.05.035

[193]Qin, L., et al., Hydrolysis of lignocellulosic biomass to sugars. In: Z. Fang, R. Smith Jr., X. Qi (eds). Production of Platform Chemicals from Sustainable Resources. Biofuels and Biorefineries (2017). Springer, Singapore. https://doi.org/10.1007/978-981-10-4172-3_1

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[198]Pimentel, P.S.S.R., et al., Enzymatic hydrolysis of lignocellulosic biomass using an optimized enzymatic cocktail prepared from secretomes of filamentous fungi isolated from Amazonian biodiversity, Applied Biochemistry and Biotechnology 193 (2021) 3915-3935. https://doi.org/10.1007/s12010-021-03642-5

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pretreatment technologies, and thermostable enzymes and thermophilic microbes for more efficient hydrolysis at elevated temperatures[199] [200].

Several integrated biorefineries are currently in operation throughout Europe, processing a wide array of biomass sources such as wheat straw, corn stover, and forestry residues. These facilities collectively process several hundred thousand tonnes of lignocellulosic biomass per year, depending on size and feedstock availability[201]. For instance, a recent optimisation model for Germany estimated that each integrated biorefinery could process at least 94,500 tonnes of dry matter annually, with potential to operate 69 decentralised mid-scale plants across the country[202]. These facilities are frequently supported by EU-funded projects and public-private partnerships, strengthening Europe's ability to valorise lignocellulosic residues into fuels, chemicals, power, and heat[203]. These initiatives are supported under collaborative frameworks such as Horizon Europe and CBE JU, which provide coordinated funding and technical support for biorefinery scale-up and innovation.

2.1.2 Bioethanol Production

Bioethanol production is a well-established bioconversion technology that involves the fermentation of sugars by microorganisms, principally yeast (generally *Saccharomyces cerevisiae*), to produce bio-based ethanol. While ethanol can be also produced chemically, this bio-based approach aligns more closely with the principles of the bioeconomy. Bio-based ethanol (or bioethanol) has emerged as a key renewable fuel in the global bioeconomy, offering a sustainable alternative to fossil fuels by reducing GHG emissions and enhancing energy security. This product is a viable alternative or blend for gasoline. It directly mitigates transportation-related carbon emissions by offsetting the CO_2 released during its combustion with CO_2 absorbed during biomass growth, contributing to a near-

[199] Bhalla, A., et al., Improved lignocellulose conversion to biofuels with thermophilic bacteria and thermostable enzymes, Bioresource Technology 128 (2013) 751-759. https://doi.org/10.1016/j.biortech.2012.10.145

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carbon-neutral cycle[204] [205]. There are several advantages to be considered, including the use of renewable feedstock and integration into circular economies by repurposing agricultural waste (particularly in second-generation bioethanol production).

The feedstocks utilised for bioethanol production in the EU are subject to variation according to the specific production route employed. A significant proportion of potential feedstocks consist of complex carbohydrate polymers. In the context of the EU, the main feedstocks for bioethanol production are sugar beet derivatives and cereals (including wheat, corn, barley, rye, or triticale), aligning with the RED II, which advocates for the promotion of sustainable biofuel production[206]. To be utilised by microorganisms, such polymers must undergo a process of hydrolysis, whereby the feedstock is broken down into fermentable sugars.

First-generation bioethanol is produced using sugar-containing feedstocks, such as sugar beet and sugarcane, and starch-containing feedstocks, such as wheat, rye, triticale, barley, and maize. It dominates the commercial bioethanol production due to well-established fermentation technologies. For instance, the overall process for starch-based feedstocks involves several key steps, including milling/grinding (releasing the starch from the feedstock), liquefaction (dissolving the starch in water and cooking), saccharification (hydrolysing the starch into sugars through the use of enzymes or acids), fermentation (converting these sugars into bioethanol and CO_2), distillation (purifying the bioethanol), and a final dehydration to achieve a high-purify product which can be used for fuel applications [207] [208]. Advanced or second-generation bioethanol, produced from lignocellulosic biomass (such as agricultural residues, forestry residues, and dedicated energy crops), addresses these limitations by utilising non-food biomass, with a view to circumventing competition with food and feed production. The process for lignocellulosic biomass differs primarily in the initial hydrolysis step, which is more challenging due to the complex structure of cellulose and hemicellulose. The four-stage production process begins with pretreatment (mechanical, chemical, or biological methods) to break down lignin and expose cellulose/hemicellulose. As was mentioned before, enzymatic hydrolysis then converts polysaccharides into fermentable sugars, followed by microbial fermentation (typically using *Saccharomyces cerevisiae*) to produce ethanol. Finally, as for first-

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[205] Bioethanol from Waste | NNFCC: The bioeconomy consultants

[206] Renewable Energy – Recast to 2030 (RED II) - European Commission

[207] Ayodele, B.V., et al., An overview of integration opportunities for sustainable bioethanol production form first- and second-generation sugar-based feedstocks, Journal of Cleaner Production 245 (2020) 118857. **https://doi.org/10.1016/j.jclepro.2019.118857**

[208] Hoang, T.D., and Nghiem, N., Recent developments and current status of commercial production of fuel ethanol, Fermentation 7(4) (2021) 314. **https://doi.org/10.3390/fermentation7040314**

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generation bioethanol, the ethanol recovery process involves distillation and dehydration to achieve fuel-grade purity (99,5% or higher)[209].

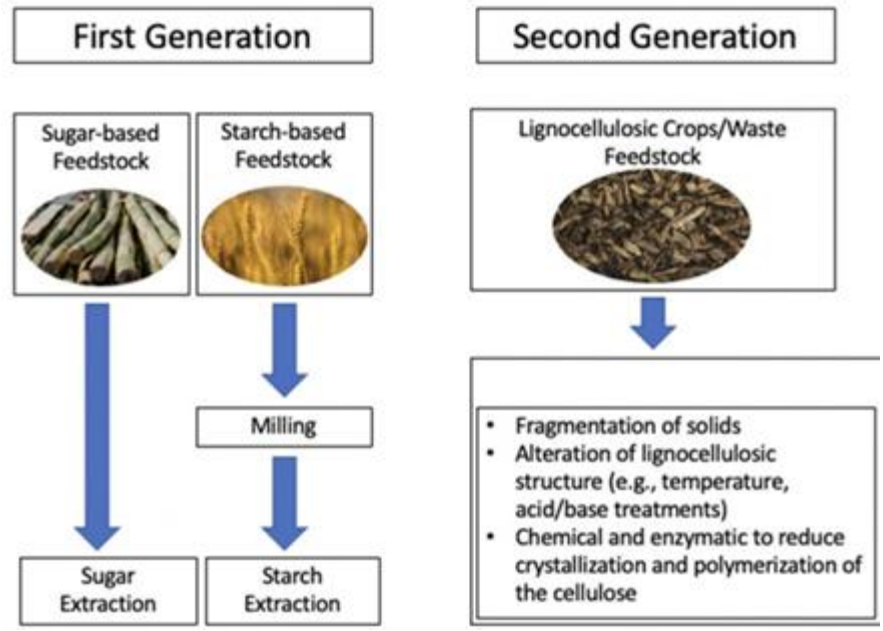


Figure 4 – General flowchart of first- and second-generation bioethanol production. Adapted from Tse et al. (2021)[210]

Bioethanol production is an important part of the EU biofuels sector. In 2023, EU bioethanol production consumption reached a record high of 6.58 billion litres, a significant increase of 26% compared to pre-COVID levels, mainly due to the expansion of the petrol fuel market in the region. However, the production of bioethanol in the EU will decline slightly by 0.9% to 5.25 billion litres in 2023, due to reduced supplies of sugar beet, a key raw material. In 2020, total EU bioethanol production will be around 5 billion litres (around 3 million tonnes of oil equivalent)[211]. Looking back to 2015, the EU produced 5.19 billion litres of ethanol, of which an estimated 75 million litres was cellulosic ethanol, a more advanced type produced from non-food feedstocks. The current capacity of first-generation bioethanol plants in the EU is around 8.48 billion litres, although capacity utilisation

[209] Robak, K., and Balcerek, M., Review of second generation bioethanol production from residual biomass, Food Technology & Biotechnology 56(2) (2018) 174-187. https://doi.org/10.17113/ftb.56.02.18.5428

[210] Tse, T.T., et al., Production of bioethanol – a review of factors affecting ethanol yield, Fermentation 7 (2021) 268. https://doi.org/10.3390/fermentation7040268

[211] European Commission, Joint Research Centre, V. Motola, et al., Clean energy technology observatory: advanced biofuels in the European union – 2024 Status report on technology development trends, value chains and markets. (2024) Publications Office of the European Union, Luxembourg. https://data.europe.eu/doi/10.2760/6538066

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was estimated at 68% in 2015[212]. In summary, first-generation bioethanol remains a market cornerstone, with commercially mature technologies supporting large-scale production from corn and sugarcane. In 2019, global bioethanol production exceeded 100 billion litres annually of global production, demonstrating technical feasibility and commercial viability for bioethanol (and biofuel) production. For instance, Brazil and the United States are responsible for the production of billions of litres of bioethanol each year from sugarcane and corn, which accounts for approximately 85% of global production[213] [214]. However, these feedstocks have been the subject of some criticism. This is due to the fact that they compete with food supplies and require intensive land and water use. This issue will be explained in more detail in Section 2.5. Second-generation technologies, though fewer, represent the state-of-the-art, leveraging advances in enzymatic efficiency (e.g. cellulase cocktails) and pretreatment methods like alkali or steam explosion. However, production (and scalability) remains constrained by technical and economic challenges, including feedstock variability (where seasonal availability and compositional differences complicate standardised processing), economic viability (where high capital and operational expenses for enzymes, fermentation inhibitors, and distillation limit profitability), lignin recalcitrance (due to lignin's structural complexity), and process inefficiencies[215] [216] [217]. For example, recent trials using rice straw achieved 21.45% ethanol yield through optimised enzymatic hydrolysis, although figures can vary based on process conditions[218]. Figure 5 presents an image of an industrial plant (40,000 Tn/day) installed in Italy.

[212] Niphadkar, S., et al., Bioethanol production: insight into past, present and future perspectives. Biofuels 9(2) (2018) 229-238. https://**doi.org/10.1080/17597269.2017.1334338**

[213] Bertrand, E., et al., First Generation Bioethanol, In: C. Soccol, S. Brar, C. Faulds, L. Ramos, (eds). Green Fuels Technology. Green Energy and Technology, Springer, Cham. **https://doi.org/10.1007/978-3-319-30205-8_8**

[214] Khairati, M., Bioethanol: advances, benefits, and future prospects, International Journal of Research and Review 11(8) (2024) 568-574. **https://doi.org/10.52403/ijrr.20240860**

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[217] Devi, A., et al., A panoramic view of technological landscape for bioethanol production from various generations of feedstocks, Bioengineered 14(1) (2023) 81-112. **https://doi.org/10.1080/21655979.2022.2095702**

[218] Ningthoujam, R., et al., Bioethanol production from alkali-pretreated rice straw: effects on fermentation yield, structural characterization, and ethanol analysis, Frontiers in Bioengineering and Biotechnology 11 (2023) 1243856. **https://doi.org/10.3389/fbioe.2023.1243856**

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Figure 5 – Image of an Italian bioethanol production plant at industrial scale with a production capacity of 40,000 Tn/year and a biomass storage hall capacity of 10,000 Tn [219].

The following table summarises the key characteristics of first- and second-generation biofuels, including bioethanol.

Table 3 – First- and second-generation biofuels, their feedstock and production steps.

Type of biofuel	Biomass feedstock	Production processes	Key technologies	CO_2 reduction potential
First-generation biofuels	Food crops (sugarcane, corn, wheat), edible oils (rapeseed, soybean)	Saccharification, fermentation, and distillation.	Mature fermentation processes	Up to 60% compared to gasoline
Second-generation biofuels	Non-food biomass: lignocellulosic materials, municipal solid waste, algae.	Pretreatment, enzymatic hydrolysis, fermentation, ethanol recovery	Biochemical and thermochemical pathways Advancing from pilot to commercial plants	70-86% due to non-food feedstcok and waste utilisation

[219] Pietrangeli, B., and Lauri, R., Occupational health issue in a 2G bioethanol production plant (2021). https://doi.org/10.5772/intechopen.94485

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Third- and fourth-generation bioethanol will be described later in the chapter devoted to "Emerging technologies in bio-based processes", especially in Biotechnology advancements.

2.1.3 Biogas Production

Biogas production has solidified its position as a mature technology within the bioeconomy, combining organic waste management, renewable energy generation and nutrient recycling, and playing a significant role in the transition towards sustainable energy and resource management through anaerobic digestion, a well-established biological process involving four key biochemical steps where microbial consortia (including fermentative bacteria, acetogens, homo-acetogens, hydrogenotrophic, and aceticlastic methanogens) decompose organic matter in oxygen-free environments[220] [221]. The technology's core purpose lies in transforming diverse feedstocks such as agricultural residues, organic municipal solid waste (including food waste), waste from food industry, biodegradable wastewaters, sludge from municipal and industrial wastewater treatment plants, or energy crops into biogas and digestate, while adhering to circular economy principles through material flow closure. Biogas is a well-known renewable energy carrier with a typical composition of 50-70% methane (CH_4), 30-45% carbon dioxide (CO_2), and 0-5% impurities, whereas digestate is a nutrient-rich by-product which can act as a biofertiliser for soil applications or further processing[222] [223].

The process typically occurs in several stages: hydrolysis, where complex organic polymers and macromolecules like carbohydrates, proteins, and lipids are degraded into simpler, soluble compounds (such as sugars or amino-acids) by extracellular enzymes; acidogenesis, where acidogenic bacteria convert these soluble compounds into volatile fatty acids (VFAs) such as propionic (CH_3CH_2COOH), butyric (CH_3CH_2 CH_2COOH), and acetic acid (CH_3COOH), along with alcohols, CO_2, and H_2; acetogenesis, where acetogenic bacteria further convert the products of acidogenesis (excluding acetic acid) into acetic acid, H_2, and CO_2; and finally, methanogenesis, where methanogenic archaea convert acetic acid and H_2/CO_2 into CH_4 and CO_2.

The anaerobic digestion process yields a diverse range of valuable products and outputs. Apart from biogas, the presence of CO_2 and other impurities and trace contaminants such as hydrogen sulphide

[220]Conrad, R., Importance of hydrogenotrophic, aceticlastic and methylotrophic methanogenesis for methane production in terrestrial, aquatic and other anoxic environments. Pedosphere 30(1) (2020) 25-309 https://doi.org/10.1016/S1002-0160(18)60052-9

[221]Laguillaumie, L., et al., Controlling the microbial competition between hydrogenotrophic methanogens and homoacetogens using mass transfer and thermodynamic constraints. Journal of Cleaner Production 414 (2023) 137549 https://doi.org/10.1016/j.jclepro.2023.137549

[222]Gienau, T., et al., Nutrient recovery from biogas digestate by optimised membrane treatment. Waste Biomass Valor 9 (2018) 2337-2347 https://doi.org/10.1007/s12649-018-0231-z

[223]Lee, M.E., et al., Biogas digestate as a renewable fertilizer: effects of digestate application on crop growth and nutrient composition. Renewable Agriculture and Food Systems 36(2) (2021) 173-181 https://doi.org/10.1017/S1742170520000186

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(H_2S), water vapour, or siloxanes, amongst others, indicates the need for further processing called biogas upgrading to increase the CH_4 content (by removing the abovementioned contaminants) and then enhance its energetic value and quality for various applications like for direct injection into existing natural gas grids, for vehicle fuel, and for more efficient electricity generation[224] [225]. This augmentation of its potential applications in transport, heating and industry represents a substantial development. Common upgrading methods include membrane separation, water and/or chemical scrubbing, adsorption on activated carbon or molecules sieves, and cryogenic separation[226]. Additionally, anaerobic digestion can be stopped in the acidogenic stage to produce VFAs, which have applications in the agri-food and chemical industries, amongst others. Hydrogen can also be generated through anaerobic digestion. Moreover, biogas can be employed to provide biogenic CO_2 as a co-product, which has potential applications in the sustainable production of e-fuels and chemicals, as well as in carbon capture and storage (CCS) technologies[227].

Anaerobic digestion systems can operate in either single-stage or two-stage reactor configurations. Single-stage systems are less complex and more economical to operate by may experience instability due to overlapping biological process. Two-stage systems, which separate the acidogenic and methanogenic phases, can improve process stability and biogas yield by mitigating issues such as acidification[228].

The following scheme graphically describes the different stages of an anaerobic digestion process.

[224]Sun, Q., et al., Selection of appropriate biogas upgrading technology – a review of biogas cleaning, upgrading and utilisation. Renewable and Sustainable Energy Reviews 51 (2015) 521-532. https://doi.org/10.1016/j.rser.2015.06.029

[225]Angelidaki, I., et al., Biogas upgrading and utilization: current status and perspectives. Biotechnology Advances 36(2) (2018) 452-466 https://doi.org/10.1016/j.biotechadv.2018.01.011

[226]Appels, L., et al., Principles and potential of the anaerobic digestion of waste-activated sludge, Progress in Energy and Combustion Science 34 (2008) 755-781. https://doi.org/10.1016/j.pecs.2008.06.002

[227]Christianides, D., et al., Biogenic CO_2 emissions in the EU biofuel and bioenergy sector: mapping sources, regional trends, and pathways for capture and utilisation, Energies 18(6) (2025) 1345. https://doi.org/10.3390/en18061345

[228]Rajendran, K., et al., Advanced anaerobic digestion through two-stage processes: current developments and future trends. Renewable and Sustainable Energy Reviews 123 (2020) 109746 https://doi.org/10.1016/j.rser.2020.109746

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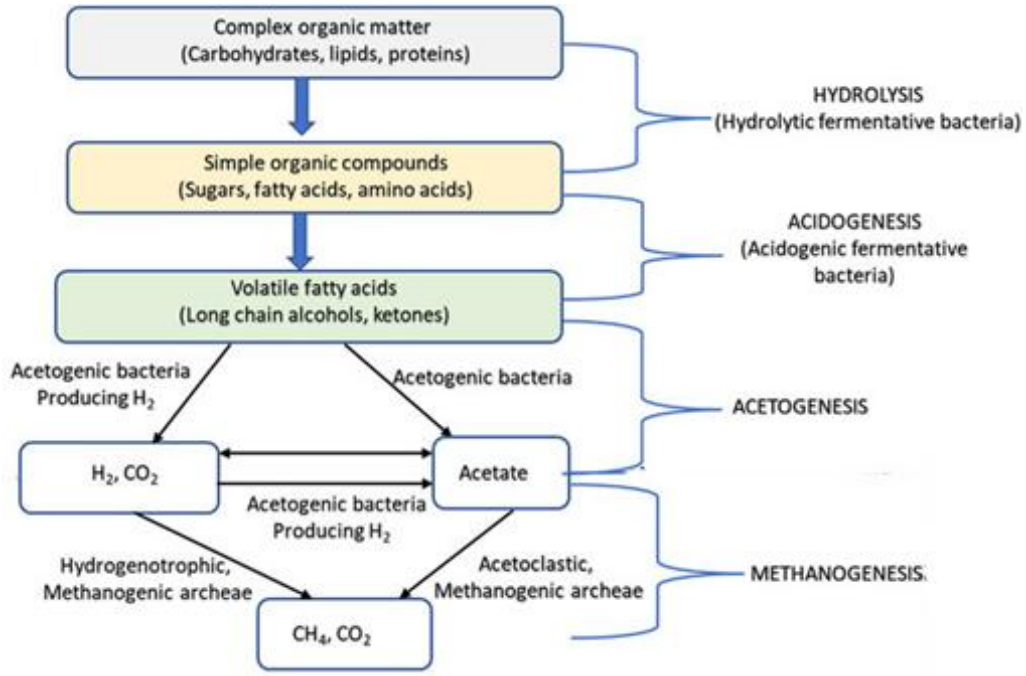


Figure 6 – Schematic diagram of the metabolism of anaerobic digestion process showing the four main stages along with the microorganisms involved in each stage[229].

Modern systems integrate feedstock pretreatment (mechanical and/or thermal processing), anaerobic digesters (usually mesophilic 35-40ºC or thermophilic 45-55 ºC), biogas upgrading and digestate management and valorisation (solid-liquid separation for biofertilizers). This configuration produces dispatchable renewable energy while reducing GHG emissions by 25-28 times CO_2 equivalent through methane capture[230].Another established advantages are energy security (due to the presence of over 19,500 European plants at the end of 2019, producing 193 TWh with a strong push toward biomethane for grid injection and transport fuel [231]), scalability (enabling implementations ranging from small-scale digesters in rural areas to centralised biorefineries like Sønderjysk Biogas in Denmark, which links 12 farms to optimise feedstock mixes[232]) and soil health

[229]Dalton, C., et al., Design of a pre-treatment integrated anaerobic digestion treatment facility for decarbonizing whiskey industry: a circular economy perspective, Heliyon 8(5) (2022) e09522. **https://doi.org/10.1016/j.heliyon.2022.e09522**

[230]Manning, D.T., and Hadrich, J.C., An evaluation of the social and private efficiency of adoption: anaerobic digesters and greenhouse gas mitigation, Journal of Environmental Management 154 (2015) 70-77. **https://doi.org/10.1016/j.jenvman.2015.02.005**

[231]EBA_Statistical Report 2020 | European Biogas Association

[232]Sonderjysk Biogas: En vedvarende og fossilfri energikilde!

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improvement through digestate application, reducing the need for synthetic fertilisers and increasing soil organic carbon by 15-30% compared to raw manure[233].

Anaerobic digestion is characterised by its ability to use a wide range of organic materials as feedstocks, contributing significantly to the principles of a circular economy. These feedstocks include primary and secondary sewage sludge, which is readily available in urban areas. Furthermore, the co-digestion of food waste, poultry litter and sewage sludge has been demonstrated to enhance biogas yields, underlining the efficacy of integrated waste management strategies[234] [235]. Urban biowaste and wastewater are also increasingly recognised as key feedstocks for the development of urban circular bioeconomy initiatives. In particular, the organic fraction of municipal solid waste (OFMSW) is a key resource that is being targeted for valorisation through anaerobic digestion and other bioconversion processes[236] [237]. In addition to urban waste streams, agricultural residues also serve as key feedstocks for biogas production, further integrating the agricultural and energy sectors within the bioeconomy[238].

However, persistent challenges constrain wider adoption. Feedstock heterogeneity needs strict parameter control (pH 6.7-7.5, C/N ratio 16:1-25:1, and HRT 15-30 days), with deviations causing process inhibition from accumulation of ammonia, VFAs, lipids or other toxic compounds[239] [240]. Economic viability remains subsidy-dependent with high capital costs and methane losses from digestate storage (caused by poor management) contributing 4% of total CH_4 emissions[241].

[233]Kumar, M., et al., A critical review on biochar for enhancing biogas production from anaerobic digestion of food waste and sludge. Journal of Cleaner Production 305 (2021) 127143. https://doi.org/10.1016/j.jclepro.2021.127143

[234]Mu, L., et al., Anaerobic co-digestion of sewage sludge, food waste and yard waste: synergistic enhancement on process stability and biogas production. Science of the Total Environment 704 (2020) 135429. https://doi.org/10.1016/j.scitotenv.2019.135429

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[239]Guo, Z., et al., Synergistic ammonia and fatty acids inhibition of microbial communities during slaughterhouse waste digestion for biogas production, Bioresource Technology 337 (2021) 125383. https://doi.org/10.1016/j.biortech.2021.125383

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[241]Buratti, C., et al., Assessment of GHG emissions of biomethane from energy cereal crops in Umbria, Italy. Applied Energy 108 (2013) 128-136. https://doi.org/10.1016/j.apenergy.2013.03.011

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Technological limitations include slow microbial adaptation (more than 3 weeks for substrate changes), biogas impurities (H_2S/siloxanes requiring costly scrubbing), maintenance costs, and unproven scalability of emerging solutions like hydrogen-assisted methanogenesis.

The production of biogas and its upgraded form, bioCH_4, is a significant and growing sector in the European Union. In 2023, the combined production of biogas and biomethane in Europe is set to reach an impressive 22 billion cubic metres. This volume exceeds the total domestic natural gas demand of Belgium, Denmark and Ireland combined and represents 7% of the European Union's total natural gas consumption in that year. It is noteworthy that there has been a substantial increase in biomethane production, which reached 4.9 billion cubic metres in 2023. It is anticipated that the installed capacity will reach 6.4 billion cubic metres per year by the first quarter of 2024. This signifies the most substantial year-on-year surge in biomethane production to date, with a notable 21% uptick concentrated in the EU. This expansion underscores the mounting importance of anaerobic digestion as a pivotal technology within the EU renewable energy landscape[242].

Recent developments have highlighted the shift towards waste valorisation over dedicated energy crops, with a view to enhancing sustainability and mitigating land-use conflicts. Similarly, cutting-edge systems now integrate biorefinery concepts, such as BioKymppi in Finland combining AD with pyrolysis to produce biochar for soil enhancement, Norway's Magic Factory extracting high-value chemicals from digestate, and the abovementioned Sønderjysk Biogas in Denmark linking 12 farms to optimize substrate mix[243] [244] [245]. Research frontiers are now based on circular bioeconomy models, with a focus on hybrid systems to maximise conversion yields and biomethane content and subsequently convert the present CO_2 into bio-based products[246]. In the same way, contaminant mitigation strategies are also being developed to minimise antibiotic resistance genes, microplastics, heavy metals and other contaminants of serious environmental concern[247].

[242] EBA Statistical Report 2024 | European Biogas Association

[243] Jazbec, M., and Turner, A., Creating a circular economy precinct (2018) Report prepared by the Institute for Sustainable Futures, University of Technology Sydney, for Sydney Water. **Creating a circular economy precinct (Institute for Sustainable Futures)**

[244] Jasinska, A., et al., Bioconversion of agricultural wastes into a value-added product: straw of Norwegian grains composted with dairy manure food waste digestate in mushroom cultivation. Horticulturae 8(4) (2022) 331. **https://doi.org/10.3390/hortoculturae8040331**

[245] Nielsen, M.B., Identifying challenges and drivers for deployment of centralized biogas plants in Denmark. Sustainability 14(13) (2022) 8021. **https://doi.org/10.3390/su14138021**

[246] Kuo, P.C., et al., Efficient conversion of waste-to-SNG via hybrid renewable energy systems for circular economy: process design, energy, and environmental analysis. Waste Management 166 (2023) 1-12. **https://doi.org/10.1016/j.wasman.2023.04.041**

[247] Haque, M.A., et al., Sustainable management and valorization of antibiotic waste. Chemical Engineering Journal 498 (2024) 155372. **https://doi.org/10.1016/j.cej.2024.155372**

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2.1.4 Biodiesel Production

Biodiesel production is recognised as a mature and scalable bioconversion technology that produces a liquid biofuel suitable for use in diesel engines, either in pure form or blended with conventional diesel fuel. It is considered part of the first-generation biofuels and has widespread commercial implementation across the EU and globally as a substitute or blending component for fossil diesel in the transport sector[248]. Biodiesel is typically produced through a series of chemical processes that involve the reaction of vegetable oils or animal fats with an alcohol, most commonly methanol, in the presence of a catalyst. The most common method of biodiesel production is base-catalysed transesterification. In this process, triglycerides present in the oils or fats react with methanol in the presence of a strong base catalyst, such as sodium hydroxide, to produce biodiesel, which is chemically known as fatty acid methyl ester (FAME), and glycerol as a by-product (which has various applications in the pharmaceutical, cosmetics and other industrial sectors and even can be bio converted into biohydrogen or bioethanol, enhancing the value chain and sustainability of biodiesel technologies)[249]. Moreover, the production of biodiesel from oil crops yields vegetable proteins as a by-product, which are valuable as animal feed, thereby contributing to the overall sustainability and economic viability of the process[250]. Another significant type of renewable diesel is hydrotreated vegetable oil (HVO), which is produced by the process of hydro processing oils and fats. The process produces a final product that is chemically very similar to conventional fossil diesel[251]. A comparative table of the properties of both biodiesel production methods, HVO, and FAME:

[248]Hirani, A.H., et al., A review on first- and second-generation biofuel productions. In: Kumar, A., Ogita, S., Yau, Y.Y. (eds). Biofuels: Greenhouse Gas Mitigation and Global Warming (2018). Springer, New Delhi. **https://doi.org/10.1007/978-81-322-3763-1_8**

[249]Haron, R., et al., Overview on utilization of biodiesel by-product for biohydrogen production. Journal of Cleaner Production 172 (2018) 314-324. **https://doi.org/10.1016/j.jclepro.2017.10.160**

[250]Rodianova, M.V., et al., Biofuel production: challenges and opportunities. International Journal of Hydrogen Energy 42 (2017) 8450-8461. **https://doi.org/10.1016/j.ijhydene.2016.11.125**

[251]Ershov, M.A., et al., Current challenge and innovative progress for producing HVO and FAME biodiesel fuels and their applications. Waste Biomass Valor 14 (2023) 505-521. **https://doi.org/10.1007/s12649-022-01180-0**

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Table 4 – Comparison of properties of FAME and HVO[252] [253] [254] [255].

Property	FAME	HVO
Oxidation stability	Lower stability, being prone to oxidation due to double bonds	High stability because there is no oxygen content
Storage stability	Requires antioxidants, presenting sludge formation after prolonged storage	Resistant to microbiological growth
Expected quality	Variable, depending on the feedstock	Constant quality, regardless of the feedstock
Bacterial contamination	High probability, resulting filter installation	Waterproof and able to avoid bacterial contamination
Energy density	37 – 38 MJ/kg	43-44 MJ/kg
Cetane Number	Moderate, varies with feedstock	Very high
Cold Flow Properties	Poor at low temperatures, additive requirement	Excellent (arctic grades via isomerisation)
Chemical composition	Oxygen-containing esters with varying fatty acid profiles	Pure hydrocarbons, no oxygen
Dilution causes	Oxidation products lead to deposit formation	Lower density affects volumetric energy
Sulphur content	Depends on feedstock, low sulphur content (< 10 ppm)	< 5 ppm (sulphur-free)
Aromatic content	May contain trace aromatics depending on processing	No aromatics
Engine compatibility	May require seal/material adaptation	Drop-in replacement for diesel engines
Feedstock flexibility	Primarily vegetable oils, sensitive to free fatty acids	Vegetable oils, animal fats, waste oils
CO_2 reduction	50-60% reduction	Up to 90% reduction

As it was evidenced by the properties shown in Table 4, HVO demonstrates superior stability due to its fully saturated hydrocarbon structure and absence of oxygen, while FAME requires antioxidant additives to meet minimum stability requirements. Similarly, the paraffinic nature of HVO provides

[252] Grzelak, P., and Zoltowski, A., Environmental assessment of the exploitation of diesel engines powered by biofuels. Combustion Engines 180(1) (2020) 31-35. https://doi.org/10.19206/CE-2020-105

[253] Dimitriadis, A., et al., Evaluation of a hydrotreated vegetable oil (HVO) and effects on emissions of a passenger car diesel engine. Frontiers in Mechanical Engineering 4 (2018) 7. https://doi.org/10.3389/fmech.2018.00007

[254] Senthamilselvi, D., and Kalaiselvi, T., Fuel properties of fatty acid methyl esters (FAME) produced with fats of gamma-irradiated mutants of *Oleaginous Microalga- Chlorella sp. KM504965*. Madras Agriculture Journal 109(1-3) (2023) 28-35. https://doi.org/10.29321/MAJ.10.000574

[255] Hunicz, J., et al., Comparative study of combustion and emissions of diesel engine fuelled with FAME and HVO. Combustion Engines 184(1) (2021) 72-78. https://doi.org/10.19206/CE-135066

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better cold weather performance and higher energy density compared to FAME's ester-based chemistry. Despite having a less complex production and reducing emissions compared to fossil diesel, FAME is more sensitive to feedstock quality, while HVO requires advanced hydrotreatment infrastructure but shows greater reduction in particulate matter and nitrogen oxides.

The production of biodiesel in the EU is characterised by the utilisation of a wide variety of feedstocks. These include various vegetable oils, such as rapeseed oil (the most widely used feedstock for biodiesel production in the UE), soybean oil, palm oil and sunflower oil, animal fats and used cooking oil. The latter feedstock has emerged as a significant feedstock, driven by regulatory incentives that encourage the use of waste-based feedstocks through mechanisms that allow for double counting[256]. This is indicative of a substantial transition towards more sustainable feedstock options. Nevertheless, the sustainability of biodiesel production is contingent on the quality of the feedstock. Specifically, edible oils, such as palm or soy, have been found to be heavily associated with land-use change and deforestation, thus rendering them unsustainable. Consequently, the transition towards non-edible oils, such as rubber seed, jatropha or waste oils, and the development of innovative catalysts can lead to substantial improvements in sustainability outcomes[257]. Other feedstocks that do not compete with crops for land usage include microalgae, which is utilised for third-generation biodiesel, and genetically modified algae, electro fuels and photobiological solar fuels, which are employed for fourth-generation biodiesel. This generation is currently being investigated as a new field of research, requiring further studies to facilitate more in-depth exploration[258] [259].

To ensure the efficient production of biodiesel, it is vital to exercise meticulous control over several operating parameters. The temperature of the transesterification reaction is critical for achieving optimum conversion rates. The type and concentration of the catalyst, which is typically a strong base such as sodium hydroxide or potassium hydroxide, has a significant impact on the efficiency of the reaction. The molar ratio of alcohol (typically methanol) to the oil or fat feedstock is another critical parameter that affects the yield and quality of the biodiesel. Furthermore, it is imperative to consider the reaction time permitted for the transesterification process to occur. The purity and moisture content of the oil or fat feedstock have been demonstrated to exert a significant influence

[256]Ashine, F., et al., Biodiesel production from Argemone Mexicana oil using chicken eggshell derived CaO catalyst. Fuel 332 (2023) 126166. **https://doi.org/10.1016/j.fuel.2022.126166**

[257]Tsai, C.H., and Tsai, W.T., Sustainable processes reusing potassium-rich biomass ash as a green catalyst for biodiesel production: a mini-review. Processes 12(12) (2020) 100608. **https://doi.org/10.1016/j.biteb.2020.100608**

[258]Syafiuddin, A., et al., The current scenario and challenges of biodiesel production in Asian countries: a review. Bioresource Technology Reports 12 (2020) 100608. **https://doi.org/10.1016/j.biteb.2020.100608**

[259]Mathew, G.M., et al., Recent advances in biodiesel production: challenges and solutions. Science of the Total Environment 794 (2021) 148751. **https://doi.org/10.1016/j.scitotenv.2021.148751**

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on the reaction and the quality of the final biodiesel product[260] [261]. In certain instances, pre-treatment has been shown to be an effective solution to these issues.

Despite its well-established status, biodiesel production in the EU is confronted with numerous significant challenges and constraints. The cost of producing biodiesel frequently exceeds that of conventional fossil diesel, a factor which may impede its extensive utilisation in the absence of policy initiatives to promote its adoption[262]. Competition with the food industry for vegetable oil feedstocks remains a concern, particularly for first-generation biodiesel. The sustainability of certain feedstocks, such as palm oil and soy, has been called into question due to their potential link to indirect land use change and deforestation. This has resulted in regulatory scrutiny and phase-out efforts in certain Member States[263]. However, higher blends of biodiesel have been observed to experience challenges in cold weather conditions, which can limit their application in colder climates. Furthermore, the quality and composition of waste-based feedstocks such as waste cooking oil, waste frying oil and waste vegetable oil can be variable, compelling more complex processing and quality control measures[264].

The biodiesel market in Europe is substantial and continues to grow. In 2022, the European Union produced over 14 million tonnes of biodiesel, representing nearly 40% of the total global production, thereby consolidating its position as the leading producer. Germany is the leading producer of biodiesel in Europe, followed by France and Spain, indicating a concentration of production in key Member States. While EU biodiesel production will reach its peak in 2019, it will decline slightly, reaching 13.7 million tonnes in 2022[265] [266]. The EU's nominal production capacity for FAME is approximately 20.3 million tonnes per year, whereas the capacity for HVO is around 5.1 million tonnes per year. It is anticipated that HVO capacity will double by 2025, indicating a growing trend towards this type of renewable diesel.

[260] Ferella, F., et al., Optimization of the transesterification reaction in biodiesel production. Fuel 89(1) (2010) 36-42. https://doi.org/10.1016/j.fuel.2009.01.025

[261] Amini, Z., et al., State of the art and prospective of lipase-catalyzed transesterification reaction for biodiesel production. Energy Conversion and Management 141 (2017) 339-353. https://doi.org/10.1016/j.enconman.2016.09.049

[262] Millinger, M., et al., Competitiveness of advanced and conventional biofuels: results from least-cost modelling of biofuel competition in Germany. Energy Policy 107 (2017) 394-402. https://doi.org/10.1016/j.enpol.2017.05.013

[263] Heimann, T., et al., Phasing out palm and soy oil biodiesel in the EU: What is the benefit?. GCB Bioenergy 16(1) (2024) e13115. https://doi.org/10.1111/gcbb.13115

[264] Razzak, S.A., et al., Cleaner biodiesel production from waste oils (cooking/vegetable/frying): advances in catalytic strategies. Fuel 393 (2025) 134901. https://doi.org/10.1016/j.fuel.2025.134901

[265] Kapustová, Z., et al., Development status in EU biofuels market. Visegrad Journal on Bioeconomy and Sustainable Development 9(2) (2020) 67-71. https://doi.org/10.2478/vjsbd-2020-0013

[266] EBB Statistical Report 2023 | European Biodiesel Board

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2.1.5 Bioplastics Production

Bioplastics are a class of materials defined by their biodegradable, biobased origin and eco-friendly nature. Their production typically involves the transformation of renewable biomass resources, such as sugars, starch, glycerol, and vegetable oils, through microbial fermentation into new sustainable alternatives with similar physicochemical, mechanical, and thermal properties as conventional plastics [267]. Common bioplastics include polyesters, poly(lactic acid) (PLA) and poly(hydroxyalkanoates) (PHAs). For instance, PLA, produced via the fermentation of sugars into lactic acid followed by polymerisation, is one of the most promising biodegradable and biocompatible aliphatic thermoplastics with extensive mechanical profile used in packaging, textiles and biomedical applications (in absorbable sutures, drug delivery nanoparticles, and tissue engineering scaffolds) due to its high versatility, high tensile strength and transparency [268]. Meanwhile, PHAs are intracellularly accumulated in bacteria under nutrient-limited conditions and are notable for their complete biodegradability in various environments[269]. Other biodegradable plastics are cellulose, starch, bio-polybutylene succinate (bio-PBS), polycaprolactone (PCL) and polybutylene adipate (PBA)[270].

The following table (as Table 5) presents a comparison of the characteristics of conventional plastics, PHA and PLA. It has been demonstrated that both bioplastics and conventional plastics have distinctive characteristics in relation to production costs and their respective carbon footprints. However, while bioplastics are associated with elevated manufacturing expenses, they demonstrate a reduced carbon footprint when compared to conventional plastics. In addition, PHA has been found to have superior natural decomposition scenarios due to the action of marine organisms[271], whereas PLA requires specific composting conditions. However, PLA offers superior mechanical strength for rigid applications (such as packaging and 3D printing), while PHA's flexibility is well-suited to films and medical implants. Recent developments in the field have focused on optimising bacterial

[267] Chico, M.F., and Sampedro, T., Production of bioplastic and their applications as food packaging: PLA and PHB. Alimentos Ciencia e Ingeniería 29(2) (2022) 31-56. https://doi.org/10.31243/aci.v29i2.1858

[268] Nduko, J.M., and Taguchi, S., Microbial production of biodegradable lactate-based polymers and oligomeric building blocks from renewable and waste resources. Frontiers in Bioengineering and Biotechnology 8 (2021) 618077. https://doi.org/10.3389/fbioe.2020.618077

[269] Kusuma, H.S., et al., Waste to wealth: polyhydroxyalkanoates (PHA) production from food waste for a sustainable packaging paradigm. Food Chemistry: Molecular Sciences 9 (2024) 100225. https://doi.org/10.1016/j.fochms.2024.100225

[270] Narancic, T., et al., Recent advances in bioplastics: application and biodegradation. Polymers 12(4) (2020) 920. https://doi.org/10.3390/polym12040920

[271] Meereboer, K.W., et al., Review of recent advances in the biodegradability of polyhydroxyalkanoate (PHA) bioplastics and their composites. Green Chemistry 22 (2020) 5519-5558. https://doi.org/10.1039/D0GC01647K

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production for PHA, with a particular emphasis on salt-mediated degradation mechanisms that prevent microplastic formation[272].

Table 5 – Comparative table between conventional plastics, PHA, and PLA[273] [274] [275] [276].

Property / Feature	Conventional plastics (e.g., PE, PP, PVC, PET)	PHA	PLA
Origin	Fossil-based	Bio-based	Bio-based
Biodegradability	Non-biodegradable	Biodegradable and compostable	Biodegradable and compostable
Density (g/cm^3)	0.89-1.45	1.0-1.3	1.2-1.25
Melting point (ºC)	100-200 (varies by type)	40-180	130-180
Glass transition temperature (ºC)	Varies (e.g., PE: -125 and PET: 67)	-30 to 5	60-65
Tensile strength (MPa)	10-50 (varies by type)	15-40	50-70
Young's modulus (GPa)	0.2-3.5 (varies by type)	1-2	2.7-16
Elongation at break (%)	10-800 (varies by type)	1-15	< 10 (can be improved with additives)
Thermal resistance	Moderate to high (depends on type)	Moderate	Moderate
Barrier properties	Good to excellent (varies)	Good (especially to gases)	Moderate (improving with composites)
Chemical resistance	Good (varies by type)	Good for packaging	Moderate
Processability	Excellent, well-established	Good; conventional methods applicable	Good, widely used in 3D printing, packaging
Transparency	Varies (e.g., PET is transparent)	Transparent or translucent	Transparent to opaque
Environmental impact	High (pollution, fossil resource use) – Persistent microplastics	Low (renewable, less pollution) – marine-safe degradation	Low (renewable, less pollution) – low-carbon footprint
Development and use	Mature, global, high-volume	Emerging, growing in packaging/medical	Fast-growing, especially in packaging/3D printing

[272]Cheng, Y., et al., Mechanically strong yet metabilizable supramolecular plastics by desalting upon phase separation. Science 386 (2024) 875-881. https://doi.org/10.1126/science.ado1782

[273]Farah, S., et al., Physical and mechanical properties of PLA, and their functions in widespread applications – a comprehensive review. Advanced Drug Delivery Reviews 107 (2016) 367-392. https://doi.org/10.1016/j.addr.2016.06.012

[274]Marmol, G., et al., Potential of cellulose microfibers for PHA and PLA biopolymers reinforcement. Molecules 25(20) (2020) 4653. https://doi.org/10.3390/molecules25204653

[275]Nanda, S., et al., Innovations in applications and prospects of bioplastics and biopolymers: a review. Environmental Chemistry Letters 20 (2022) 379-395. https://doi.org/10.1007/s10311-021-01334-4

[276]Ranakoti, L., et al., Critical review on polylactic acid: properties, structure, processing, biocomposites, and nanocomposites. Materials 15(12) (2022) 4312. https://doi.org/10.3390/ma15124312

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Figure 7 depicts the common fermentation configurations utilised for synthesising PHA molecules. In contrast, PLA research has centred on polymer blending and nanocomposite enhancements with TiO_2 to enhance thermal stability[277] [278].

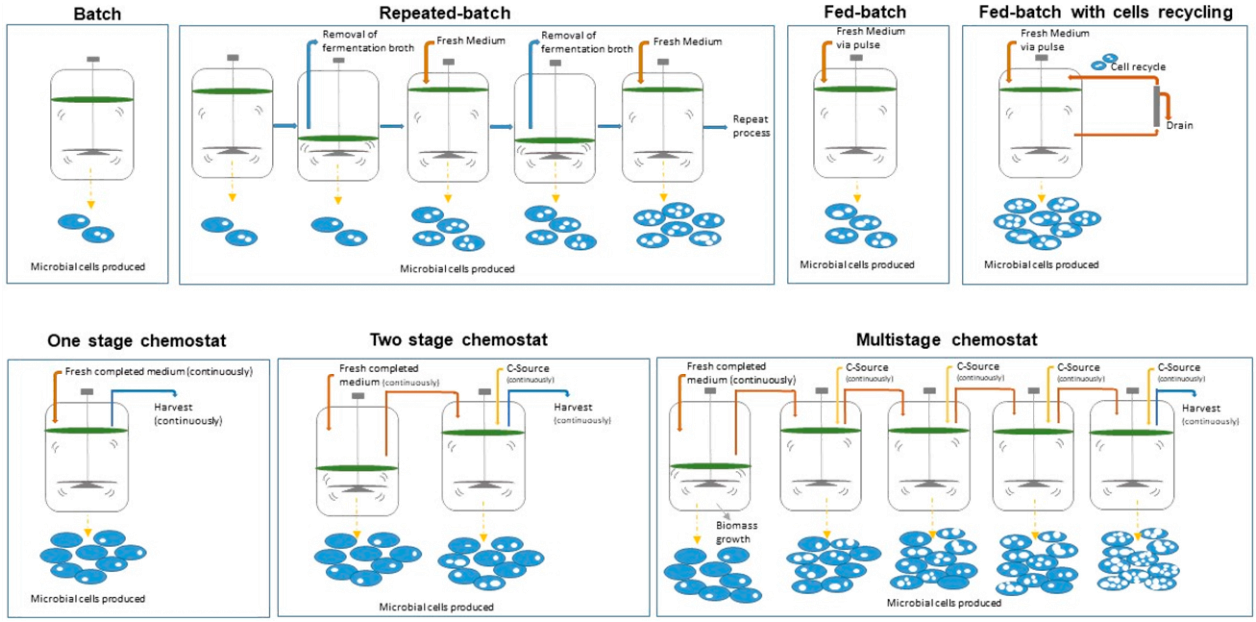


Figure 7 – Common fermentation processes employed for synthesising PHA molecules[279] [280].

Typical feedstocks include sugar crops (e.g., sugar beet and corn), agricultural residues, glycerol, and food waste. Advances in mixed microbial cultures and in metabolic engineering, and the utilisation of industrial waste as feedstock have been shown to significantly lower production costs and improve circularity[281] [282].

[277]Mallick, S., et al., PLA-TiO_2 nanocomposites: thermal, morphological, structural, and humidity sensing properties. Ceramics International 44(14) (2018) 16507-16513. https://doi.org/10.1016/j.ceramint.2018.06.068

[278]Kervran, M., et al., Thermal degradation of polylactic acid (PLA)/polyhydroxybutyrate (PHB) blends: a systematic review. Polymer Degradation and Stability 201 (2022) 109995. https://doi.org/10.1016/j.polymdegradstab.2022.109995

[279]Koller, M., A review on established and emerging fermentation schemes for microbial production of polyhydroxyalkanoate (PHA) biopolyesters. Fermentation 4 (2018) 30. https://doi.org/10.3390/fermentation4020030

[280]McAdam, B., et al., Production of polyhydroxybutyrate (PHB) and factors impacting its chemical and mechanical characteristics. Polymers 12(12) (2020) 2908. https://doi.org/10.3390/polym12122908

[281]Chen, J., et al., Metabolic engineering of *Eschericha Coli* for the synthesis of polyhydroxyalkanoates using acetate as a main carbon source. Microbial Cell Factories 17 (2018) 102. https://doi.org/10.1186/s12934-018-0949-0

[282]Pagliano, G., et al., Recovery of polyhydroxyalkanoates from single and mixed microbial cultures: a review. Frontiers in Bioengineering and Biotechnology 9 (2021) 624021. https://doi.org/10.3389/fbioe.2021.624021

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Production costs remain a key barrier. For instance, PHA production costs are estimated around €5/kg, compared to €1/kg for conventional plastics. However, recent breakthroughs in synthetic biology and metabolic engineering are revolutionising the field, with innovative whole-cell biosynthetic systems enabling direct microbial production of PLA copolymers, such as poly(lactate-co-3-hydroxybutyrate) [P(LA-co-3HB)] from engineered *Escherichia Coli* without the need for metal catalysts. For PHAs, synthesis occurs intracellularly in bacteria under nutrient-limited conditions, with mixed microbial cultures and non-sterile fermentation technologies achieving cost reductions of up to 30%[283]. Advanced downstream processing technologies have traditionally relied on solvent-intensive methods that compromise both production costs and sustainability. Recent research trends advocate for high-efficiency integrated membrane-based separation systems and green extraction techniques, including supercritical CO_2, enzymatic digestion, and/or membrane filtration, which achieve high-purity final products (> 90%), enhance scalability and reduce environmental impacts[284] [285].

Other challenges are their variable mechanical properties, limited waste-stream integration and lifecycle emissions. LCAs have shown that early stages such as biomass pretreatment and saccharification account for most environmental impacts, highlighting the need for energy-efficient improvements[286] [287]. The EU's proposed Bioeconomy Strategy aims to address these via mandatory bio-based plastic targets in key sectors and harmonised sustainability criteria. Commercial-scale facilities in France, the Netherlands, and Germany currently achieve annual capacities up of 50,000 tonnes, with global PHA production projected to surge more than six-fold by 2024, reaching over 159,700 tonnes[288].

2.1.6 Biochemicals Production

Biochemicals are sometimes called bio-based chemicals, green chemicals, plant-based chemicals or biomass-derived chemicals but all these terms are referred to the same concept, which is chemical

[283] Yadav, B., et al., Bioconversion of waste (water)/residues to bioplastics – a circular bioeconomy approach. Bioresource Technology 298 (2020) 122584. **https://doi.org/10.1016/j.biortech.2019.122584**

[284] Pérez-Rivero, C., et al., A sustainable approach for the downstream processing of bacterial polyhydroxyalkanoates: state-of-the-art and latest developments. Biochemical Engineering Journal 150 (2019) 107283. **https://doi.org/10.1016/j.bej.2019.107283**

[285] Cho, E., et al., Separation and purification technologies in polyhydroxyalkanoate (PHA) manufacturing: a review. Environmental Engineering Research 30(5) (2025) 240710. **https://doi.org/10.4491/eer.2024.710**

[286] Ghomi, E.R., et al., The life cycle assessment for polylactic acid (PLA) to make it a low-carbon material. Polymers 13(11) (2021) 1854. **https://doi.org/10.3390/polym13111854**

[287] Del Oso, M.S., et al., Evaluation and optimization of the environmental performance of PHA downstream processing. Chemical Engineering Journal 412 (2021) 127687. **https://doi.org/10.1016/j.cej.2020.127687**

[288] Zinjal, T., and Boora, M.P., Gelatin-based bioplastic degradation and its impact on soil fertility. International Journal of Research Publication and Reviews 5(7) (2024) 1267-1270. **https://doi.org/10.1016/j.biortech.2019.122584**

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products derived from materials of biological feedstocks. The biochemical production within the EU's bioeconomy is predominantly reliant on microbial fermentation and enzymatic conversion. Both bioconversion processes, microbial fermentation and enzymatic hydrolysis, are significant due to their role in bio-based industrial strategies, not only in biochemical production, as they exhibit a reduced environmental footprint in comparison to petrochemical synthesis. These sustainable processes are key to produce biochemicals such as lactic acid, succinic acid, itaconic acid, and other organic acids and alcohols, which serve as crucial building blocks for polymers (PLA, PBS, latex, hydrogels…), adhesives, lubricants, cosmetics, food preservatives and additives, plasticisers, fibres, personal care products, and industrial solvents[289] [290].

The versatility of biochemicals, resulting from their ability to utilise a wide range of feedstocks, further enhances their attractiveness by promoting supply chain flexibility. Typically, production is carried out in multi-product biorefineries that co-integrate biofuel and bioplastic production, thus optimising resource efficiency through cascading use and closed-loop operations.

Fermentation oriented to biochemical production is a process that uses engineered microbial strains, including *Actinobacillus succinogenes*, *Lactobacillus spp.*, and *Aspergillus terreus*, under strictly controlled operating conditions. These include the aeration rates (depending on aerobic or anaerobic requirements), the mesophilic temperature range and regulated pH (typically between 4.5 and 6.5). These conditions are optimised to ensure maximum enzyme activity and microbial metabolism while avoiding metabolic inhibition. With the purpose of enhancing yield and operational efficiency, process intensification approaches through incorporating *in situ* product removal and AI-driven control systems are increasingly being adopted[291].

Common carbon sources prioritise low-cost, non-food feedstocks, which include sugar beet, wheat straw hydrolysates, food waste and crude glycerol, amongst others. For instance, the analysis of cheese whey permeate has demonstrated high lactic acid productivity and feedstock efficiency when fermented under optimised non-axenic conditions[292]. Moreover, potato waste and spent yeast hydrolysates have exhibited significant potential in the production of succinic acid[293]. Furthermore,

[289]Klement, T., and Büchs, J., Itaconic acid – a biotechnological process in change. Bioresource Technology 135 (2013) 422-431. https://doi.org/10.1016/j.biortech.2012.11.141

[290]Spekreijse, J., et al., Insights into the European market of bio-based chemicals. Analysis based on ten key product categories (2019) Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/549564

[291] Escanciano, I.A., et al., Modeling the succinic acid bioprocess: a review. Fermentation 8(8) (2022) 368. https://doi.org/10.3390/fermentation8080368

[292]B. Delmoitié, B., et al., Tailoring non-axenic lactic acid fermentation from cheese whey permeate targeting a flexible lactic acid platform. Journal of Environmental Management 373 (2025) 123529. https://doi.org/10.1016/j.jenvman.2024.123529

[293]Escanciano, I.A., et al., Bioproduction of succinic acid from potato waste. Kinetic modeling. Industrial Crops and Products 203 (2023) 117124. https://doi.org/10.1016/j.indcrop.2023.117124

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the potential of lignocellulosic agricultural and forestry residues has been demonstrated in terms of their ability to produce high-value bio-based chemicals. This objective is realised through the attainment of excellent feedstock conversion efficiencies, thereby reducing dependency on imported biomass[294] [295] [296]. Another promising feedstock to be used is the captured CO_2, especially from biogas or industrial fermentation streams, as a carbon source in biochemical production pathways such as succinic and lactic acids. The following serve as illustrative examples of this strategy: the production of succinic acid with CO_2 from biogas by means of *Actinobacillus succinogenes* to simultaneously upgrade biogas and produce high-purity succinic acid[297]; the direct CO_2 fixation for succinic acid whilst reducing lactic acid formation[298]; the production of lactic acid from CO_2 using a multienzyme cascade under industrial off-gas conditions[299]; and the integrated ethanol fermentation and succinic acid production through capturing and using fermentation CO_2[300]. This strategy not only contributes to carbon capture and utilisation (CCU) but also enhances circularity and sustainability in the EU's bioeconomy.

The European Union is demonstrating a growing interest in the production and application of biochemicals. The current output of biochemicals in the European Union is approximately 4.7 million tonnes annually, representing approximately 3% of the total chemicals market[301]. Europe's global market share for biochemicals and biomaterials is twice that of the fossil-based sector, with the former accounting for 31% and the latter for 16%[302].However, this share varies considerably across between different product categories, indicating a diverse and evolving market landscape. In accordance with a business-as-usual scenario, the overall bio-based market is predicted to

[294]Akhtar, J., et al., Recent advances in production of succinic acid from lignocellulosic biomass. Applied Microbiology and Biotechnology 98 (2013) 987-1000. **https://doi.org/10.1007/s00253-013-5319-6**

[295]Cubas-Cano, E., et al., Biotechnological advances in lactic acid production by lactic acid bacteria: lignocellulose as novel substrate. Biofuels, Bioproducts and Biorefining 12(2) (2018) 290-303. **https://doi.org/10.1002/bbb.1852**

[296]Guo, J., et al., Reduction and reuse of forestry and agricultural bio-waste through innovative green utilization approaches: a review. Forests 15(8) (2024) 1372. **https://doi.org/10.3390/f15081372**

[297]López, J.C., et al., Simultaneous biosuccinic production and biogas upgrading: exploring the potential of sugar-based confectionery waste within a biorefinery concept, Bioresource Technology 384 (2023) 129362. **https://doi.org/10.1016/j.biortech.2023.129362**

[298]Yang, Z., et al., Enhanced direct gaseous CO_2 fixation into higher bio-succinic acid production and selectivity, Journal of Environmental Sciences 143 (2024) 164-175. **https://doi.org/10.1016/j.jes.2023.05.035**

[299]Carceller, A., et al., Lactic acid from CO_2: a carbon capture and utilization strategy based on a biocatalytic approach. Environmental Science & Technology 57(51) (2023) 21727-21735. **https://doi.org/10.1021/acs.est.3c05455**

[300]Zhang, Q., et al., Carbon capture and utilization of fermentation CO_2: integrated ethanol fermentation and succinic acid production as an efficient platform. Applied Energy 206 (2017) 364-371. **https://doi.org/10.1016/j.apenergy.2017.08.193**

[301]Spekreijse, J., et al., Insights into the European market of bio-based chemicals. Analysis based on ten key product categories (2019) Publications Office of the European Union, Luxembourg. **https://doi.org/10.2760/549564**

[302]Spekreijse, J., et al., Bio-based value chains for chemicals, plastics and pharmaceuticals – A comparison of bio-based and fossil-based value chains, Publications Office, 2021, **https://data.europa.eu/doi/10.2760/712499**.

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demonstrate a modest compound annual growth rate (CAGR) of 3.6%. However, platform chemicals and adhesives are projected to experience more rapid growth, surpassing an expected CAGR of 5%[303]. Similarly, the procurement of comprehensive and reliable market data on biochemicals is challenging due to limitations in existing statistical systems and product coding, which hinder a thorough understanding of the market and its dynamics. It is also noted that certain sectors, such as those utilising tall oil-based products, have a longer history of incorporating biomass feedstocks, while the broader market is regarded as being in its nascent stage.

Despite the promising outlook, the widespread adoption and expansion of biochemicals in the EU face several significant challenges and constraints, which are discussed in detail in this report. Market competition in the production of biochemicals compared to their fossil-based counterparts is a significant economic constraint[304] [305]. The long-term availability and price volatility of feedstock further impacts cost predictability. As a case in point, the price of wheat straw prices has been observed to fluctuate within the range of €80–120/tonne, while the price of crude glycerol has been noted to range €300–500/tonne[306]. Additionally, there are specific technical challenges that must be addressed, such as the difficulties in obtaining unsaturated compounds from biomass and the need for the development of bio-based alternatives for certain components, such as the polyol part of alkyd resins[307]. The quality of some bio-based alternatives may also be perceived as inferior to that of fossil-based options. Downstream purification, particularly chromatographic separation, approximately 30-50% of the total production costs due to the necessity for high-purity outputs[308] [309].

2.1.7 Industrial Enzyme Production

Industrial enzymes are proteins that are utilised in a variety of industrial processes for the purpose of catalysing chemical reactions. Their production constitutes a fundamental element of EU's

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[304]Peinemann, J.C., and Pleissner, D., Continuous pretreatment, hydrolysis, and fermentation of organic residues for the production of biochemicals. Bioresource Technology 295 (2020) 122256. **https://doi.org/10.1016/j.biortech.2019.122256**

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[306] Escanciano, I.A., et al., Modeling the succinic acid bioprocess: a review. Fermentation 8(8) (2022) 368. **https://doi.org/10.3390/fermentation8080368**

[307]Sati, A., et al., Bio-based alkyd-polyesteramide-polyurethane coatings from castor, neem, and karanja oils with inherent antimicrobial properties for enhanced hygiene. Coatings 15(4) (2025) 370. **https://doi.org/10.3390/coatings15040370**

[308]Bähner, F.D., et al., Challenges in optimization and control of biobased process systems: an industrial academic perspective. Industrial & Engineering Chemistry Research 60(42) (2021) 14985-15003. **https://doi.org/10.1021/acs.iecr.1c01792**

[309]Dessie, W., et al., Towards the development of efficient, economic and environmentally friendly downstream processing for bio-based succinic acid. Environmental Technology & Innovation 32 (2023) 103243. **https://doi.org/10.1016/j.eti.2023.103243**

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bioeconomy. The predominant method of industrial enzyme production is through submerged fermentation (SmF), a process defined as the decomposition (preferably anaerobic) and subsequent growth of substrates by microorganisms in the presence of abundant water. This process employs genetically engineered microbial strains, principally filamentous fungi (e.g., *Aspergillus niger*) and bacteria (e.g., *Bacillus subtilis*)[310] [311]. These organisms are optimised for high-yield enzyme secretion and are cultivated under strictly controlled aerobic conditions in bioreactors. The process is initiated with the preparation of inoculum, followed by fermentation, downstream recovery and purification (following a similar structure to other abovementioned bioconversion techniques). The utilisation of ultrafiltration and precipitation techniques is a common practice in the concentration of the desired enzymes[312]. Ongoing innovations in biocatalysts, synthetic biology and protein engineering have further enabled the tailoring of enzymes with improved thermal stability, substrate specificity and catalytic efficiency[313].

Key operational parameters critically influence both enzyme yield and activity, typically operating at pH 4.5-6.0, 30-40 ºC, and optimised dissolved oxygen levels, controlled via agitation and aeration[314]. Substrate feeding profiles and oxygen transfer coefficients are adjusted dynamically to maintain growth and productivity, particularly in large-scale fermenters[315]. The fermentation media used for industrial enzyme production have traditionally been glucose, corn steep liquor and yeast extract. Glucose remains the dominant carbon source due to its high fermentability but rising raw material costs and sustainability requirements have driven the search for more circular and cost-effective alternatives[316]. Corn steep liquor, a by-product of starch processing, is widely used for its nitrogen and micronutrient content, although recent advances in nutrient recycling have allowed its partial

[310]Salim, A.A., et al., Production of enzymes by a newly isolated Bacillus sp. TMF-1 in solid state fermentation on agricultural by-products: the evaluation of substrate pretreatment methods. Bioresource Technology 228 (2017) 193-200. https://doi.org/10.1016/j.biortech.2016.12.081

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[313]Boukid, F., et al., Bioengineered enzymes and precision fermentation in the food industry. International Journal of Molecular Sciences 24(12) (2023) 10156. https://doi.org/10.3390/ijms241210156

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substitution with algal extracts, thereby reducing reliance on animal-derived inputs[317] [318]. Yeast extract, although essential for providing amino acids and growth factors, remains one of the most expensive media components. In response, synthetic biology platforms are engineering *Pichia pastoris* strains to grow on minimal media, significantly reducing reliance on complex nutrients[319] [320]. Alongside these developments, agro-industrial by-products have gained prominence as sustainable feedstock options in line with Europe's circular bioeconomy strategy. Materials such as wheat bran, sugar beet pulp, fruit peels, brewer's spent grain (BSG) and sugarcane bagasse are increasingly being incorporated into fermentation systems, being successfully used as substrates for lipase and protease production[321] [322]. In parallel, the valorisation of lignocellulosic residues has emerged as a strategic focus, offering a scalable route to bio-based enzyme production using underutilised agricultural side-streams. These approaches not only improve process sustainability but also contribute to waste reduction and nutrient recycling throughout the enzyme production value chain[323] [324].

The enzyme portfolio comprises a diverse array of enzymes, including proteases, amylases, cellulases, and lipases, along with emerging niche enzymes such as phytases and transaminases. These are integral to a wide range of applications, which include, but are not limited to, the production of biofuels, textiles, food processing, detergents, and biopharmaceuticals. The development of

[317]Zhou, K., et al., Corn steep liquor: green biological resources for bioindustry. Applied Biochemistry and Biotechnology 194 (2022) 3280-3295. **https://doi.org/10.1007/s12010-022-03904-w**

[318]Pervez, S., et al., Algal biomass: a sustainable, economical and renewable approach for microbial production of pectinolytic enzymes using submerged and solid-state fermentation techniques. Biocatalysis and Biotransformation 35(6) (2017) 442-449. **https://doi.org/10.1080/10242422.2017.1364731**

[319]Developing a validated technology platform for the application of oxygen dependent enzymes in synthesis and transformation of alcohols | BIOOX | Project | Fact Sheet | FP7 | CORDIS | European Commission

[320]Ergün, B.G., et al., Second generation Pichia pastoris strain and bioprocess designs. Biotechnology for Biofuels and Bioproducts 15 (2022) 150. **https://doi.org/10.1186/s13068-022-02234-7**

[321]Iram, A., et al., Ideal feedstock and fermentation process improvements for the production of lignocellulolytic enzymes. Processes 9(1) (2021) 38. **https://doi.org/10.3390/pr9010038**

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[324]Ilic, N., et al., Valorization of lignocellulosic wastes for extracellular enzyme production by novel Basidiomycetes: screening, hydrolysis, and bioethanol production. Biomass Conversion and Biorefinery 13 (2023) 17175-17186. **https://doi.org/10.1007/s13399-021-02145-x**

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engineered enzymes for the purpose of targeted catalytic reactions in the synthesis of pharmaceuticals and fine chemicals is now underway[325].

The European Union is one of the world's leading hubs for industrial enzyme production, supported by a strong biotechnology sector, advanced research infrastructures and well-established industrial value chains. Major production centres are located in countries such as Denmark, Germany and the Netherlands, which host several of the global leaders in enzyme manufacturing and supply high-value enzyme products to international markets. The competitiveness of the European enzyme sector is further reinforced by substantial investments in research, innovation and scale-up activities, including public-private initiatives supported by the Circular Bio-based Europe Joint Undertaking (CBE JU), which has accelerated the development and commercialisation of enzyme-enabled bioprocesses across multiple industrial sectors. Enzymes play an increasingly important role in the transition towards a sustainable bioeconomy, particularly through their application in precision fermentation, biocatalysis, biomass conversion and resource-efficient manufacturing processes. As a result, Europe remains one of the most important global markets for industrial enzymes and a leading exporter of enzyme-based technologies and products[326].

Despite technological maturity, the sector faces high downstream processing costs, which can account for up to 50% of total production costs[327] [328]. Other constraints must be considered, including the regulatory challenges associated with genetically modified organisms (GMO)-derived enzymes, limitations in scalability for solid-state fermentation (thus reducing the water consumption of the process), and the environmental implications of liquid effluents. The harmonisation of EU regulatory frameworks remains an ongoing process, particularly in the context of enzymes classified as food and feed processing aids.

2.1.8 Current stage of development in the EU bioeconomy framework

After analysing the main established bioconversion processes employed in EU bioeconomy, Table 6 shows their maturity assessment and stage of development with its corresponding TRLs.

[325] Fasim, A., et al., Large-scale production of enzymes for biotechnology uses. Current Opinion in Biotechnology 69 (2021) 68-76. https://doi.org/10.1016/j.copbio.2020.12.002

[326] Boukid, F., et al., Bioengineered enzymes and precision fermentation in the food industry. International Journal of Molecular Sciences 24(12) (2023) 10156. https://doi.org/10.3390/ijms241210156

[327] Gimenes, N.C., et al., An overview of proteases: production, downstream processes and industrial applications. Separation & Purification Reviews 50(3) (2021) 223-243. https://doi.org/10.1080/15422119.2019.1677249

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Table 6 – Maturity assessment of key biorefinery processes with its corresponding TRLs.

Technology	Current TRL range in Europe	Development stage in Europe
Enzymatic hydrolysis	6-8	Widely used for lignocellulosic biomass conversion, with ongoing efforts to improve enzyme efficiency and reduce costs.
First-generation bioethanol	9	Mature technology, primarily for first-generation feedstocks.
Second-generation bioethanol	8-9	Mature technology, primarily for first-generation feedstocks, with increasing focus on advanced biofuels from lignocellulosic biomass.
Distillation	9	Well-established for product separation and purification in biorefineries.
Anaerobic digestion	9	Mature technology for biogas production from organic waste and agricultural residues.
Biodiesel production	7-9	Mature technology using vegetable oils and animal fats as feedstocks.
Bioplastics production	8-9	Commercial deployment with increasing focus on advanced properties through functionalisation
Biochemicals production	7-9	Commercial deployment
Industrial enzyme production	9	Fully commercial development

Note: The TRL ranges presented in this table are derived from the citations used and may not fully reflect the entire range of development across all European research institutions and companies.

These well-established technologies are continuously advancing through refinements to overcome their technical limitations. For example, enzymatic hydrolysis in lignocellulosic biorefineries is now capable to achieve up to 90% sugar conversion rates via engineering cellulases, though challenges persist. The integration of bioeconomy principles and biorefinery innovations offers pathways to address persistent challenges in bioconversion technologies, though significant gaps remain between research breakthroughs and industrial implementation. For instance, lignocellulosic biorefineries face irregularities in biomass supply chains and market uncertainties hinder scalability, with just few pilot-scale projects achieving commercial viability due to heterogeneous feedstock pretreatment costs[329].

Bioconversion technologies face hurdles in translating lab-scale success to industrial viability, particularly for anaerobic digestion, where volumetric efficiency drops by 20-35% when moving from lab to industrial reactors. Many advanced biorefinery concepts remain in pilot stages due to feedstock variability (e.g., multi-feedstock systems requiring adaptable pretreatment methods[330]), energy intensity (thermochemical processes line hydrothermal liquefaction consuming 40-60% of

[329]Singh, N., et al., Global status of lignocellulosic biorefinery: challenges and perspectives, Bioresource Technology 344 (2022) 126415. https://doi.org/10.1016/j.biortech.2021.126415

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operational costs) or policy gaps (e.g., lagging certification frameworks for bio-based products, which delay market entry), amongst others.

While biorefineries demonstrate potential for multi-product valorisation, scaling these processes requires robust infrastructure and harmonised supply chains. For instance, algal biorefineries exemplify this duality. These processes enable wastewater treatment with excellent nutrient recovery and biocrude production but face infrastructural obstacles to large-scale deployment such as high capital costs and inconsistent biomass harvesting systems[331] [332] [333].

2.2 Efficiency Challenges

Efficiency challenges have been a critical concern in bio-based processes for some time. Many processes, especially for lignocellulosic structures, have struggled to match the productivity and yield of traditional chemical processes. The primary challenges pertained to the bioconversion routes, which encountered issues such as low yields, slow reaction rates and limited product specificity, particularly in the conversion of complex biomass feedstocks such as lignocellulose[334]. As from the study cited, the inherent recalcitrance of lignocellulosic materials poses significant challenges to efficient breakdown and utilisation. This is primarily due to the low accessibility of crystalline cellulose fibres and the presence of lignin and hemicellulose on the surface of cellulose, which impedes enzymatic hydrolysis[335,336].

Additionally, another major challenge is the formation of emulsions in aqueous-organic systems, especially when high biocatalyst concentrations are used[337]. Likewise, the presence of this nascent, stable emulsions is also problematic in the context of biodesulfurisation reactions, hindering the separation of the desired product from the aqueous phase and then negatively affecting the overall

[331] Chandra, R., et al., Algal biorefinery: a sustainable approach to valorize algal-based biomass towards multiple product recovery, Bioresource Technology 278 (2019) 346-359. https://doi.org/10.1016/j.biortech.2019.01.104

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process efficiency[338]. It is challenging to break these emulsions down, even with conventional methods such as centrifugation, the use of chemical breakers, and adjustments to temperature and pH[339].

The accumulation of water is another challenge in bioconversion processes, particularly when dealing with water-insoluble substrates or products. The presence of water can interfere with the recovery of the produced bioproducts and may also dilute the reaction medium, potentially reducing reaction rates and yields[340].

Furthermore, the challenge of product inhibition can significantly impact bioconversion yields. In some cases, the accumulation of the desired product can inhibit the bioconversion process, creating a major bottleneck. For instance, this can be observed in the conversion of p-xylene to p-toluic and 2,3-dihydroxy-p-toluic acids [341]. The presence of inhibitory compounds, such as furfural, 5-hydroxymethylfurfural, or acetate, in sugar streams derived from lignocellulose deconstruction can also have a negative impact on the performance of biotechnological processes[342,343].

Cell permeability can be another efficiency challenge, as some bioconversions rely entirely on changing cell permeability, which can be difficult to control and optimise. This factor, combined with the need for frequent cleaning and sterilisation in biobased processes to prevent the accumulation of biological cell material, can lead to reduced equipment utilisation and increased operational complexity[344].

From a process engineering perspective, multi-step biocatalytic reactions often face significant yield limitations due to the cascading effect of individual reaction bottlenecks. As the number of reaction

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steps increases, the cumulative effect of yield limitations in each step, or limitations in the average yield per reaction step, has a critical impact on the final product yield. This situation highlights the critical importance of optimising each individual step in a multi-step biobased process. Even small inefficiencies in a single step can affect the entire reaction sequence, resulting in significantly reduced final product yields. In addition, conversion efficiency issues are compounded by the fact that most bio-based production processes are not yet as mature as commercial fossil-based processes. They can be less efficient in terms of energy consumption, leading to higher production costs and reduced competitiveness. The complexity of biosystems, which are typically time-variant, multi-scale and non-linear, adds another layer of difficulty to process optimisation and control.

2.3 Energy Consumption Issues

Energy consumption is another crucial aspect of bio-based processes, posing significant challenges for the transition from fossil fuel-dependent systems to bio-based alternatives. The bioeconomy is based on two key objectives: reducing dependence on fossil resources and promoting sustainable development. However, it faces significant energy demands in its processes, and, counterintuitively, often relies on fossil fuels for process energy[345].

The energy intensity of bio-based processes is a primary challenge in this regard. Modern bioeconomy approaches have substantial energy demands, and the physical interrelationships between energy sources and production systems are complex. It is worth noting that biofuel and bioenergy production demand substantial amounts of energy across various stages, including the cultivation, harvesting, processing, and conversion of biomass. This heightened energy intensity has the potential to prompt investigations into the net energy balance of certain bio-based products[346]. The continued use of fossil fuels for process energy in bio-based industries represents a significant challenge to achieving genuine sustainability[347]. Many biorefinery operations continue to depend on fossil fuels for the energy required to power their processes. This reliance has the potential to compromise the environmental benefits of bio-based products and hinder progress towards a fully renewable energy system.

Furthermore, the land-intensive nature of renewable energy sources poses and additional challenge in the bioeconomy. Most renewable energy sources, including bioenergy, require more land than fossil fuels or even nuclear power to generate equivalent amounts of energy. This land-intensiveness is particularly pronounced for biomass-based energy, as increasing population and wealth create

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greater demands on limited land resources[348]. The efficiency of biomass utilisation remains a critical concern. Traditional forms of biomass use for cooking, heating, and lighting frequently exhibit a significant degree of inefficiency. These methods can consume biomass at levels up to ten times higher than is required to generate equivalent levels of energy. This inefficiency is costly in terms of wasted biomass resources, and has a negative impact on health, the local environment and global GHG emissions due to changes in land use[349] [350].

However, the transition to more efficient bio-based systems is faced with significant technological and economic barriers. The development and large-scale deployment of technologies for efficient biomass conversion, such as advanced biofuels and biogas production, require substantial investment and face challenges in achieving cost-competitiveness with fossil fuels[351]. The variability in biomass composition also complicates the development of standardised, efficient conversion processes. Additionally, the geographical distribution of biomass resources frequently does not align with energy demands centres, thus calling for complex and potentially energy-intensive transportation and distribution systems [352]. These energy consumption issues highlight the complexity of transitioning to a bioeconomy and underscore the need for continued innovation and system-wide approaches to improve energy efficiency and reduce the need for fossil fuels in bio-based processes. In order to ensure a reliable and sustainable flow of biomass to bio-based facilities, whether new bioenergy plants, biorefineries, or retrofitting plants (explained later), it is essential to manage feedstock sourcing, transportation, storage, and pre-treatment carefully. Each stage in this process presents its own set of challenges, including securing consistent supply, optimising transport and storage, and preventing the degradation of raw materials.

Finally, the integration of bio-based processes into existing energy infrastructure poses logistical and technical challenges, particularly when it comes to retrofitting. The process of retrofitting entails the modernisation of existing installations through the integration of advanced biomass technologies, as opposed to the construction of entirely new bioenergy plants. This approach is frequently favoured due to its lower capital investment requirements, more efficient project timelines, and minimised

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production downtime and risks when compared with constructing new facilities from scratch[353]. However, existing infrastructure are often designed for fossil-based energy systems. Consequently, adapting these systems to accommodate variable and sometimes less predictable bio-based feedstocks can be complex[354] [355]. The technical challenges that must be confronted include the necessity to modify core equipment, to integrate advanced monitoring and control systems, and to ensure compatibility with current operational processes. Moreover, it is essential that plant operators receive comprehensive training to manage new technologies and to handle the increased variability in feedstock quality and supply that comes with bio-based inputs.

Consequently, the ongoing efforts to optimise energy use and develop more energy-efficient bioconversion methods are crucial steps in addressing these challenges and moving towards a more sustainable bioeconomy. These ongoing efforts demonstrate a multifaceted approach to optimising energy use and developing bio-based processes in the bioeconomy sector that are more energy-efficient. In this regard, recent initiatives are centred on several pivotal domains, as outlined below:

- **Smart and dynamic biorefinery concepts**: researchers and industry leaders are developing biorefinery models that are both energy-efficient and environmentally sustainable, with the goal of achieving net-zero or even negative carbon emissions. These integrated systems are designed for large-scale production of advanced biofuels alongside valuable by-products and bioenergy[356]. The central features are as follows:
    - Real-time adjustment of processes to minimise energy consumption and waste generation.
    - Utilisation of biogenic waste, residues, algae and aquatic biomass through diverse conversion pathways.
    - Integration of mass and energy flows to enhance overall process efficiency.
    - Use of cascading models to maximise biomass utilisation.
    - Addressing process heat and power needs through co-produced bio-heat and bio-power.
    - Incorporation of renewable energy sources, such as agrivoltaics in solar parks, to reduce reliance on fossil fuels.

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  - Optimisation of thermal flows to lower carbon footprint.
  - Capturing and reusing biogenic effluent gases to minimise emissions.
  - Sequestering carbon via outputs such as biochar for soil enrichment.
- **Circular bioeconomy approaches**: the circular economy is becoming an integral component in a wide variety of bioeconomy activities. The overarching objective of this approach is threefold: to reduce waste, optimise resource utilisation, and minimise environmental impact. Additionally, the transformation of biomass into beneficial ingredients and high-value bio-based products through dynamic biorefining is a key focus[357] [358].
- **Integration of renewable energy into bioeconomy processes**: this action represents a pivotal consideration, including the combination of agricultural and solar production through agrivoltaics, the maximisation of land efficiency, and the mitigation of reliance on fossil fuels, amongst other considerations.
- **Advanced biofuel technologies**: research is ongoing to develop the next-generation synthetic renewable fuel technologies with the objective of:
  - Accelerating the readiness of cost-effective technologies for synthetic renewable fuel production.
  - Improving process efficiency.
  - Minimising emissions.
  - Ensuring sustainability through lifecycle assessment.
- **Innovative biomass conversion methods**: various methods for biomass utilisation are being explored and improved such as thermochemical conversion (e.g., pyrolysis, gasification, and torrefaction), biochemical (e.g., anaerobic digestion and fermentation), and co-production/co-generation (combining biomass with other energy sources) [359].

2.4 Environmental Issues

When developing and implementing bio-based processes, environmental considerations play a significant role. Key priorities include reducing water consumption, minimising waste generation, and ensuring the sustainability of feedstock production. Recent scientific research and policy assessments have demonstrated that environmental issues are critical in shaping the current state of the European bioeconomy. The EU's bioeconomy strategy emphasises reducing dependency on fossil resources and achieving greenhouse gas neutrality. However, there are still challenges in balancing economic growth with ecological sustainability. A recent JRC study shows that the EU has

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made progress in food security and renewable energy (reaching 23% of total energy consumption by 2022), but climate change mitigation efforts have stagnated. This is attributable to reduced carbon sequestration by land sinks, compounded by forest disturbances such as wildfires and pest outbreaks[360]. This emphasises the delicate balance between the utilisation of biomass and the maintenance of ecosystem health.

The EU's reliance on biomass imports has a significant impact on its environmental footprint. Scientific analyses indicate that Europe's per-capita ecological footprint exceeds global biocapacity by 200%. In addition, 30% of the company's biomass demand is met through imports, which are often sourced from biodiverse regions in Latin America and Africa[361] [362]. This external dependency gives rise to concerns regarding transboundary biodiversity loss and land-use changes in exporting countries. The adoption of unsustainable agricultural practices in these countries may accelerate deforestation, habitat fragmentation and the loss of carbon-sequestering vegetation[363]. For instance, the EU's demand for soy and palm oil has been linked to ILUC that threaten tropical ecosystems. There is a need for more stringent sustainability criteria to be implemented within global supply chains, as biodiversity loss and ecosystem degradation from land-use change for biofuel production have been most pronounced in these areas[364] [365] [366]. Furthermore, while bioenergy constitutes 60% of the EU's renewable energy mix, research indicates that certain biofuels can exhibit a higher

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carbon intensity than fossil fuels when indirect land use change is accounted for[367] [368] [369] [370]. This phenomenon is especially evident in first-generation biofuels derived from food crops, which often require significant land conversion.

However, the expansion of monoculture plantations for bio-based products is associated with significant risks, including soil degradation and water scarcity, particularly in southern Europe, where the irrigation demands of bioenergy crops place considerable pressure on already limited water resources. The European Union's forests, which cover approximately 40% of its land area, play a crucial dual role as both biomass resources and natural carbon sinks. Nevertheless, increasing harvesting rates, together with climate-related disturbances such as droughts, heatwaves, wildfires, and pest outbreaks, have reduced their carbon sequestration capacity. Recent assessments indicate that the average EU forest carbon sink declined by approximately 27% between the periods 2010–2014 and 2020–2022, raising concerns about the long-term sustainability of biomass extraction and its implications for achieving European climate targets[371]. Additionally, the bioeconomy's impact on biodiversity and land use is complex and potentially substantial, exerting influence on competition with food production (where the prioritisation of crops for energy, chemicals, or materials could have a negative effect on food prices in certain geographies and contexts), soil degradation (where the exploitation of agricultural residues for fuels and chemicals may compete with soil management practices), and water depletion and pollution (where increased agricultural activities can lead to water scarcity and pollution, including eutrophication). The abovementioned effects extend beyond biodiversity and land degradation, representing a substantial economic loss for the EU.

The bioeconomy plays a dual role in the management of emissions of gases that trap heat in the atmosphere or GHG, offering potential for climate mitigation while requiring careful navigation of ecological trade-offs. By replacing fossil-based materials and energy sources, bio-based solutions can contribute to reduce GHG emissions when compared to conventional counterparts, particularly in industrial applications. This can be achieved by combining circular production models and

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industrial symbiosis[372]. According to OECD estimates, bio-based plastics related to bioeconomy and circularity can potentially imply a replacement of about 400 million tonnes of fossil resources per year[373].

However, there are still significant challenges to be addressed. A substantial proportion of global biomass remains allocated to low efficiency uses, such as animal feed production[374]. Furthermore, it should be noted that bioenergy systems and bio-based products are not inherently carbon neutral[375]. In the context of bioenergy systems, they may emit more CO_2eq than fossil fuels in certain scenarios when accounting for ILUC. This is due to the loss of carbon sequestration potential from land conversion, and the fact that monoculture plantations can reduce carbon storage capacity by 30-50% compared to natural ecosystems[376] [377].

Achieving the right balance in these areas requires a strategic approach. Firstly, high-value, durable bioproducts (e.g., bioplastics or construction biomaterials) should be prioritised over energy applications. Secondly, land-sparing policies should be implemented to limit agricultural expansion and prevent deforestation. Thirdly, lifecycle certifications should be adopted to address non-CO_2 emissions such as methane from anaerobic digestion and nitrous oxide from biofertilizers[378]. While bioeconomy strategies have the potential to mitigate 20-30% of agrifood emissions[379], current implementations often fall short of this target because they still require significant improvements to ensure their alignment with global climate targets for 2050: These improvements highlight the importance of precise biomass allocation, systemic circular design, and strict sustainability criteria. This is essential to prevent the escalation of land-use conflicts while ensuring the maximisation of climate benefits. Achieving balance between multiple sustainability criteria is imperative for effective

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production. A thorough, balanced approach that considers environmental, economic and social sustainability criteria is vital for ensuring the continued viability of production processes.

The bioeconomy generates a large amount of waste, particularly from agricultural and food processing industries. Circular bioeconomy initiatives such as the valorisation of agricultural and forestry residues and biowaste, offer partial solutions with the potential to reduce municipal waste generation by up to 40% if implemented effectively[380]. These initiatives aim to close resource loops by converting residual streams into valuable by-products and producing compostable bio-based products. The utilisation of lignocellulosic residues for bio-based materials and bioenergy has the potential to reduce waste generation while creating economic value. Waste-to-value approaches - including anaerobic digestion, pyrolysis, and bioprocessing- are essential for reducing organic waste accumulation and developing a more sustainable, bio-based economy[381] [382].

The issue of policy coherence remains a significant hurdle. While the EU Bioeconomy Strategy is aligned with the Green Deal's climate targets, there is a lack of integration with the Biodiversity Strategy 2030, resulting in a discordance of priorities in land-use planning, as was previously mentioned. Research has revealed that 20% of the EU's agricultural land is currently used for non-food biomass production, which is resulting in intensified competition about food security and wild habitats[383] [384].

These findings highlight a paradox of the bioeconomy in the EU: while it serves as a pillar of the EU's decarbonisation agenda, it also drives ecosystem pressures through land-use change, biodiversity loss, and resource overexploitation. In the absence of robust monitoring systems and transnational governance frameworks, the region is at risk of further biodiversity decline, particularly if biomass demand is not sourced and managed sustainably. This challenge creates uncertainties and may undermine the EU's 2050 neutrality goals, particularly if bio-based industries expand without clear sustainability criteria. The EU is increasingly reliant on biomass for material and energy purposes, and there is growing pressure on ecosystems from forestry and agriculture. This necessitates closer monitoring of land use for biomass production, both within and outside the EU. Furthermore, while the renewability of biomass is an important consideration, it is not a guarantee of sustainability in

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and of itself. The viability and sustainability of biomass depend on responsible management and sustainable production. Inadequate management of biomass production can have several negative consequences, including deforestation, biodiversity loss and food security risks. The sustainable supply of biomass, from primary production, agriculture, forestry, fisheries, aquaculture and industrial waste and processing, is a key bottleneck in the bioeconomy (as will be explained later). As a result, both sustainable production and responsible consumption require strict regulation and monitoring.

In order to overcome the challenges and ensure the bioeconomy's alignment with biodiversity and climate goals, it is essential that policies address bioeconomy-induced biodiversity losses and the uncertainties surrounding resource availability and environmental resilience. Moreover, it is vital to achieve a balance between utilisation and ecosystem preservation. This can be achieved through enhanced monitoring frameworks, sustainability certifications and integrated policies. This includes the conversion of agricultural and food waste into biofuels, biochar, and biomaterials, with the aim of reducing landfill waste and promoting sustainability[385]. One such innovation is the valorisation of digestate, a byproduct of anaerobic digestion, which has been promoted as a biofertilizer to enhance soil health while reducing reliance on carbon-intensive mineral fertilisers (and chemical-based agricultural inputs). This is due to its content of organic matter and essential macronutrients such as nitrogen, phosphorus, and potassium, which support soil fertility[386]. Similarly, advancing life cycle assessments of bio-based products can help to identify and mitigate their environmental impact across value chains. Furthermore, it is vital to prioritise the use of long-term material resources over the consumption of short-lived disposable products, following the cascading use principle, and to significantly reduce consumption of animal products to alleviate pressure on land use.

2.5 Competition With Traditional Processes

The competition between bio-based and traditional processes in the bioeconomy is characterised by cost structures, technological maturity, and shifting market dynamics. While traditional fossil-based technologies benefit from decades of infrastructural optimisation, improved methodology and economies of scale, bio-based alternatives are gaining ground through innovation and systemic valuation of environmental impacts. This competition is therefore a key driver of innovation in this field[387]. As bio-based technologies continue to improve, they are increasingly able to compete with established chemical processes in terms of cost, efficiency, and product quality. This competition has resulted in the development of hybrid processes, including the recently introduced concepts of

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"drop-in" and "slot-in" approaches[388] [389]. These innovative methods combine biological and chemical approaches to capitalise on the strengths of both. In this context, concepts such as "slot-in" and "drop-in" approaches are starting to emerge in the market. These approaches are designed to integrate bio-based solutions into existing chemical infrastructure with minimal modifications ("slot-in") and to replace directly fossil-based products in the established market with bio-based versions of them, maintaining the existing chemical production and distribution systems ("drop-in"). These solutions have been developed to remove any obstacles to adoption and encourage sustainability without compromising efficiency.

The cost competitiveness of bio-based processes and technologies is closely related to the production challenges posed by the corresponding bio-based products. The cost of bio-based chemicals currently stands at 20-50% higher than traditional petrochemical alternatives. This is primarily due to production costs, which are associated with smaller manufacturing scales because bio-based production is still in its development phase and lacks the economies of scale that traditional processes enjoy. Feedstock expenses, such as agricultural biomass, algae, or wood, are also a factor. Furthermore, underdeveloped supply chains, where the logistics and infrastructure for bio-based materials are not as mature as those for fossil-based products, and energy-intensive bioconversion processes also contribute to the cost disparity[390] [391] [392]. For instance, the cost of biosurfactants is typically between $20-25/kg, whereas synthetic surfactants generally range from $1-3/kg. This cost difference is primarily attributable to the higher costs associated with media and downstream processing[393]. For instance, Belgian biotech start-up AmphiStar, founded in 2021 in Gent, has secured €12.5 million to scale up production of its fully upcycled microbial biosurfactants, drive the development of new biosurfactants, and strengthen global partnerships. These biosurfactants, made entirely from biowaste without fossil or palm inputs, reducing the environmental impact compared to conventional alternatives, according to a recent lifecycle analysis[394]. Another

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[391] Götz, M., and A. Kruse, A., A proposal for evaluating the economic viability of biorefineries against petrochemical benchmarks. Chemie Ingenieur Technik 96(3) (2024) 355-362. **https://doi.org/10.1002/cite.202300124**

[392] Satam, C.C., et al., Techno-economic analysis of 1,4-butanediol production by a single-step bioconversion process. Biofuels, Bioproducts and Biorefining 13(5) (2019) 1261-1273. **https://doi.org/10.1002/bbb.2016**

[393] Sharon, A.B., et al., Statistical optimization strategies on waste substrates for solving high-cost challenges in biosurfactants production: a review. IOP Conference Series: Earth and Environmental Science 1197 (2023) 012004. **https://doi.org/10.1088/1755-1315/1197/1/012004**

[394] Belgian BioTech developer AmphiStar secures €12.5 million for clean biosurfactants | EU-Startups

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pertinent example would be that of bio-based plastics. While bioplastics are the dominant force in the bio-based market (accounting for 19-25% of market share in 2019)[395] [396], their adoption is hindered by inconsistent performance in high-temperature applications when compared to their petroleum-based counterparts. However, recent progress in the field of enzymes has resulted in the successful application of biocatalysts at an industrial scale. This development has led to a reduction in the efficiency gap, but it should be noted that yield improvements still vary according to the specific process employed[397] [398].

With reference to market penetration and regulatory barriers (which have been accurately analysed in deliverable D4.2), the global bio-based market is projected to grow at a CAGR of 9.2% from 2022 to 2031, reaching approximately $271.8 billion by 2031[399]. This growth is mainly driven by EU public procurement policies that encourage the adoption of bio-based products, growing consumer demand for carbon-neutral alternatives in packaging, and industrial applications especially in biolubricants and biosolvents[400]. Additionally, both the bio-based products and the energy market (except for the food and feed sectors) are forecast to demonstrate CAGR of 3.3%, reaching a combined total of $5 trillion by the year 2030, as scaling improvements are implemented[401].

However, achieving economic viability remains contingent on technological advancements, process optimisations, and supportive policies (and regulatory barriers) to drive cost reduction. For instance, technical standards for biodegradability and toxicity vary globally, creating compliance hurdles for manufacturers. Additionally, the absence of standardised LCA hinders buyers' ability to justify sustainability premiums, further slowing adoption.

Moreover, there are several technical challenges that still need to be resolved. This will allow the scalability and adoption of bio-based processes to be compared to traditional processes. Firstly, the presence of scalability bottlenecks associated with the efficiency loss of fermentation processes at an industrial scale is due to microbial sensitivity under industrial conditions, such as pH, temperature,

[395] Spekreijse, J., et al., Bio-based value chains for chemicals, plastics and pharmaceuticals – A comparison of bio-based and fossil-based value chains, Publications Office, 2021, **https://data.europa.eu/doi/10.2760/712499**

[396] Mozaffari, N., et al., A review: investigation of plastics effect on the environment, bioplastic global market share and its future perspectives. Technogenic and Ecological Safety 5 (2019) 47-54. **https://doi.org/10.5281/zenodo.2600664**

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[399] Global Bio-Based Chemicals Market Report to 2031: Increasing Consumer Adoption of Bio-Based Products Drives Growth - ResearchAndMarkets.com

[400] Why the bio-based materials market is finally poised for growth | Arthur D. Little

[401] Circular-bioeconomy: The business-opportunity-contributing-to-a-sustainable-world (2023) | World Business Council for Sustainable Development (WBSCD)

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and oxygen levels. Secondly, the separation of target molecules from bioreactor outputs (downstream processing) remains one of the most energy-intensive steps in bioprocessing, accounting for up to 60% of total production energy costs. This step is still a major hurdle for biorefineries that are aiming to achieve cost-competitive production[402] [403]. Thirdly, the limitations imposed by redox, due to the fact that glucose-dependent systems exhibit lower electron transfer efficiencies compared to hydrogen-based catalytic systems that are used in traditional chemical processes, are also a significant challenge. Consequently, conventional biocatalytic processes typically yields of up to 72%, while optimised chemical processes achieve yields of 85-92%. Finally, the constraints imposed by infrastructure necessitate substantial upfront investments and specific requirements. For instance, the capital investment required for biorefineries can be three to five times higher than that for equivalent petroleum facilities[404]. Furthermore, the current level of biomass production demands 40% more arable land per unit of energy than is required for oil production. These challenges result in a delay in market parity between bio-based products and traditional alternatives, particularly in price-sensitive sectors such as bulk chemicals, where bio-based solutions remain two to three times more expensive.

2.6 CIRCULAR APPROACHES

Circular approaches are gaining prominence in bio-based process development, emphasising the importance of closed-loop systems and the valorisation of waste streams. These approaches aim to maximise resource efficiency and minimise environmental impact by creating interconnected processes where waste from one stage becomes a valuable input for another. The circular bioeconomy concept represents a significant shift from traditional linear economic models, offering solutions to global issues such as environmental pollution, resource scarcity, and climate change.

The implementation of cascading use principles constitutes a pivotal aspect of circular bioeconomy approaches. This involves optimising the efficient utilisation of resources by using biomass in products that generate the greatest economic value over the course of their lifetimes[405]. To this end, these generated products are cascaded over multiple periods to maximise their use and presence in the value chain to ultimately be recycled, recovered or composted to be completely valorised. This principle extends product lifetimes, encourages reuse and prioritises higher-value applications

[402]Kuhn, D., et al., Intensification and economic and ecological assessment of a biocatalytic oxyfunctionalization process. Green Chemistry 12 (2010) 815-827. **https://doi.org/10.1039/B921896C**

[403]Darkwah, K., et al., A perspective on challenges and prospects for applying process systems engineering tools to fermentation-based biorefineries. ACS Sustainable Chemistry & Engineering 6(3) (2018) 2829-2844. **https://doi.org/10.1021/acssuschemeng.7b03762**

[404]KBBPSS Knowledge based bio-based products' pre-standardization WP5 Bootlenecks and impacts on functionality tests. Deliverable Nº5.3: Market-entry-barriers.pdf

[405]Circular-bioeconomy: The business-opportunity-contributing-to-a-sustainable-world (2023) | World Business Council for Sustainable Development (WBSCD)

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before disposal. Preference is given to higher-value applications and continuous reuse, with energy recovery as the last option. This approach has been shown to increase resource efficiency and significantly reduce the carbon footprint for each ton of final product produced[406] [407]. For instance, research findings indicate that adopting circular bioeconomy approaches, such as the valorisation of biowaste in conjunction with cascading biomass use, can lead to a substantial reduction in municipal waste generation.

With the purpose of implementing the cascading use principles, the introduction of closed-loop systems represents a seminal component within the paradigm of the circular bioeconomy. Theoretically, the objective of these systems is to retain resources in endless circulation within the economy for as long as possible through continuous reuse and recovery, thereby reducing waste generation and reliance on virgin materials. This process entails the collection and recycling of materials at the conclusion of their designated lifecycle, or the reintroduction of these materials to the nutrient cycle through the processes of biodegradation or composting, contributing to soil fertility and ecosystem health. The capacity to return nutrients through these processes is of enormous benefit to the sustainability of the entire system, and it is predicated on the use of renewable inputs[408] [409]. Policies supporting cascading biomass use and closed-loop systems can therefore improve efficiency and reduce waste[410]. For example, circular production models can increase benefits through cascading biomass use, extending the material utility in multi-stage processes (such as converting crop residues into bioplastics, then residual waste into biogas and finally using digestate as fertiliser), while reducing manufacturing emissions through industrial symbiosis[411].

Green innovation has been shown to play a vital role in increasing the value generated per unit of biological resource. This includes the development of novel technologies for biomass conversion as well as industrial side-streams, byproducts, and wastes. These innovations have resulted in the establishment of a diverse spectrum of novel bio-based value chains, encompassing a range of

[406]Lange, L., et al., Developing a sustainable and circular bio-based economy in EU: by partnering across sectors, upscaling and using new knowledge faster, and for the benefit of climate, environment & biodiversity, and people & business. Frontiers in Bioengineering and Biotechnology 8(6) (2021) 619066. https://doi.org/10.3389/fbioe.2020.619066

[407]Philp, J., and Winickoff, D., Realising the circular bioeconomy. OECD Science, Technology and Industry Policy Papers 60 (2018) OECD Publishing, Paris. https://doi.org/10.1787/31bb2345-en

[408]Mohan, S.V., et al., Algal biorefinery models with self-sustainable closed loop approach: trends and prospective for blue bioeconomy. Bioresource Technology 295 (2020) 122128 https://doi.org/10.1016/j.biortech.2019.122128

[409]Velvizhi, G., et al., Biodegradable and non-biodegradable fraction of municipal solid waste for multifaceted applications through a closed loop integrated refinery platform: paving a path towards circular economy. Science of the Total Environment 731 (2020) 138049 https://doi.org/10.1016/j.scitotenv.2020.138049

[410]Ramos Huarachi, D.A., et al., Life cycle thinking for a circular bioeconomy: current development, challenges, and future perspectives. Sustainability 15 (2023) 8543 https://doi.org/10.3390/su15118543

[411]Lubjuhn, S., and Venghaus, S., Unlocking the potential of the bioeconomy for climate change reduction: the optimal use of lignocellulosic biomass in Germany. Journal of Industrial Ecology 28(1) (2023) 144-159. https://doi.org/10.1111/jiec.13455

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products from simple fossil substitutes to bio-based products with unique functionalities that do not have a fossil equivalent[412].

Moreover, European policies advocate for the adoption of cascading use and green chemistry innovations as a means of reducing costs, optimising biomass usage and integrating bio-based solutions into supply chains[413] [414]. This underscores the necessity for interdisciplinary collaboration to curtail capital expenditures and align pricing with environmental externalities[415].

As research and development in bio-based processes continue to advance, the field faces both opportunities and challenges. Overcoming technical hurdles to achieve full-scale implementation (especially in waste-processing technologies), improving process economics, and addressing scalability issues are crucial for the widespread adoption of these technologies across various industries. These challenges underscore the complexity of transitioning to a circular bioeconomy and highlight the need for continuous advancements in R&D, process efficiency, scalability, stronger market demand for bio-based products, and supportive policies, amongst others (such as public-private partnerships, or funding for innovation). This will be analysed in other deliverables (D4.2, D4.3, and D4.4) within the framework of the ToBeReaL project.

2.7 MARKET DEMAND

The global market for sustainable bioprocesses (also known as bio-based processes) is experiencing significant growth, driven by increasing environmental concerns, regulatory pressures, and consumer demand for eco-friendly products. In the contemporary business landscape, there is an increasing emphasis on reducing carbon footprints and transitioning towards circular economy models. Consequently, bio-based processes are gaining traction across various sectors. The market demand for these processes is particularly strong in industries such as chemicals, pharmaceuticals, food and beverages, and biofuels.

In the chemical industry, there is growing interest in green chemistry and bio-based alternatives to petrochemical products. In the current business climate, companies are allocating resources to the research and development of bio-based plastics, solvents and other chemical intermediates. The pharmaceutical sector is also exploring bioprocesses to produce active pharmaceutical ingredients

[412] Bröring, S., et al., Innovation types in the bioeconomy. Journal of Cleaner Production 266 (2020) 121939 **https://doi.org/10.1016/j.jclepro.2020.121939**

[413] Bio-based products and processes | Bioeconomy | European Commission

[414] Bezama, A., Measuring circularity: a (still) ongoing methodological challenge. Waste Management & Research 41(5) (2023) 953-954 **https://doi.org/10.1177/0734242X231170615**

[415] IEA-Bioenergy_Task-42 Biorefining in a Future BioEconomy-Triennium-2016-2018-1 | International Energy Agency

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(APIs) and other drug components, driven by the need for more sustainable and cost-effective manufacturing methods.

The demand for natural ingredients and clean-label products in the food and beverage industry is increasing, resulting in the adoption of bioprocesses to produce flavours, colours, and preservatives. In addition, the biofuels market is experiencing continuous growth, with the production of bioethanol and biodiesel making use of a variety of bioconversion technologies.

Preliminary market analysis indicates that the global bio-based chemicals market is expected to demonstrate growth at a CAGR of approximately 10% over the next five years. Government initiatives promoting the use of renewable resources and favourable policies for bio-based products are supporting this growth. For instance, the European Union's Bioeconomy Strategy aims to accelerate the deployment of sustainable bioprocesses across various sectors.

Consumer awareness and preferences are also driving market demand. A recent survey demonstrated that over 60% of consumers expressed a willingness to pay a premium for products manufactured using sustainable processes. This tendency is especially evident in the personal care and cosmetics sector, where there is a growing demand for bio-based ingredients.

However, challenges persist in terms of the large-scale implementation of bioprocesses to satisfy industrial requirements. Factors influencing market adoption rates include process efficiency, cost competitiveness with traditional petrochemical processes, and the necessity for specialised infrastructure. Despite the challenges encountered, the overall market trajectory for sustainable bioprocesses is positive. This is due to the expectation that innovations in biotechnology and process engineering will address many of the current limitations. In the context of contemporary business practices, there is an increasing emphasis on achieving sustainability goals and mitigating environmental impact. This has resulted in a noticeable increase in demand for bio-based processes, which is expected to maintain its upward trend. This presents significant opportunities for technology providers, raw material suppliers and end-product manufacturers to capitalise on the growing market for sustainable bioprocesses across various industries.

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3 ECONOMIC BARRIERS

3.1 SUPPLY-SIDE BARRIERS: FEEDSTOCK AVAILABILITY IN THE EU

3.1.1 Overview of sustainable biomass sources - availability, prices, logistics

A sustainable and well-coordinated biomass supply chain is essential for the successful transition to a bio-based and circular economy in the EU. Biomass feedstocks, which include agricultural residues, forestry by-products, organic waste streams and specialised crops, are a type of renewable resource. However, their availability, market prices and logistical complexity vary significantly between Member States, leading to fragmented supply systems and economic bottlenecks.

3.1.1.1 Agricultural Residues

Agricultural residues, including straw, maize straw and manure, are a significant by-product of the EU agricultural sector, with an annual production estimated at over 956 million tonnes[416]. However, due to competing uses as a soil improver, animal bedding and local energy applications, only a portion of this amount can be collected sustainably[417]. This competition has the effect of limiting the availability of high-quality industrial applications.

Seasonality and geographical fragmentation further limit continuity and scope of supply, leading to logistical challenges and price volatility. The delivery price for agricultural residues is typically between €20 and €80 per tonne, depending on location, processing and transport requirements[418]. Countries with well-developed infrastructure for biomass logistics, such as Germany, France and the Netherlands, show a more significant mobilisation of raw materials, while others are still underutilised.

The logistics of collecting and transporting agricultural residues have a significant impact on their economic viability. Research has indicated that the cost-efficiency of harvesting systems varies according to distance. Self-loading wagons are more economical at shorter distances, while baling is preferable above certain thresholds. Furthermore, the removal of nutrients through the removal of residues necessitates compensatory measures that impact overall costs[419].

[416]Scarlat, N., et al., The role of biomass and bioenergy in a future bioeconomy: Policies and facts. Environmental Development 15 (2015) 3-34 **https://doi.org/10.1016/j.envdev.2015.03.006**

[417]Biomass | Bioenergy | Renewable energy | European Commission

[418]Carraro, C., et al., Waste and residue availability for advanced biofuel production in the European Union and the United Kingdom. Working Paper 2021-39 International Council on Clean Transportation (ICCT). (2021). Retrieved from https://theicct.org/sites/default/files/publications/eu-uk-biofuel-production-waste-nov21.pdf

[419]Honorato-Salazar, J.A., et al., Logistics and Costs of Agricultural Residues for Cellulosic Ethanol Production in Mexico. Energies, 15(12) (2022) 4480. **https://doi.org/10.3390/en15124480**

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Investments in regional biomass hubs, cooperative collection systems and intermodal transport networks are essential to improve the utilisation of agricultural residues. The development of such infrastructure has the potential to reduce inefficiencies, create economies of scale and support the EU's transition to a sustainable bioeconomy.

3.1.1.2 Forestry Biomass

Biomass derived from forestry, including wood waste, bark and sawdust, contributes significantly to the EU bioeconomy, especially in the Nordic and Baltic countries. In 2022, approximately 491 million m^3 of roundwood was produced in the EU-27, of which around 36% was used for energy purposes[420]. Forest biomass is valued for its year-round availability, stable calorific value and established supply chains. However, mobilisation is often hampered by fragmented land ownership, limited road access and sustainability concerns in areas of high biodiversity[421].

The EU Forest Strategy for 2030 promotes sustainable forest management and the valorisation of side streams, but warns against excessive harvesting, especially under the RED II criteria for advanced biofuels[422]. In remote areas, transport costs can account for 40-60% of the total cost of delivering biomass, highlighting the need for decentralised biorefinery models and better multimodal logistics[423].

3.1.1.3 Organic Waste Streams

Municipal biowaste, food industry residues and sewage sludge are promising sources of biomass but are currently underutilised. In the EU, approximately 130 million tonnes of biowaste are generated per year, of which only 40% is currently collected and treated for resource recovery[424]. The separate collection system varies from country to country, with higher recycling rates in Austria and Italy than in less developed systems in parts of Eastern and Southern Europe[425].

As outlined in the EU policy instruments, such as the Circular Economy Action Plan (CEAP) and the revised Waste Framework Directive, separate collection of biowaste is to be implemented by 2023.

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[420] Forests, forestry and logging (2024) | Statistics explained | Eurostat

[421] European Commission. (2022). Implementing Regulation (EU) 2022/2448 of 13 December 2022 on establishing operational guidance on the evidence for demonstrating compliance with the sustainability criteria for forest biomass laid down in Article 29 of Directive (EU) 2018/2001 of the European Parliament and of the Council. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32022R2448

[422] European Commission. (2021). New EU Forest Strategy for 2030. COM (2021) 572 final. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021DC0572

[423] IEA-Bioenergy Task39-40-45-Assessment of successes and lessons learned for biofuels deployment - Sustainable biomass supply chains for international markets (2023) | International Energy Agency

[424] Bio-waste in Europe – turning waste into a resource (2020) | EEA Briefing | European Environment Agency.

[425] European Commission. (2020). A new Circular Economy Action Plan: For a cleaner and more competitive Europe. COM (2020) 98 final. Brussels. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0098

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Furthermore, the end-of-waste criteria for compost and digestate have been promoted[426]. However, challenges such as substandard inputs, impurities, and the absence of harmonised quality standards hinder the widespread adoption of recycling in biochemical and biomaterial applications.

3.1.1.4 Logistics and Infrastructure Challenges

Biomass is inherently bulky, moisture-rich and geographically dispersed, which poses significant logistical challenges. In contrast to fossil fuels, biomass often requires pre-treatment steps such as drying, baling, chipping or pelletisation before transport and utilisation. These characteristics increase handling, storage and transportation requirements, making logistics a major contributor to overall feedstock costs, particularly for low-density agricultural and forestry residues. Efficient supply chain design is therefore essential to ensure the economic viability of bio-based value chains[427].

Investment in regional biomass hubs, cooperative collection systems and intermodal transport networks (e.g. the integration of road and rail) is therefore urgently required. The EU's bioeconomy strategy promotes infrastructure improvement through national roadmaps, while projects like BE-Rural and BIOEASTsUP support local biomass mobilisation in rural regions[428] [429].

Therefore, the sustainable sourcing of biomass remains a decisive factor in expanding the European bioeconomy. While raw materials are abundant, there are systemic barriers to their effective use. These include uneven mobilisation, economic inefficiency and logistical fragmentation. In order to ensure cost-effective and sustainable supply chains, coordinated action at regional and EU levels is required. This should include mapping biomass resources, harmonise standards and invest in targeted infrastructure.

3.1.2 Biowaste potential and capture rates

Biowaste, comprising food waste, garden and park waste, and other biodegradable organic matter, is a significant yet underutilised biomass resource in the European Union. Its utilisation is essential for a truly circular bioeconomy, as it enables the recovery of valuable materials, nutrients and energy. However, despite its potential, a significant amount of biowaste is not currently collected or treated in a way that supports higher-value applications such as composting, anaerobic digestion or bio-based materials. The **Tech4Biowaste database** provides the bio-based industry with a

[426]Directive (EU) 2018/851 of the European Parliament and of the Council amending Directive 2008/98/EC on waste. Official Journal of the European Union. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0851

[427]Nunes, L.J.R., and Silva, S., Optimization of the residual biomass supply chain: process characterization and cost analysis. Logistics 7(3) (2023) 48. **https://doi.org/10.3390/logistics7030048**

[428]Bio-based strategies and roadmaps for enhanced rural and regional development in the EU | BE-Rural | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[429]Advancing Sustainable Circular Bioeconomy in Central and Eastern European countries | BIOEASTsUP | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

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comprehensive overview of existing and emerging technologies for biowaste utilisation and valorisation. The technology database contains the latest information and is available to all. This will be of benefit to many stakeholders during and following the project's duration. It will provide interested stakeholders with information and technical details on the technologies, while also providing a platform for technology providers to showcase their innovative solutions[430].

3.1.2.1 Biowaste generation and theoretical potential

In the EU-27, approximately 130 million tonnes of biowaste are generated on an annual basis, with food waste accounting for over 60% of the total[431]. This equates to approximately 300 kg per capita per year, though it should be noted that these figures can vary significantly between individual Member States due to differing consumption habits, waste management systems and reporting practices. Germany, the Netherlands and Austria are notable examples of countries that have implemented comprehensive biowaste management systems, incorporating separate collections. In contrast, other countries, particularly in Eastern and Southern Europe, still lack the infrastructure for systematic collection.

The theoretical utilisation potential of this stream is considerable. If fully collected and efficiently processed, biowaste in the EU has the potential to generate up to 4 million tonnes of compost, 2 billion m³ of biogas and significant quantities of digestate for soil improvement, thereby contributing substantially to energy production and soil health[432]. Furthermore, the utilisation of biowaste as a feedstock for advanced bio-based chemicals, bioplastics and enzymes has the potential to reduce reliance on virgin biomass.

3.1.2.2 Capture rates and capture systems

Despite its potential, only around 40% of the total biowaste generated in the EU is currently collected separately for recycling or recovery, with rates varying widely between countries. High-performing countries such as Austria and Italy achieve collection rates in excess of 70%, which can be attributed to strong legal frameworks, local incentives and public awareness. In contrast, countries such as Romania, Bulgaria and Cyprus have a rate below 15% due to limited infrastructure, fragmented administration and insufficient enforcement of collection obligations.

One of the most significant factors influencing collection rates is the implementation of distinct waste collection schemes. Research has shown that kerbside collection schemes for organic waste are an effective way of increasing recycling rates, especially when combined with public education

[430] Database – Tech4Biowaste

[431] European Environment Agency. Bio-waste in Europe – turning waste into a resource (2020). EEA Briefing 06/2020. Retrieved from https://www.eea.europa.eu/publications/bio-waste-in-europe

[432] Searle, S.Y., and Malins, C.J., Waste and residue availability for advanced biofuel production in EU Member States. Biomass and Bioenergy, 89 (2016) 2–10. **https://doi.org/10.1016/j.biombioe.2016.01.008**

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campaigns. Conversely, joint collection systems or mixed waste systems often result in a high level of contamination, which limits the suitability of organic waste for high-value recovery routes.

Following the 2018 revision of the Waste Framework Directive (2008/98/EC)[433], Member States were obliged to ensure the separate collection of biowaste by the end of 2023. While this has accelerated progress in several countries, implementation remains uneven, and many regions have yet to fulfil the requirements.

3.1.2.3 Obstacles to effective valorisation

Apart from collection, the quality and composition of biowaste remain a significant problem. Contaminants such as plastics, metals and non-biodegradable packaging can interfere with composting and fermentation processes, resulting in lower product quality or costly pre-treatment. Additionally, the absence of harmonised end-of-waste criteria for compost and digestate within the EU serves to create market barriers and uncertainties for producers and users.

The economic challenges persist. The operation of composting and anaerobic digestion facilities necessitates substantial investment, and in regions with low waste volumes or inadequate infrastructure, revenues from energy sales or compost sales frequently fall short of covering operational expenses. With the purpose of improving the financial viability of biowaste utilisation, policy incentives must be implemented, including subsidies for biowaste processing plants and renewable energy premiums for biogas.

It can be concluded that the biowaste stream is a valuable raw material for the European bioeconomy, which has not yet been fully utilised. Increasing collection rates and improving recovery infrastructure are priorities if the circular economy is to be realised, greenhouse gas emissions from landfill are to be reduced and renewable products generated. In order to unlock this potential, harmonised legal frameworks must be put in place, along with investment in decentralised collection systems and public education.

3.1.3 Emerging feedstocks

The European bioeconomy must increasingly surpass conventional raw materials to ensure a resilient and diversified biomass supply. Emerging feedstocks such as non-food oil crops, aquatic biomass (e.g. micro- and macroalgae), perennial grasses and industrial side streams offer innovative and sustainable ways to produce high-value bio-based materials, fuels and chemicals. These feedstocks mitigate competition with food and land use and improve regional resource utilisation and valorisation potential.

3.1.3.1 Oil plants and industrial oilseeds

[433]European Commission. (2018). Directive (EU) 2018/851 amending Directive 2008/98/EC on waste. Official Journal of the European Union. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32018L0851

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In the context of advanced biofuels and bio-based chemicals, non-food oil crops such as camelina (*Camelina sativa*), carinata (*Brassica carinata*), crambe (*Crambe abyssinica*), and castor bean (*Ricinus communis*) are gaining attention due to their adaptability to marginal soils, low input requirements and high oil yields. These crops are especially well-suited to Mediterranean and Eastern European regions where arable land is under pressure or underutilised. Camelina, for instance, has demonstrated yields of 1-2 tonnes per hectare, with a high content of omega-3 fatty acids and suitability for biodiesel, lubricants and bioplastics[434].

However, the use of oil crops as feedstock is still hampered by uncertain market acceptance, a lack of processing infrastructure and agronomic constraints. In order to expand production and ensure economic viability, it is vital to provide policy support and value chain integration. This will link producers, processors and end users.

3.1.3.2 Algae-based biomass (microalgae and macroalgae)

Algae represent a highly promising emerging feedstock, exhibiting high productivity per hectare, independence from competition with food crops, and capacity for growth in saline or wastewater. Microalgae can be cultivated in open ponds or photobioreactors, providing a source of lipids, proteins, pigments and bioactive compounds suitable for applications in food supplements, cosmetics, biofuels and pharmaceuticals. Macroalgae (seaweed) harvested or cultivated along the coasts is rich in polysaccharides such as alginate, carrageenan and agar, which are widely used in the food, chemical and packaging industries.

Europe has strategically invested in developing its algae biomass potential. The Blue Bioeconomy Roadmap, supported by the EU Blue Growth Strategy, outlines key targets for increasing algae production. Pilot initiatives in countries such as Ireland, France, Portugal and Norway are testing integrated multitrophic aquaculture (IMTA) and seaweed farming as sustainable sources of income for coastal communities[435]. However, challenges persist, including high production costs, low yields in temperate climates and regulatory gaps regarding safety, cultivation permits and biomass standards.

3.1.3.3 Perennial and lignocellulosic energy crops

Miscanthus, switchgrass (*Panicum virgatum*) and reed canary grass (*Phalaris arundinacea*) are perennial grasses with considerable potential as low-input lignocellulosic feedstocks. These plants can be cultivated on marginal or degraded land, support soil carbon sequestration and provide

[434] Berti, M., et al., Camelina uses, genetics, genomics, production, and management. Industrial Crops and Products 94 (2016) 690–710. **https://doi.org/10.1016/j.indcrop.2016.09.034**

[435] European Commission. (2022). Towards a Strong and Sustainable EU Algae Sector. COM (2022) 592 final. Retrieved from https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12780-Blue-bioeconomy-towards-a-strong-and-sustainable-EU-algae-sector_en

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biomass for combustion, biogas or advanced biochemical processing[436]. The European Union supports the adoption of these crops through measures such as rural development and carbon farming. However, large-scale adoption is still hampered by uncertainty of long-term viability, a lack of specialised harvesting equipment and gaps in the value chain.

3.1.3.4 Valorisation of industrial CO_2 and other novel raw materials

Innovations are also transforming industrial emissions and waste gases into raw materials for microbial or algae-based biomass production. Technologies such as gas fermentation (e.g. with *Clostridium ljungdahlii*) enable the conversion of CO_2 or syngas into bioethanol, organic acids or proteins. These approaches are designed to facilitate industrial symbiosis and promote the principles of the circular economy. However, most remain at pilot or demonstration scale and necessitate substantial R&D investment[437]. Another example is the Steelanol Initiative, which is an industrial initiative that captures and recycles carbon emissions from steel production to produce sustainable, advanced bioethanol. Utilising state-of-the-art gas fermentation technology, it converts waste gases into valuable biofuels, thereby reducing greenhouse gas emissions and enhancing energy independence. This project exemplifies a circular economy approach by transforming industrial carbon into renewable energy sources[438].

The use of emerging raw materials has the potential to increase the diversity of raw materials, close resource cycles and promote regionally customised bio-based value chains. With the purpose of ensuring the successful deployment of this project, it is essential that a coordinated policy framework is in place, that there is sustainable R&D support, and that robust supply chains are established. The strategic integration of these resources will be crucial for building a resilient European bioeconomy and reducing dependence on traditional biomass sources.

3.1.3.5 Belgium[439] [440] [441] [442]

[436]Lewandowski, I., et al., The development and current status of perennial rhizomatous grasses as energy crops in the US and Europe. Biomass and Bioenergy 25(4) (2016) 335–361. **https://doi.org/10.1016/S0961-9534(03)00030-8**

[437]Bengelsdorf, F.R., and Dürre, P., Gas fermentation for commodity chemicals and fuels. Microbial Biotechnology 10(5) (2017) 1167-1170. **https://doi.org/10.1111/1751-7915.12763**

[438]http://www.steelanol.eu/en

[439]Rapport bio-economie (FOD Volksgezondheid, 2024): Bio-economie en klimaattransitie in België: hoe kunnen vraag en aanbod van biomassa op lange termijn op elkaar worden afgestemd? 2024 – POLICY PAPER

[440]Werkagenda bioeconomie (2023) – Bioeconomie van ambitie tot actie.(Bioeconomy Work Agenda (2023) – From Ambition to Action) [website Vlaanderen Circulair]

[441]Natuur en Bos | Agentschap voor Natuur en Bos.

[442]B2BE Facilitator - Bio-economie in Vlaanderen.

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Current production of biomass feedstock

It is estimated that the bio-based economy accounts for 20.8% of the apparent biomass use in Belgium (i.e., the outcome of production, import, and export data), across all sectors and based on dry matter.

Forestry products and by-products make up more than 70% of the total bio-based economy, which corresponds to nearly 15% of the overall bioeconomy. While crop and animal agriculture remain the primary sources of biomass, their use is predominantly geared toward food for humans and animals, rather than industrial or energy applications.

In Belgium, the following sources of primary and secondary production can be considered: crop and animal agriculture; fisheries and aquaculture; forestry; landscape management; and waste management. Due to a lack of data, by-products and residues from production are excluded from this analysis. Conversely, the import and export of primary products and resources are considered.

The share of arable land in Belgium has remained relatively stable since 1950. Pastures and grasslands, however, have significantly declined between 1950 and 2020, while forested areas have increased. Although the total agricultural area has decreased, this has been offset by rising productivity and yields. The loss of biomass-producing land is largely attributed to the conversion of agricultural land and pastures, driven by urban expansion and the increase in built-up areas.

The (plant-based) primary biomass production in Belgium amounts to 16.1 million tonnes of dry matter per year (Mt DM/year) in 2020, excluding waste. This corresponds to an average of 5.2 tonnes DM/ha, which is considered high and can be attributed to the high productivity of the agricultural sector. The total production is distributed as follows: crop agriculture accounts for 86%, forestry for 13%, and landscape management for 1% of the total output. These main sectors are illustrated in Figure 8 (see left column: *primary biomass*), which also details the total waste and net imports.

The biomass production from crop agriculture in Belgium is estimated at 13,755,728 tonnes of dry matter per year and is dominated by four main categories: (a) arable forage crops, accounting for 4,110,455 tonnes DM/year; (b) permanently grass-covered surfaces, at 3,357,446 tonnes DM/year; (c) grains, contributing 1,991,761 tonnes DM/year; and (d) sugar crops, producing 1,605,329 tonnes DM/year. A significant share of grain production, along with the entirety of the first two categories, is used for animal consumption. As a result, nearly two-thirds of the primary output from crop agriculture is intended for animal feed, rather than for direct human consumption. This distinction between primary biomass and biomass available for final consumption underlines the critical importance of animal-based processing in the biomass chain.

In addition, for three product categories—seed grains, oilseeds, and pulses—imports significantly exceed domestic production. This trend is primarily driven by the import of soybeans, which are subsequently processed into oils and associated by-products.

Forestry products in Belgium are estimated at 2,148,825 tonnes of dry matter per year, with a relatively balanced share between softwood (43%) and hardwood (57%). The majority of this production originates from Wallonia (82%), as most of Belgium's forested areas are in that region.

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In addition to domestic production, Belgium imports approximately 4.4 million tonnes DM per year and exports 1.9 million tonnes DM per year, resulting in an apparent consumption in the sector of 4,639,425 tonnes DM annually.

Climate change presents a major uncertainty for the wood industry, as many tree species are unable to adapt to the changing environmental conditions. This adds further unpredictability to production figures in a sector already characterized by long planning and growth cycles.

The biomass available for final consumption (see Figure 8, second column)—defined as primary biomass minus the share used for livestock feed, and plus the animal product output from livestock farming—amounts to approximately 13 million tonnes of dry matter per year, excluding imports and waste.

The total biomass production from the livestock sector in Belgium is estimated at 5,087,990 tonnes of dry matter per year. Of this, 1,519,649 tonnes DM/year consist of main products such as pork, milk, poultry, beef, and, to a lesser extent, eggs. The remaining 3,568,341 tonnes DM/year are residues, primarily made up of slurry and rejected products (e.g., mastitis milk).

When focusing solely on production residues, cattle dominate the rankings, as beef production generates a large amount of residual biomass. This clearly highlights the low production efficiency of meat, with beef yielding as little as 3% efficiency when compared to the direct consumption of plant-based proteins.

In terms of import data, the sectors are relatively balanced, with production and consumption figures closely aligned, except in the case of eggs, where some discrepancy remains.

Finally, fisheries and aquaculture generate very limited biomass production in Belgium. The total production is estimated at just 6,190 tonnes of dry matter per year, with domestic consumption primarily met through imports.

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Figure 8 – Biomass in Belgium: Production, Imports, Final Consumption, and a Focus on Consumption by Source and Type of Use within the Bio-based Economy
(source: Rapport bio-economie FOD Volksgezondheid, 2024)

Figure 8 - Legend translation

X-Axis Categories:

Primaire biomassa (productie + netto-invoer) → Primary biomass (production + net imports), Biomassa beschikbaar voor eindverbruik (productie + netto-invoer) → Biomass available for final consumption (production + net imports), Eindverbruik → Final consumption

Color Legend (Bars):

Invoer → Imports, Afval → Waste, Landschap → Landscape, Bosbouw → Forestry, Plantaardige landbouw bestemd voor veevoeder → Crop agriculture for feed, Plantaardige landbouw – voor eindverbruik → Crop agriculture – for final use, Dierlijke landbouw → Animal agriculture, Visserij → Fisheries

Right Labels on Top Bars:

Andere (o.m. restafval, gier) → Other (e.g. residual waste, slurry), Beschikbaar voor menselijke voeding → Available for human consumption, Biogebaseerde economie (energie & grondstoffen) → Bio-based economy (energy & raw materials)

Zoom-In Circle: Bio-Based Economy Breakdown

Plantaardige landbouw → Crop agriculture, Dierlijke landbouw → Animal agriculture, Bosbouw → Forestry, Afval → Waste, Vaste biomassa → Solid biomass, Biogas → Biogas, Biobrandstoffen → Biofuels, Overig timmerhout → Other sawn timber, Pulp/hout → Pulp/wood, Textiel → Textiles, Chemie → Chemicals, Bouwsector → Construction sector

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Current use of biomass feedstock

There are many potential applications for biomass, and the products derived from it often undergo a series of transformations—making them partially or entirely bio-based. This complexity makes it difficult to obtain accurate usage data or to construct a comprehensive picture of biomass flows and end-uses.

In Belgium, biomass is used for food, animal feed, and within the bio-based economy. In other words, there is an inherent competition between different applications of biomass—a competition that is likely to intensify as the share of the bio-based economy is further expanded within the broader climate transition agenda.

At the same time, a portion of available biomass is currently underutilised or not-valorised. This includes waste from the food industry, sewage sludge, and slurry—resources that could potentially be better integrated into the bioeconomy.

The main economic sectors of the bio-based economy in Belgium (see Figure 8, right-hand box) include the textile industry, wood industry, construction sector, chemical industry, biofuels (such as biomethanation), and solid biomass fuels (excluding wood).

Based on existing estimates, the following usage categories have been identified for agriculture in Belgium:

- **Grains** grown for seed (including imports) are primarily used in the following sectors, in descending order: animal feed industry (36%), starch and biofuel production (22%), milling (16%), on-farm use for livestock and losses (14%), and malting (12%).
- **Oilseeds** are mainly used in the bio-based textile and chemical industries, with the exception of sunflowers and minor crops (not categorized due to small consumption volumes), which are primarily used for animal feed and human consumption. A portion of rapeseed production is also used for animal feed (data unavailable), and a very small share is intended for human consumption.
- **Fibre crops** are, according to available data, entirely allocated to industrial uses.
- **Agro-industrial crops** (such as sugar beets, potatoes, and chicory) are processed into products and by-products for human consumption, animal feed, fertilisation, chemicals, or biogas production; the specific distribution amongst these uses is unknown. Some components of these crops are returned to the soil or destroyed prior to harvest.
- **Protein crops** (including beans, peas, pulses, and other legumes) are cultivated entirely for human or animal consumption. Crop residues are generally left on the soil, and waste can be valorised through biogas production.
- No data are available regarding industrial uses of products from **nurseries, horticulture, and fruit cultivation.** However, in the latter two categories, waste can be valorised through biomethanation.

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- **Forage crops** (primarily fodder beets, silage maize, and temporary grassland) are almost entirely used for animal feed, except for a portion of maize production that is allocated to biogas production.

Forestry products, wood, and wood residues play a significant role in the bio-based economy. These materials are used in roughly equal proportions for three main applications: as sawn timber for construction and carpentry, as pulpwood for paper pulp or particleboard, and as wood fuel.

Animal agriculture is primarily directed toward the food industry, though certain slaughter by-products—such as leather, wool, and slaughter waste—are also utilized within the processing sector (the extent of this use is not quantified). Additionally, a small portion of slurry is used in the production of biogas.

Furthermore, **waste from the food industry, households, and sewage sludge** is also partially used for biogas production, contributing to the circular use of organic materials within the bioeconomy.

Future biomass feedstock demand (2050)

The demand for biomass is expected to rise significantly by 2050, despite a substantial decrease in overall raw material demand.

This chapter is the result of a prospective scenario-analysis with the ambition to attain climate neutrality by 2050. For this it is essential to deploy both new technologies and adopt new patterns of consumption and production. Below the conclusions in view of the 'CORE-95' scenario are discussed. In this scenario three key trends are considered:

a) **Reduction in energy demand**: Compared to the 'Business-As-Usual' (BAU) scenario in 2050, final energy demand decreases by 57% in the 'CORE-95' scenario. In addition, fossil fuels are phased out, primarily through electrification, a generation system based almost entirely on renewable energy sources, and the use of climate-neutral fuels.
b) **Shift in consumption and production patterns**: The 'CORE-95' scenario projects a 44% decrease in raw material demand compared to the BAU scenario. This is attributed to significant shifts, particularly driven by the collaborative and functional economy, resulting in adjustments in mobility, housing, food, and waste consumption patterns. On the production side, more efficient resource use and a transition to different types of raw materials also contribute to reduced demand.
c) **Transformation of the agricultural production model**: At the agricultural level, changes in dietary habits lead to changes in land use. Agricultural land is freed up, which—depending on policy choices—can be repurposed to enhance carbon sequestration and biodiversity. This land may be converted into natural grasslands, forests, or non-food agricultural land (especially for biomass production). Dietary changes include reduced caloric intake, less food waste, and lower meat consumption. On the production side, the use of chemical pesticides and synthetic fertilizers is significantly reduced or eliminated altogether. Moreover, land management is reorganized to further cut emissions.

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In the 'CORE-95' scenario, along with supporting assumptions, the potential **demand for biomass** within the bio-based economy in Belgium is projected to reach approximately **290% of 2018 levels by 2050** (see Figure 9)[443]. Depending on assumptions regarding the use of bioenergy in industry and maritime transport, this demand could range from 260% to 430%. Despite a substantial decline in overall raw material demand and a strategic focus on reserving bioenergy for hard-to-electrify applications, biomass demand is expected to rise significantly by 2050.

Biomass has considerable potential to support Belgium's transition to climate neutrality, particularly in the chemical, construction, packaging, and textile sectors, where products derived from fossil fuels or with high greenhouse gas emissions can be replaced with bio-based alternatives. When produced and consumed sustainably—where biomass regeneration meets or exceeds harvest levels—bio-based products can offer a significantly lower carbon footprint than their conventional counterparts.

The projected trends for biomass demand are described in two main categories: biomaterials and bioenergy.

Demand for biomaterials - Although changes in collective and individual behaviour help reduce total raw material demand, bio-based materials become increasingly important in sectors replacing emission-intensive or fossil-based feedstocks:

- **Paper and cardboard**: Demand for new biomass in the paper industry is expected to decline by 27% by 2050, driven by population trends, substitution of plastic with cardboard packaging, and an increase in recycled biomass use.
- **Buildings**: Biomass plays a central role in decarbonizing construction. Demand is projected to rise by +700% by 2050 compared to 2018. By then, 40% of cement and 20% of steel in building structures will be replaced with wood. Insulation and cladding will be entirely bio-based.
- **Textiles:** Demand is expected to decrease by 13% compared to 2018. This is due to the replacement of 80% of synthetic textiles with bio-based alternatives (e.g. linen), 67% recycling rate, and significant behavioural shifts that reduce overall textile consumption.
- **Chemicals:** By 2050, 100% of fossil fuel demand in the chemical sector (compared to 2018) is expected to be replaced with biomass. Key chemical building blocks such as ethylene, propylene, methanol, and chlorine could all be derived from biomass. For example, wood can substitute petroleum derivatives in producing methanol and chlorine, while grains and sugar beets are used to produce ethanol, which can then be transformed into ethylene and propylene.

[443] Bouwsector (grondstoffen) → Construction sector (materials), Overig timmerhout (grondstoffen) → Other sawn timber (materials), Pulp hout, papier (grondstoffen) → Pulpwood, paper (materials), Textiel (grondstoffen) → Textiles (materials), Chemie (grondstoffen) → Chemicals (materials), Biogas (energie) → Biogas (energy), Biobrandstoffen (energie) → Biofuels (energy), Vaste biomassa (energie) → Solid biomass (energy)

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Demand for bioenergy - Behavioural and technological changes are expected to reduce final energy demand from 500 TWh in 2018 to 225 TWh by 2050. Bioenergy will serve part of this demand, particularly for applications that are difficult to decarbonize:

- Biogas: Demand is expected to increase by +333% by 2050.
- Biofuels: Demand is expected to grow by +90% by 2050.
- Solid biomass: Demand will decline by 58% by 2050 compared to 2018.

These projections underscore the strategic importance of sustainable biomass as both a material and energy source in Belgium's climate-neutral future.

Future biomass feedstock supply (2050)

The total supply of biomass (both food and non-food) is expected to stabilise or even decline between now and 2050 in scenarios aimed at achieving climate neutrality. The biomass supply for the bio-based economy will primarily come from forests, by-products and residues from food production, specially cultivated crops, excess grass from pastures, green spaces, and waste from the food industry. Thus, the development of the bioeconomy generally does not come at the expense of food production.

The land required for livestock production will shrink, making room for an expansion of grasslands and forests, which will provide ecosystem services, including carbon sequestration. The area dedicated to non-food crops will increase, enabling the cultivation of specialised crops for the bioeconomy.

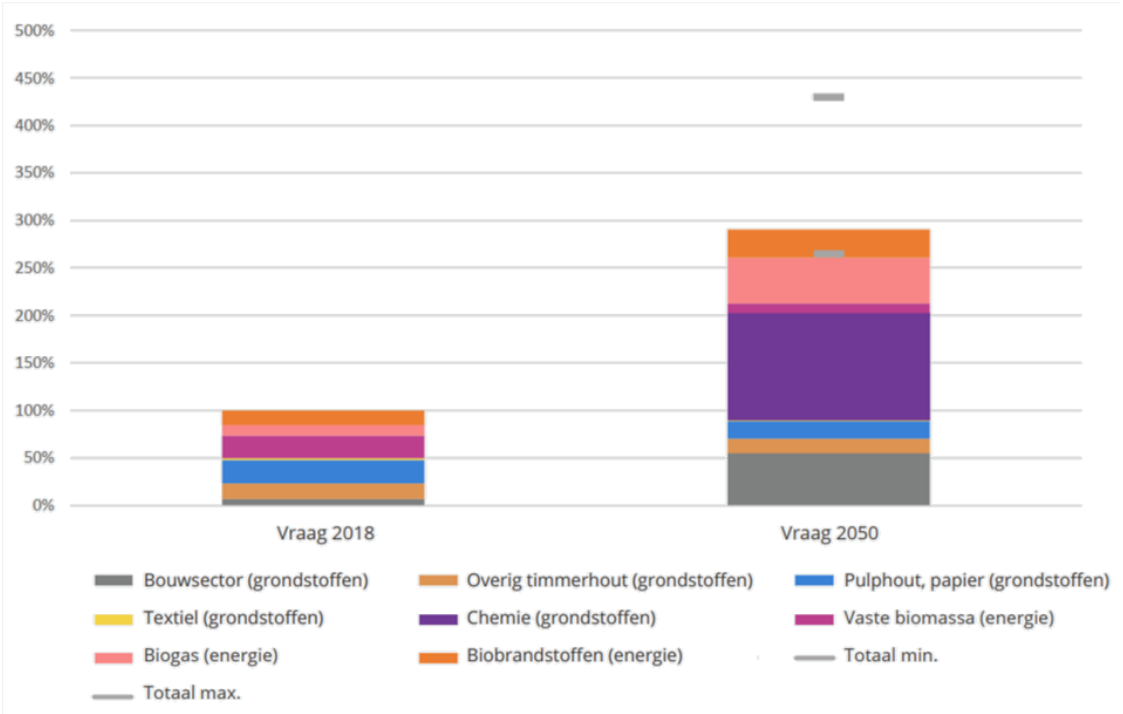


Figure 9 – Biomass demand in Bio-Based Economy (Materials & Energy) in 2018 and 2050.

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Expected trends in biomass supply:

- A decline in the production of by-products and residues from food production.
- An increase in biomass production from non-food crops.
- A slight increase in grass production.
- A potential rise in forest biomass after 2050, due to the temporal nature of forest growth cycles.

In Belgium, the development of the bioeconomy is constrained by the need to preserve and expand natural carbon sinks. Given the long timelines of forest production, the availability of forest biomass is likely to increase after 2050.

Emerging feedstocks through the Bioeconomy survey Flanders

Recently, ANB and B2BE Facilitator, in collaboration with the EFI, organised an online survey on the bioeconomy in Flanders. The survey was widely distributed to bioeconomy stakeholders and completed by 111 respondents, of whom 56% were government-related, 21% from industry, and 23% other stakeholders. The survey yielded several interesting insights.

The 8 most promising streams for the bioeconomy in Flanders, according to the respondents, are:

1. Residual streams from the agri-food chain.
2. Fibre-rich crops such as hemp, flax, miscanthus, bamboo, reed, and Japanese knotweed.
3. Protein-rich crops, including edamame, dry beans, lentils, grain sorghum, quinoa, soy, field peas, forage sorghum, and chickpeas.
4. Production of biological materials from waste streams, such as CO_2, grey water, and waste gases.
5. Biomass from small landscape elements (e.g., hedgerows, woody field margins, etc.).
6. Residual streams from local wood processing.
7. Locally sourced wood for material applications.
8. Short-rotation coppice wood.

- *Potential bioeconomy value chains*

Based on previous bioeconomy monitoring studies and surveys the Bioeconomy Work Agenda (2023) highlights the following value chains:

- Industrial crops – focus on fibres
- Crop residues
- Wet residual streams and manure
- Residual streams from the food industry

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- Regional residual streams from landscape management and organic household waste
- Woody streams
- New bio-based raw materials

An in-depth SWOT analysis has been conducted for each value chain. To maintain clarity and conciseness in this section, these individual analyses are not included here.

3.1.3.6 Bulgaria[444] [445] [446] [447] [448]

Bulgaria possesses a diverse biomass feedstock base, including agricultural residues, forestry biomass, municipal waste, and dedicated energy crops. The total available residual biomass is estimated at approximately 5.2 million tons per year, while other studies suggest a potential of 6.7 million tons, reflecting variations in yield assumptions and collection efficiencies. Despite this significant availability, underdeveloped infrastructure, inefficient collection systems and weak policy incentives hinder the full utilisation of these resources. The country has yet to implement a well-integrated biomass supply chain, leading to substantial losses in potential feedstock that could otherwise support the growing bioeconomy.

Forest Biomass

Forests cover approximately 37% of Bulgaria's total land area, making them a vital resource for biomass production. However, most of this biomass is used in traditional applications, with over three million tons of firewood burned annually for household heating. The efficiency of this utilisation remains low, with heating systems frequently operating at an efficiency rate below 40 per cent. The Executive Forest Agency estimates that the energy potential of wood biomass could reach 5.5 million tons by 2025 if modern forestry management techniques and sustainable harvesting methods were applied. However, the sector faces ongoing challenges, including illegal logging, inefficient use of forestry residues, and a lack of advanced wood-processing facilities. Although sawdust, bark and small branches could be used to produce biogas or high-value bio-based products, they remain largely unexploited. The high reliance on traditional firewood in rural areas is a key factor in the exacerbation of inefficiencies. Further investment in pellet and wood chip production, alongside the

[444] Kaneva, K., et al. Executive summary of the strategic concept paper for bioeconomy: Bulgaria (2023) BIOEASTsUP H2020 Project

[445] Republic of Bulgaria, Ministry of Energy & Ministry of the Environment and Water. (2021). Integrated Energy and Climate Plan of the Republic of Bulgaria 2021–2030

[446] Adjarova, L., et al., National Bioeconomy Dossier: Bulgaria. WWF Bulgaria (2020) Bio-Based Industries Joint Undertaking (BBI-JU), Horizon 2020

[447] Kotseva-Tikova, M., Benefitting from the development of the bioeconomy: the case of Bulgaria. Regional Formation and Development Studies, 38(3) (2022) 25-33. **https://doi.org/10.15181/rfds.v38i3.2442**

[448] Bulgarian Industrial Association, Thracian University, & Stakeholders Working Group of Stara Zagora Region. Strategy for Development of the Bioeconomy in Stara Zagora Region (2021). BE-Rural, Horizon 2020

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establishment of lignocellulosic biorefineries, could significantly enhance the value derived from forestry biomass.

Agricultural Biomass

Bulgaria's agricultural sector generates a significant amount of crop residues, yet only a small proportion of these is currently being effectively valorised. The estimated annual residual biomass from agriculture is approximately 2.2 million tons, including straw from wheat, barley, and maize, as well as residues from sunflower, rapeseed, and orchard pruning's. At present, most of these residues are utilised for animal bedding, composting and small-scale bioenergy production, with large volumes remaining unutilised or being incinerated, contributing to air pollution and environmental degradation. While there is growing interest in utilising these residues for biogas production, biofuels and bio-based chemicals, logistical constraints and a lack of biomass aggregation centres continue to pose challenges. The development of a network of collection hubs and bioprocessing facilities could significantly enhance the efficiency of agricultural biomass valorisation, supporting the transition to a circular bioeconomy. However, the incentives for farmers to participate in biomass collection schemes remain limited, slowing progress towards large-scale adoption.

Waste Biomass

Waste management inefficiencies continue to represent a significant barrier to biomass valorisation in Bulgaria. The country has one of the lowest rates of municipal solid waste separation in the European Union, with only 4.8 percent of municipal waste being collected separately. Nevertheless, industrial waste streams from the food processing sector, paper mills, and other agro-industrial activities present substantial opportunities for bioeconomic applications. Bulgaria generates approximately 3.08 million tons of municipal waste per year, with industrial waste accounting for an additional 108 million tons. Despite this, the country has only twenty-one biogas plants, most of which rely on agricultural waste, with very few processing municipal or industrial organic waste. Furthermore, there are currently no operational biomethane production facilities, underscoring a significant gap in Bulgaria's capacity to integrate biogas into its national energy mix. Expanding anaerobic digestion infrastructure and improving waste separation policies could provide viable solutions for increasing the efficiency of utilising biomass waste.

Energy Crops and Emerging Feedstocks

Bulgaria has considerable potential for cultivating dedicated energy crops, particularly on underutilised agricultural land. The country has over 509,000 hectares of land available for biofuel feedstock production, and several crops have been identified as promising candidates for biomass generation. Miscanthus and switchgrass have been extensively studied for their potential to supply bioenergy due to their high biomass yields, low input requirements, and adaptability to marginal lands. Pilot projects have demonstrated the viability of these processes for biomass combustion, bioethanol production, and bioplastic applications. However, large-scale adoption remains limited. The absence of strong market incentives, coupled with a lack of dedicated processing infrastructure, has slowed the expansion of these crops into mainstream agricultural systems.

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Another emerging sector that holds potential for Bulgaria's bioeconomy is industrial hemp cultivation. Hemp is a versatile crop that can be used in bioplastics, textiles, biofuels and construction materials, offering a renewable alternative to fossil-based products. Bulgaria has initiated the expansion of its hemp cultivation areas, however, regulatory challenges pertaining to THC content and the absence of processing facilities continue to impede industry growth. Investment in fibre extraction and bio-based plastic processing facilities would allow hemp to play a more significant role in Bulgaria's transition to a bio-based economy.

In addition to energy crops, Bulgaria is exploring alternative biomass sources, including non-traditional oilseed crops, medicinal and aromatic plants, and forestry by-products. The country is already one of Europe's largest producers of lavender and rose oil, with thousands of tons exported annually for use in the pharmaceutical and cosmetics industries. These aromatic plants offer additional possibilities for bio-based product development, such as biodegradable packaging materials and high-value biochemical extraction. Furthermore, agro-industrial by-products, such as sunflower husks from oil production and grape pomace from wineries, represent untapped resources that could be converted into biofuels, biochar, or high-value food additives. However, the potential of these feedstocks remains largely untapped due to insufficient biorefining capacity and a lack of coordination between agricultural producers and the bio-based industry.

3.1.3.7 Croatia[449] [450] [451] [452] [453] [454] [455]

Croatia is experiencing numerous supply-side constraints in relation to emerging bioeconomy feedstocks, including **oil crops, algae and lignocellulosic biomass**. Despite the country's significant biomass potential, the commercialisation of alternative bio-based raw materials is hindered by infrastructure limitations, weak market demand and lack of technological advancement.

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Limited Cultivation and Production Capacities

The development of alternative bio-based feedstocks, such as algae, oil crops and lignocellulosic biomass, is in its early stages in Croatia. The country lacks large-scale algae cultivation infrastructure, and there are no industrial-scale biorefineries dedicated to processing algae into biofuels, bioplastics, or bio-based chemicals. In a similar vein, the production of oil crops continues to be underdeveloped. This is due to several factors, including fragmented of agricultural land ownership, outdated farming techniques and inadequate irrigation systems. Lignocellulosic biomass, derived from forestry and agricultural residues, is largely exported as raw material instead of being processed domestically into high-value bio-based products.

Lack of Infrastructure and Processing Facilities

Infrastructure gaps present a major constraint to the utilisation of emerging bio-based feedstocks in Croatia. The country lacks:

- Industrial-scale algae processing plants to support biofuel and biochemical production.
- Efficient logistics and storage facilities for oil crops, leading to post-harvest losses and quality degradation.
- Advanced biorefineries for lignocellulosic biomass, preventing the domestic production of second-generation biofuels and bio-based chemicals.
- Specialised transportation networks to handle perishable or volatile bio-based feedstocks effectively.

Market and Investment Barriers

The limited demand for emerging bio-based feedstocks in Croatia is driven by two key factors. Firstly, there is limited market integration, and secondly, the costs of bio-based products are high in comparison to fossil-based alternatives. Investment in algae-based products, oil crops, and lignocellulosic materials remains low due to:

- High costs of production compared to imported bio-based feedstocks.
- Weak private-sector engagement in bio-based industries, particularly in niche markets like algae biofuels.
- Limited policy support in the form of subsidies or investment incentives for alternative feedstock development.

In order to overcome these barriers, Croatia must prioritise investment in bioeconomy infrastructure, improve coordination between research and industry, and enhance regulatory support for alternative feedstock markets.

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3.1.3.8 Cyprus[456] [457] [458] [459] [460] [461] [462]

Cyprus has a diverse but underutilised biomass feedstock base, consisting mainly of agricultural residues, biodegradable municipal waste, industrial by-products, and limited forestry biomass. Despite these resources, the country's bioeconomy is still in its early development phase, largely due to land constraints, water scarcity and limited processing infrastructure. The island also faces high logistical costs for biomass collection, transportation, and processing, which hinder the large-scale deployment of bio-based industries. However, with targeted policy support, investments in circular economy infrastructure, and research on alternative feedstocks, Cyprus has the potential to develop a more integrated and competitive bioeconomy.

Agricultural Biomass

Agriculture in Cyprus generates a significant amount of biomass waste, primarily from vineyards, citrus and olive groves, and cereal production. The estimated annual biomass yield from these sources is substantial, with fruit-bearing trees producing 0.434 t/decare/year, citrus trees 0.319 t/decare/year, vineyards 0.497 t/decare/year, and olive trees 0.282 t/decare/year. These agricultural residues, while abundant, are currently underutilised or burned due to the lack of a structured biomass collection network. Current agricultural waste management systems primarily focus on animal feed and composting, but there is great potential for biochar production, biofuels, and biochemical extraction. Expanding biorefinery infrastructure could improve the valorisation of olive mill wastewater, winery residues, and cereal straw into bio-based chemicals, fertilisers, and bioenergy. Nevertheless, the restricted number of processing facilities and the considerable investment costs continue to present a challenge.

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Waste Biomass – Organic Fraction of Municipal solid waste (OFMSW)

OFMSW in Cyprus is a significant source of biodegradable biomass, with an estimated 9.2 million tonnes of organic waste produced annually from food processing, household waste, and livestock manure. This represents a significant opportunity for the increased production of biogas and bio-based materials. While Cyprus has implemented anaerobic digestion plants for biogas production, the sector remains underdeveloped due to inefficient waste collection, high operational costs, and a lack of public awareness regarding waste separation and valorisation. The integration of biodegradable waste into circular economy strategies could be a valuable initiative, with the potential to support the production of bio-based fertilisers, biofuels and compost. However, logistical challenges, such as inefficiencies in waste segregation and limited infrastructure for large-scale waste processing, must first be addressed if the economic and environmental benefits of biomass valorisation are to be maximised.

Forestry Biomass

The potential for forestry biomass in Cyprus is restricted by two key factors: the island's low forest coverage and its strict conservation policies. While thinning operations, sawmill residues, and forest maintenance activities generate some biomass, the overall supply remains insufficient for large-scale industrial applications. The primary sources of forestry biomass in Cyprus include pruning and thinning residues, sawmill by-products such as wood chips and bark, and deadwood from fire-prevention clearings. While some of this material is used for wood pellet production and local heating applications, the lack of large-scale forestry-based bioeconomy industries limits its broader potential. Cyprus has the potential to enhance the valorisation of biomass from forestry waste by integrating it into biogas production, sustainable construction materials, and biochar production. However, key limitations persist, including conservation priorities and the small-scale nature of the sector.

Energy Crops Biomass

The cultivation of dedicated energy crops in Cyprus is constrained by land and water availability, with only 2.62% of the total land area (24,207 ha) considered suitable for energy crop production. The island's limited water resources, competing land-use priorities, and high production costs are the main factors contributing to this challenge. Economic factors further challenge the cultivation of energy crops in Cyprus. The cost of production is significantly higher than that of fossil fuel alternatives, which makes the sector less attractive for investment. However, research has identified certain drought-resistant species with potential for limited-scale bioenergy production, including *Arundo donax* (giant reed), *Cynara cardunculus* (cardoon) and *Eucalyptus spp.*, all of which can be grown in marginal lands with minimal irrigation requirements. The introduction of policy incentives to support the cultivation of these species for bioenergy and biochemical extraction could enable Cyprus to gradually expand its domestic feedstock supply without compromising food security.

Emerging Feedstocks in Cyprus for Developing the Bioeconomy

- Industrial By-Products and Waste Valorisation

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Industrial by-products represent a significant and largely untapped feedstock for Cyprus' bioeconomy. Breweries, wineries and food processing industries generate significant quantities of organic residues, much of which is currently being discarded or utilised for low-value applications. For instance, brewery waste (spent grains) is rich in nutrients and can be repurposed for biogas production or bioethanol extraction, while olive mill wastewater, which is typically a major pollutant, could be processed into bio-based chemicals and fertilisers. Winery residues, notably grape pomace, are a valuable source of polyphenols and fibres, making them suitable for use in cosmetics, pharmaceuticals and biobased packaging material. However, the lack of integrated waste management systems, processing infrastructure, and financial incentives currently limits the commercial-scale valorisation of these by-products.

- Algae Biomass (Microalgae & Macroalgae)

Microalgae and macroalgae are becoming increasingly important as high-yield biomass sources for biofuels, animal feed and biochemicals. Their fast growth rates, ability to thrive in non-arable land, and capacity to absorb CO_2 from industrial emissions make them an attractive biofuel source for a sustainable bioeconomy. Several pilot-scale projects in Cyprus are investigating the potential of algae for biodiesel and bio-based chemical production. However, high production costs, limited commercial-scale facilities, and the need for advanced bioreactor technologies are key barriers to widespread commercialisation. Investment in algae-based biorefining technologies, particularly CO_2-enhanced algae cultivation using industrial plant emissions, has the potential to significantly improve the feasibility of algae biomass as a bioeconomy feedstock.

- Invasive Plant Species & Marginal Land Crops

Invasive and drought-resistant plant species are being explored for bio-based applications, particularly those that can thrive in Cyprus' arid climate. It has been determined that certain invasive species, including Acacia spp. and Ailanthus altissima (also known as tree of heaven), have the potential to be sources of biochar and wood-based bioproducts. Other species, such as *Ricinus communis* (castor plant), offer biochemical applications for bio-based lubricants, pharmaceuticals and biodegradable plastics. In addition, research is being conducted on *Ceratonia siliqua* (carob trees) for their potential in biochemical extraction and bio-based polymer development, following their long-standing use in food and livestock feed production. While these species provide valuable feedstock potential, their integration into the bioeconomy requires careful resource management, market development, and technological improvements in biomass processing.

- Circular Economy Feedstocks

Cyprus is making progress in utilising biodegradable waste to produce high-value bioproducts. This is achieved through initiatives such as the processing of organic fraction of municipal organic waste for compost and biogas, as well as the repurposing of brewery waste and coffee grounds for biochar and biofuels. Furthermore, opportunities are being explored in the use of dairy waste (whey) and meat-processing byproducts to produce biochemicals and protein-based biomaterials. To maximise feedstock efficiency and reduce waste in Cyprus' bioeconomy, it is essential that investment in

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biorefinery technologies is expanded, and that financial incentives are created for industries to integrate circular economy principles.

3.1.3.9 Czechia[463] [464] [465] [466] [467] [468]

The Czech Republic is actively formulating bioeconomy strategies that prioritise sustainable agriculture, forestry and waste management. The Ministry of Agriculture's approach emphasises the importance of using secondary raw materials and waste from the food industry, promoting edible packaging and integrating biotechnologies to improve resource efficiency. Research institutions, such as the Research Centre for Bioeconomics and Low-Carbon Economy, contribute by developing innovations for sustainable use of bioresources and reduction of carbon footprint. Their work covers bioenergy, bioproducts and sustainable agricultural practices, and fosters collaboration between academia, industry and government. The Czech Republic has a wide range of biomass resources that drive its bioeconomy. Biomass plays an important role in the renewable energy sector, bio-based industries and in circular economy measures. Most of the Czech Republic's biomass sources come from forests, agriculture, organic waste and specialised energy crops. The map above shows the main sources of biomass in the Czech Republic.

Forest Biomass

With forests covering approximately 34% of the Czech Republic's territory, forestry is a major source of biomass. Czech forests are affected by bark beetle infestation, and the damaged wood is now more readily available for use as biomass. Overharvesting of forest biomass would have an impact on carbon storage and biodiversity. For long-term sustainability, higher rates of biomass harvesting are needed. The main types of forest biomass are:

- Wood Residues: Sawdust, bark, wood chips, and offcuts from sawmills and the wood industry.
- Logging Residues: Tops, branches, and non-commercial wood residue left over from harvest operations.
- Forest Thinning: Small trees removed for forest management to enhance wood production.

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Agricultural Biomass

Agriculture is a significant source of biomass, primarily in the form of crop and animal production residues. Czech farming generates significant quantities of crop residues, much of which are currently unused or returned to the soil. It is imperative to effectively manage the interplay between bioenergy and soil quality, given that excessive residue removal can adversely impact soil fertility. In order to maximise the use of manure, it is essential that there is increased investment in biogas equipment. Key biomass sources include:

- Cereal Straw: Wheat, barley, rye, and oat crop straw.
- Corn Stover: Maize stalks and leaves.
- Rapeseed Residues: Residues from processing rapeseed (for biofuels production).
- Livestock Manure: Valuable feedstock for anaerobic digester biogas production.

Waste Biomass

Domestic, food, and industrial organic waste represents an untapped source of biomass in the Czech Republic. The waste-to-energy sector is expanding, with an increasing focus on biogas and biomethane generation. Improved waste collection and separation procedures are required to sort even more biodegradable waste for energetic use. The potential of the circular economy can be realised through the utilisation of policy incentives to develop bio-based materials from waste. The following types of waste biomass are included:

- MSW: Domestic and food organic waste.
- Industrial Organic Waste: Brewery, food processing, and paper mill organic waste.
- Sewage Sludge: Biomass from sewage treatment plants, used in biogas generation.

Energy Crops Biomass

There is suitable land in the Czech Republic for growing dedicated energy crops for bioenergy and bio-based products. The availability of land is not straightforward due to the pre-eminence of agricultural use. The economic viability of energy crops is contingent on medium- and long-term policy support and market demand. It is essential that investment in second-generation biofuels from energy crops is increased. Key crops are:

- Miscanthus: High biomass-yielding perennial grass, used for biofuels and bioproducts.
- Willow and Poplar: Coppice wood biomass-producing fast-growing trees, utilized for short-rotation coppicing to produce wood biomass for energy.
- Sorghum and Hemp: Emerging crops with potential to produce biofuels and bioplastics.

Emerging Feedstocks in the Czech Republic for Developing the Bioeconomy

- Industrial Hemp and Other Niche Crops: this is a standard practice that involves minimal input and facilitates carbon sequestration. It is also a valuable component of crop rotation systems. This is a fast-growing crop with a variety of applications:
    - Fibres for bioplastics and textiles.
    - Hurds for construction (hempcrete).

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- Seeds/oil for cosmetics and food.

- Algae and Microbial Biomass (Early-Stage): despite the challenges posed by costs and scalability, there is ongoing exploration of algae by universities and biotech start-ups in the experimental/pilot stages, and in the context of:
  - Biofuels
  - Protein-rich animal feed
  - Natural pigments and nutraceuticals

3.1.3.10 Estonia[469] [470] [471] [472] [473] [474] [475] [476] [477] [478] [479] [480] [481] [482] [483]

Estonia's biomass resources are dominated by forestry, which covers approximately 52% of its territory (2.3 million hectares with a total growing stock of 481 million m^3 in 2014) and around a third of the country being arable land, So, 73,2% of Estonia's land area (3.32 million hectares) is used for

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wood and agricultural biomass production. Despite this, the country still faces economic and structural challenges in optimising feedstock availability.

Forestry-based Biomass

Forestry stands as a cornerstone of Estonia's bioeconomy. The most common tree stands are pine (31%), birch (29%), and spruce (19%). Wood-based value chains substantially contribute to the country's bio-based economy, accounting for roughly €2.5 billion of production annually (in 2016). The sector also significantly valorises residues and by-products. However, it is noted that less than 10% of timber undergoes chemical processing in Estonia, compared to about 40% in Finland, indicating a potential for greater valorisation beyond mechanical processing and energy production. Key challenges include:

- Export dependency: approximately 40% of forestry biomass products (e.g., pellets) are exported, reducing domestic availability.
- Underutilised residues: annual lignocellulosic biomass potential reaches 3.65 million dry tonnes (excluding primary harvest) yet logging residues and low-grade hardwoods remain underexploited for biochemicals or bio-based materials.
- Sustainability pressures: EU bans on Russian wood imports may increase demand for Estonian biomass, risking price inflation and overharvesting without robust sustainability criteria.

Agriculture-based biomass

Agriculture also plays a vital role, focusing on cultivating cereals, oilseeds, and biomass for renewable energy. The main agricultural production includes cereals (wheat and barley), with annual production ranging from 900,000 to 1,600,000 tonnes. Despite limited data exists, sludges and effluents from agriculture are identified as underused feedstocks. Plant biomass, mainly used as cattle feed, amounts from 3,200,000 to 4,300,000 tonnes annually, supporting significant milk and meat production. Other key agricultural products include oleaginous seeds and fruits, dry pulses, rape and turnip rape, amongst others. Animal dejections from the primary sector are a significant residual biomass stream, estimated at 85,000 tonnes per year, but systemic collection infrastructure is lacking. Similarly, national statistics on accompanying residues like straw, plant residues, and animal skins are lacking. Additionally, there are opportunities for valorising horticultural waste such as biodegradable mulches or bioactives, which remain untapped due to fragmented farm sizes and low valorisation awareness.

Food processing and Industrial waste biomass

Estonia's industrial sectors generate substantial residual streams and waste. Wood residues from the wood industry (e.g., sawdust, bark) are the most abundant, estimated at 450,000 tonnes/year, being underutilised for high-value applications like lignin extraction. Other important residual streams include effluents from the pulp and paper industry, and the organic fraction of municipal solid waste. Precise data on waste generation and management are not available across all industrial sectors, where whey and slaughterhouse by-products lack integration into bio-based supply chains (e.g., bioplastics or animal feed alternatives). Additionally, the organic fractions of municipal solid waste

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are rarely segregated for bioenergy or composting, indicating the opportunities to valorise underused waste

Economic barriers

Despite the availability of various biomass sources, several supply-side barriers impede their full utilisation. A significant bottleneck in Estonia's bioeconomy is the low added value, with a high share of exports being unprocessed or low-processed products. The ability of the Estonian bioeconomy to create added value per employee has been approximately one-third below the EU average. For instance, in 2019, the value added per employee in the food sector in the EU averaged €45,500 compared to €27,900 in Estonia. Despite projects like Fibenol's lignin-based biorefinery, most biomass is used for low-value energy-generation. Small volumes of bioresources, due to the export of 90% of wooden house compounds as raw materials missing value-added opportunities, and the logistics costs arising from collecting and transporting disperse biomass impose restrictions on the centralised processing and application of various technologies and economic viability. The business sector's modest capacity to spend on R&D initiatives limits opportunities for introducing new technologies and product development. While Estonia is well-placed to export food products, achieving competitiveness requires creating higher-value products.

Technical and structural barriers

There is a lack of comprehensive planning for the circular bioeconomy and industries with a wider scope, hindering the development of value chains. Additionally, the existing regulatory gaps result in lacking a harmonised methodology for calculating sustainable biomass availability or enforcing sustainability criteria. Insufficient cooperation that supports the growth of added value is also a barrier. While the timber industry is relatively traditional, focusing on mechanical processing, there is a need to significantly increase the valorisation of resources produced in agriculture, particularly cereals and raw milk, beyond basic food and feed. The lack of comprehensive data on accompanying agricultural residues and specific biowaste streams makes it difficult to plan for their effective utilisation. Furthermore, at different levels of education, insufficient attention is paid to the transfer of knowledge regarding the circular bioeconomy and related R&D and innovation capacity, leading to a lack knowledge of bio-based opportunities (particularly for marine biomass such as red seaweed) and a lack of specialists who can link existing bioresources to different processing methods and bioproducts. The abovementioned modest capacity of the business sector draws weak collaboration between SMEs, academia and industries, presenting a fragmented innovation and slow technology transfer.

Emerging feedstocks in Estonia

Several emerging feedstocks hold potential for Estonia's bioeconomy. There is growing interest in the use of biowaste and byproducts, which is not yet widespread.

Algae and shellfish cultivation and processing technologies are being considered for nutrient removal from the Baltic Sea and valorisation of inland water bioresources, especially red seaweed, which has been identified as a priority in the BioBaltic project with a high potential for bioactive compounds and biodegradable packaging, and microalgae, which has been untapped for biofuels or pharmaceuticals

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due to high production costs and non-commercial farms. Agricultural straw is identified as an untapped resource, although its primary use in maintaining soil humus balance is crucial. The increased demand for protein crops and varieties suitable for organic farming presents another opportunity. Coastal waste, marine plants, beech wood, and reeds can be also mentioned as potential bioresources. For instance, beech wood is an underused material for synthesising bioplastics or coatings despite its abundance.

However, of all these emerging feedstocks, lignin is seen as a cornerstone of Estonia's bioeconomy, in line with its abundant forest resources. Lignin is being tested as a replacement for fossil-based bitumen in asphalt and as a binding agent in sustainable adhesives. Other potential application is its role to synthesise platform chemicals for drug production, such as antioxidants and UV-protective coatings. Currently, Fibenol has pioneered the production of hardwood extrusion-based lignin from plywood industry residues, converting more than 90% of the biomass into high-value products such as biochemicals, coatings, and adhesives, and expanding through its participation in various EU projects such as REYDISGN, COUNTLESS, WOODCELL or SWEETWOODS, which aimed to establish a flagship plant in Estonia for the production of high-purity lignin and platform chemicals from hardwood sugars, positioning lignin as a viable substitute for fossil-based chemicals in industries such as construction and packaging.

Valorisation pathways and recommendations

Despite Estonia being actively pursuing strategies to enhance its bioeconomy and reduce GHG emissions through innovation, sustainable resource use, and circular economy principles. However, some barriers have been identified. To address them and leverage emerging feedstocks, the following actions can be considered:

- Short-term actions

To enhance the availability of data concerning biomass and by-product generation and demand at regional and local levels, it is essential that Estonia implements measures to improve the collection and dissemination of such data. This should include the development of relevant digital platforms. Recent government directives to line ministries to store research data and results in the Estonian Research Information System (ETIS) can be used to establish a centralised database.

It is vital that Estonia promotes increased collaboration between research groups and businesses in the bioeconomy sector. The facilitation of connections between businesses, regional stakeholders, organisations, and centres with expertise in innovation development is of paramount importance.

The creation of regional biomass hubs could be a beneficial course of action for the aggregation of feedstocks, thus reducing transport costs. In addition to providing financial support for subsidising the installation and development of biogas infrastructures designed to energetically valorise manure and crop residue into useful resources, Estonia should consider measures to encourage and support the implementation of voluntary quality schemes (e.g., ISO, BRCGS) in the food sector. This would enhance competitiveness and ensure the sustainability of biomass, aligning with EU regulations on deforestation.

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- Medium-term actions

The Estonian government should develop and promote the uptake of alternative raw materials, including those from the blue economy, and novel foods. Estonia has significant potential to innovate in plant-based protein production, leveraging local crops such as oats, peas, and soya. These efforts enhance Estonia's food sector competitiveness and align with global trends to reduce reliance on animal proteins and mitigate environmental impacts. Consequently, the development and introduction of local plant-based and processed animal proteins as feed components can be crucial to reduce GHG emissions from livestock agriculture.

The development of tailored regional circular bioeconomy roadmaps based on local bioresources, community needs, and opportunities is also recommended, as well as the translation of activities into innovative local initiatives and cooperation forms. For this reason, the Circular Bioeconomy Roadmap for Estonia provides a framework for regional development by promoting collaboration amongst stakeholders from public, private, and non-profit sectors, encouraging local initiatives that add value to bioresources while fostering sustainability. Research and development, innovation, and technology transfer in key areas for increasing the added value of Estonia's bioeconomy should be supported, including in the chemical industry, the wood and paper industry, and furniture manufacturing. To this end, aligning the education system with industry needs is essential for training specialists in chemical engineering, forestry processing, marine sciences, and other bioeconomy-related fields. This ensures a skilled workforce capable of driving innovation.

The investment in modular biorefineries to decentralise the processing of forestry and agricultural residues could also facilitate this, enhancing resource efficiency and supports the valorisation of underused biomass. Within this framework, the establishment of a digital biomass marketplace to connect suppliers with bio-based industries would streamline resource allocation and drive innovation across sectors.

Another interesting approach is the strengthening of marine bioeconomy R&D through Nordic-Baltic partnerships, such as the BioBaltic project, which can unlock sustainable opportunities in aquaculture, fisheries, and marine biotechnology. Finally, the exploration of synergistic methods to use potential energy surpluses in cooperation with other sectors is also recommended, such as the cultivation of vegetables under glass in conjunction with power plants and the production of green hydrogen to enhance renewable energy infrastructure.

- Long-term actions

The potential of Estonia's bioeconomy is constrained by export-oriented raw material sales and an underdeveloped valorisation infrastructure. In order to enhance the utilization of resources beyond the export of raw materials such as cereals and raw milk, it is essential that Estonia implements comprehensive strategies that promote value-added processing. A strategic investment in large-scale biorefineries, particularly those utilising marine biomass and wood residues to produce lignin and cellulose derivatives, in conjunction with cross-sector collaborations, has the potential to establish Estonia as a significant player in the field of sustainable bio-based materials.

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The advancement of technological solutions in synthetic biotechnology, cell agriculture, hydroponics, and vertical farming, in conjunction with related ICT innovations, is imperative. The fostering of a competitive business environment that stimulates circular bioeconomy growth by encouraging private investment and active participation in EU projects and industry networks is of equal importance. Furthermore, the enhancement of knowledge transfer in the domain of circular bioeconomy-related R&D and innovation across all levels of education is poised to foster sectoral development.

It is also crucial to raise consumer awareness of the environmental impact of consumption choices and to promote low-impact bio-based alternatives. The establishment of national bioeconomy certification scheme could enhance market trust and demand, while a recognised European bioeconomy development centre would bolster R&D, attract foreign investment, and drive the export of high-value technology-intensive goods and services.

3.1.3.11 France[484] [485] [486] [487] [488]

France has a significant reservoir of biomass, with more than 389,000 agricultural holdings, extensive coastline and substantial forestry. This offers considerable potential for the development of bio-based and sustainable value chains.

The following feedstocks are available in France and are suitable for use in bioeconomy sectors:

Agriculture

- **Annual culture residue** covers approximately 50% of French arable land, amounting close to 10 million hectares. The most common are wheat, corn and barley, in order of importance. Oleaginous crops, including rapeseed, sunflower, soybean and flax, account for approximately 2 million hectares. In contrast, proteaginous crops, such as broad beans, field beans, peas and lupins, are less prevalent and cover slightly more than 210,000 hectares. Cereal, oilseed, and protein crop straw, as well as corn stover, are the residual parts of plants left after grain harvesting and constitute a valuable raw material for biorefineries. Below are approximations of the amount of these raw materials on the French territory:

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  - Oleaginous straws: 14 Mt dry matter per year.
  - Cereal straws: 50 Mt dry matter per year.
  - Corn stover: 12 Mt dry matter per year.
  - Proteaginous straws: 530 Kt dry matter per year.
  - Beet leaves: 2 Mt dry matter per year (mainly in the Northern part of France).
- **Livestock manure**: more than 40 million tonnes of manure are produced annually in France, a feedstock suitable for methanisation.
- **Agricultural and forestry crops dedicated to non-food uses**:
  - Miscanthus: 60 kt of dry matter per year.
  - Hemp: 800 kt of dry matter per year.
  - Flax: 50 kt of dry matter per year.
- **Perennial crop residues** coming essentially from the annual pruning and renewal of vines and orchards.

Forestry

Approximately 30% of the French territory is dedicated to forests, and France possesses the third largest forest massif in Europe. The most common wood species are Silver Fir, Norway Spruce, Douglas Fir, Sessile Oak, English Oak and Beech. Wood sourced from sustainably managed forests and wood residues is a key component of the French bioeconomy. The sector's value chain is amongst the most well-established in France, though there is still room for improvement.

Secondary waste streams of food industries

- By-products of the cereal industries: milling (about 1 Mt dry matter per year), semolina (about 240 kt dry matter per year), starch manufacturing (about 2 Mt dry matter per year) and malting (about 350 kt dry matter per year).
- Co-products of oilseed: rapeseed meal (about 2 Mt of gross matter), sunflower meal (about 600 kt of gross matter), soybean meal (about 500 kt of gross matter).
- Co-products of the sugar beet industry representing several Mt of gross matter per year.
- By-products of the fruit and vegetable processing industries (peas, green beans and tomatoes) for a total of about 80 kT of gross matter per year.
- Winemaking co-products representing about 2 Mt of gross matter per year and co-products of wine distilleries amounting to less than 500 kt of gross matter per year.
- Co-products of the meat industries such as animal flours and animal fats.
- Co-products of the milk industry and especially the whey rich in nutrients (about 600 Mt of dry matter per year) and skimmed milk (375 Kt of dry matter per year).
- Co-products of the fishing and aquaculture industries.
- Cider mill co-products.
- Co-products of the potatoes industry including peels and starch.

Emerging biomass

- Algal biomass

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France, its overseas territories, and its aquaculture sector have significant potential for developing strong value chains around algae. As an illustration of France's leading position in Europe, it should be noted that in 2022, France was the foremost European producer of algae and cyanobacteria, accounting for 47% of the EU's total production.

In 2021, two-thirds of macroalgae were used for human and animal food, while three-quarters of microalgae were used for cosmetics and pharmaceuticals. Spirulina is intended almost exclusively for human consumption, with three-quarters of sales made through short supply chains. R&D efforts are now focusing on biorefinery processes to enhance the recovery of diverse components from marine biomass. The development of new substances, strains and processes allows us to exploit the full potential of this biomass.

The development of the algal field in France is still dependent on the implementation of a more efficient organisational structure within the sector, the establishment of a regulatory framework that would allow for adaptation and modernisation, and the comprehensive collection of technical and economic data, amongst other challenges.

- Urban waste

While the valorisation of urban waste, such as food waste, is compulsory in France since 2020, it is primarily used for energetic purposes, such as methanisation or the production of compost. Nevertheless, food waste has the potential to be converted into higher-value-added products. In recent years, France has seen the emergence of bioconversion technologies for the exploitation of these resources, including insect farming, algae cultivation and fermentation. Several start-ups, including Mutatec, have already deployed insect farms and transformed up to 200,000 tons of biowaste per year into protein feed for aquaculture and animal feed. In Brittany, an AlgoSolis project has been testing the industrial cultivation of microalgae, partly fed with organic effluent from local agriculture. In addition, bacteria have the capacity to produce biopolymers from fermented organic waste. For instance, Dionymer is a start-up company that utilises bacteria that naturally accumulate PHA. There is significant potential for the further development of bioconversion of organic household waste in the country.

Other types of urban waste include urban and industrial effluents. Despite their high nutrient content, notably nitrogen, phosphorus and potassium, these effluents are not being used to their full potential. Whilst there are several challenges to be addressed, including the potential content of pollutants, biorefineries have the potential to treat and valorise these wastes. Existing projects remain at the research phase. The National Institute for Agriculture, Food and Energy (INRAE) has been conducting research in the field and is the lead of several initiatives, including Bio2E, to support technological innovation projects from fundamental research to demonstrator.

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3.1.3.12 Greece[489] [490] [491] [492] [493] [494] [495] [496] [497] [498] [499] [500] [501] [502] [503]

Greece has a wide range of biomass feedstock sources, including agricultural residues, forestry biomass, waste biomass and emerging bio-based materials. Despite this abundance, their utilisation remains limited due to fragmented policies, insufficient infrastructure, and a lack of strong connections between research institutions and industry. However, with growing interest in sustainable energy and circular bioeconomy practices, various regions in Greece, particularly Western Macedonia and Central Greece, are making significant strides in the valorisation of these resources.

Agricultural Biomass

Agriculture plays a critical role in the Greek bioeconomy, accounting for almost 26% of manufacturing enterprises through agri-food processing and related activities. However, significant quantities of

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agricultural residues are currently underutilised, representing a substantial untapped energy and material potential. Research indicates that Greece generates approximately 23 million tons of agricultural and agro-industrial residues per year, with significant contributions from Western Macedonia, Thessaly, and Central Greece. Cereal crop residues, including wheat, corn, and barley, are amongst the most prevalent sources of agricultural biomass. These residues are widely available in Thessaly and Central Macedonia, where intensive farming is practised, yet much of this biomass remains uncollected or burned in the fields. If utilised effectively, these residues have the potential to be converted into bioenergy, bio-based fertilisers and feedstock for biorefineries. In addition, a significant quantity of by-products from olive trees, including prunings and olive pomace, can be found in large quantities in the Peloponnese, Crete, and Central Greece. These by-products have the potential to serve as a viable raw material for the production of biofuels, biochar, and high-value biochemicals. The viticulture sector, particularly in Northern Greece and Central Macedonia, also makes a significant contribution to agricultural biomass through the generation of vineyard residues and grape pomace. At present, these by-products are largely discarded or used in low-value applications, despite their high potential for biogas production, extraction of polyphenols, and production of bioethanol. The increased use of these by-products could generate new revenue streams for wine producers and contribute to reducing the environmental impacts of waste disposal.

Forestry-Based Biomass

Even though Greece is covered in forests, covering 30% of the country's land, the forestry sector is underdeveloped, with a contribution to the national GDP of only 0.04%. This underutilisation stems from several challenges, including fragmented land ownership, outdated management practices, and a lack of investment in bio-based industries. Nevertheless, the potential of forestry biomass is considerable, especially in Western Macedonia and Epirus, where forests are plentiful. In recent years, Western Macedonia has been exploring the potential of forestry residues to produce sustainable wood-based products, bio-based chemicals, and bio-construction materials. The production of wood pellets, biochar and advanced biomaterials has the potential to modernise the region's post-lignite economy, offering an alternative to traditional fossil-fuel-based industries. Furthermore, the implementation of enhanced forest management practices, including the utilisation of logging residues and sawmill by-products, has the potential to facilitate the development of a more sustainable and circular bioeconomy.

Waste Biomass and Circular Bioeconomy Opportunities

Greece produces significant quantities of organic waste from households, industries and agricultural processing, yet biomass valorisation efforts remain relatively limited. Waste biomass represents a valuable resource for energy generation, composting, and the production of bio-based materials. However, to fully capitalise on this potential, significant investment is needed in waste management infrastructure and policy support. Municipal solid waste represents a significant source of unused biomass, particularly in urban areas such as Athens and Thessaloniki. While some municipalities have implemented composting and anaerobic digestion programmes, a significant proportion of food waste and organic matter still ends up in landfills. The expansion of biogas and composting initiatives has the potential to enhance the country's waste-to-energy capabilities and contribute to the

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generation of carbon-neutral energy. Industrial waste streams also present a valuable opportunity for the valorisation of biomass. In Thessaly and Central Greece, the dairy industry produces significant quantities of whey and organic by-products. These could be utilised for the production of biodegradable plastics, pharmaceuticals and bio-based food additives. Furthermore, food processing by-products from the fruit and vegetable industries have the potential to be used in the extraction of bioactive compounds and the production of packaging materials. A focus on scaling up biorefinery technologies and improving the logistics of waste biomass collection is essential to capitalise on these opportunities.

Energy Crops and Emerging Feedstocks

As Greece transitions towards a more sustainable and bio-based economy, alternative biomass sources such as energy crops and algae-based bioresources are gaining attention. These emerging feedstocks offer promising applications in bioenergy production, bioplastics, and pharmaceutical industries. Miscanthus and sorghum are high-yield energy crops that have shown strong potential for bioethanol and biomass pellet production in Western Macedonia. Their ability to grow on marginal lands with minimal water and fertilizer requirements makes them a sustainable alternative to traditional agricultural crops. However, the widespread adoption of dedicated energy crops requires financial incentives and improved agricultural policies to encourage farmers to integrate these crops into existing farming systems. Algae cultivation is also emerging as a potentially transformative bio-feedstock, particularly in coastal areas of the Aegean and Ionian Seas. Greece's marine biodiversity provides an opportunity for the large-scale production of algae for biofuels, bioplastics, and high-value nutraceuticals. However, the high cost of production, lack of commercial-scale algae farms, and insufficient technological investment remain key barriers to large-scale adoption. Increased research collaboration and policy-driven incentives could help scale up algae-based bioeconomy projects. Another emerging feedstock is industrial hemp (*Cannabis sativa L.*), which is gaining attention for its applications in bioplastics, textiles, and eco-friendly construction materials. While cultivation has been legalized in certain regions, regulatory challenges, processing limitations, and the need for specialized infrastructure hinder its expansion. Thrace and Northern Greece have the potential to become key hemp-producing regions if targeted investments and value-chain developments are pursued.

Key Regional Developments & Future Directions

Western Macedonia, a region with a long-standing reputation as Greece's primary lignite-based electricity-producing region, is undergoing a significant transition towards a sustainable bioeconomy. The region has historically relied on lignite for energy, accounting for over 75% of Greece's total energy production until recent years. However, with the Greek government's decision to phase out lignite by 2028, Western Macedonia is now shifting toward renewable energy sources, including biomass, bioenergy, and circular bioeconomy applications. Western Macedonia has abundant agricultural residues, which, if properly utilised, could significantly contribute to Greece's bioenergy sector. The region generates approximately 551,400 tons of crop residues per year, of which 276,201 tons are technically available for bioenergy production. The region's major crop residues include wheat, maize, barley, rye, and sunflower stalks, as well as pruning's from apple, peach, and

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vine cultivation. Wheat residues account for the largest share of agricultural biomass, with a theoretical energy potential of approximately 794 GWh per year. Maize residues also present a high energy potential of 335 GWh, while apple tree pruning, one of the most dominant residues in the region, contribute around 168 GWh. It is estimated that the total bioelectricity potential from agricultural residues in Western Macedonia could reach 216 GWh per year if fully exploited. This could meet over 50% of the region's residential electricity consumption.

Greece has a strong foundation for a sustainable and competitive bioeconomy, but investment in infrastructure, research, and policy integration is crucial for scaling up biomass utilisation. To unlock its full potential, Greece must enhance its logistics and processing capabilities for biomass, expand its circular bioeconomy applications, support novel feedstocks, and provide financial incentives for bio-based industries. It is vital that regional bioeconomy hubs are strengthened and collaboration between stakeholders encouraged if long-term success is to be ensured.

By focusing on bioenergy, waste valorisation and alternative biomass sources, Greece can position itself as a leader in sustainable bioeconomy innovation. This would reduce reliance on fossil fuels while fostering economic and environmental sustainability.

3.1.3.13 Hungary[504] [505] [506] [507] [508] [509]

Emerging feedstocks such as oil crops, algae and lignocellulosic biomass hold significant potential for the bioeconomy in Hungary. However, their uptake is hindered by several supply-side barriers, including land use constraints, technological challenges and insufficient financial support. This section identifies the key obstacles hindering the growth of these new feedstocks in Hungary.

Land Use and Availability Constraints

The availability of land for the cultivation of oil crops and other biomass sources is limited by existing agricultural priorities. In Hungary, a significant proportion of land is dedicated to traditional crops such as wheat, maize and sunflower, which dominate the agricultural landscape. The reallocation of land to produce bio-based raw materials has met with resistance due to concerns about food security and rural livelihoods. Furthermore, the European Commission (2021) has stipulated additional

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restrictions on the expansion of bio-based feedstocks in accordance with EU regulations on land use and sustainability criteria.

Climatic and Environmental Challenges

Climatic conditions have been shown to have a considerable influence on the viability of new raw materials. Hungary is prone to seasonal droughts and extreme weather events, which can reduce crop yields and biomass productivity. Oil crops such as rapeseed and soya beans require stable rainfall patterns, while the cultivation of algae depends on a controlled aquatic environment, which may not be available everywhere. The fact that certain raw materials lack climate resistance is a key factor in limiting their use on a large scale.

Technological Limitations in Feedstock Cultivation and Processing

The development of high-yielding, resistant varieties of new raw materials is ongoing. In Hungary, there is a lack of specialised breeding programmes and advanced agricultural technologies to optimise the productivity of oil crops and algae. Large-scale algae production requires bioreactors and controlled environments, which are capital-intensive and not yet widely available in Hungary. The limited availability of precision agriculture technologies has a further impact on the efficiency of feedstock production.

Infrastructure and Logistics Constraints

In order to ensure the efficient supply of new raw materials, it is essential to have in place a well-developed infrastructure for collection, storage and processing. However, Hungary faces challenges in building biorefineries and processing plants due to high capital costs and insufficient investment incentives. Transport costs for biomass are also high, which has a negative impact on the economic feasibility of widespread cultivation and processing.

Financial and Policy Barriers

Investment in new commodities is being hindered by a lack of targeted financial support and political incentives. Hungary's current subsidy programmes are biased towards traditional agriculture, resulting in limited funds available for bio-based feedstocks. The private sector is reluctant to participate in the development of alternative biomass resources due to the high initial investment costs and uncertain returns. Additionally, the unclear political framework surrounding the certification of raw materials is contributing to a climate of uncertainty amongst investors and producers.

Market Demand and Commercial Viability

Emerging raw materials are competing with conventional bio-based materials and fossil-based alternatives. The lack of strong market demand for algae-derived biofuels and bioplastics limits the incentives to expand production. Additionally, the absence of long-term procurement agreements between feedstock producers and bio-based industries contributes to market volatility, deterring farmers and investors from participating in the production of alternative feedstocks.

Hungary's emerging commodities face numerous supply-side obstacles that hinder their large-scale introduction. Overcoming land-use constraints, climatic vulnerabilities, technological limitations,

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infrastructure gaps, financial barriers and market uncertainties is crucial for increasing commodity production in the country. In order to unlock the potential of these resources, it is vital that policy interventions, increased R&D investments and private sector engagement will be given due consideration.

3.1.3.14 Italy[510 511 512 513 514 515 516 517 518 519 520 521 522 523 524 525 526 527 528]

Feedstock Availability in Italy: Mapping Key Biomass Sources

Biomass is a key component in the development of the bioeconomy. In this context, Italy, thanks to its rich biodiversity and its agricultural and forestry traditions, has a wide range of biomass that can

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be used to reduce dependence on fossil sources and encourage the transition to a low-carbon economy.

The strategic biomasses for the Italian bioeconomy are derived from the following major sectors: agrifood, forestry, bioindustry, marine bioeconomy and organic waste.

- **Agriculture:**

Agriculture is a significant sector in Italy, contributing approximately 31 billion euros to the GDP. The total agricultural area is 17.1 million hectares, of which 12.9 million are utilised. The main Italian agricultural crops are divided into tree crops (fruit trees and vineyards) and arable crops (cereals and legumes), followed by vegetables, legumes and protein crops. Here is an overview of the main agricultural crops in Italy:

  - Tree crops (orchards and vineyards):
    - Vineyards: about 700,000 hectares, with a high concentration in Piedmont, Veneto, Tuscany and Puglia, which represent the main Italian wine regions.
    - Olive groves: about 1.2 million hectares, with Apulia being the main producing region, followed by Calabria, Sicily and Tuscany.
    - Apple and pear trees: about 180,000 hectares.
    - Citrus fruits: about 200,000 hectares concentrated in Sicily, Calabria and Puglia, with Sicily being the main region for the production of oranges, lemons and mandarins.
    - Peaches and nectarines: about 40,000 hectares.
  - Cereals:
    - Soft wheat: about 1.4 million hectares.
    - Durum wheat: about 1.3 million hectares, mainly in Southern Italy.
    - Corn: about 1.0 million hectares, with a strong concentration in the northern plains.
  - Vegetables:
    - Industrial tomatoes: about 70,000 hectares in Puglia and Campania.
  - Legumes and protein crops:
    - Soybeans: about 80,000 hectares, mainly distributed in northern Italy.
    - Beans: about 30,000 hectares, with production mainly concentrated in Umbria, Lazio, Campania and Puglia.
    - Lentils: about 6,000 hectares, mainly in Umbria and Lazio.

With 910,000 people employed in agriculture, rural development is a very important priority, especially in peripheral areas, which have more difficulty accessing services of public interest than cities and smaller centres. Agriculture and forestry have significant potential in the context of the bio-based and circular economy, in terms of efficient resource management, protection of biodiversity and soil, sustainable land management, production of ecological and social services, valorisation and reuse of residues and waste, as well as in terms of production of bioenergy and organic products, through the adoption of sustainable production models and the efficient use of renewable resources.

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- **Food industry:**

The industrial sector is largely composed of very small companies (approximately 85% of companies have fewer than nine employees). However, it has demonstrated its resilience and capacity for growth during periods of economic downturn, due to its inherent structural characteristics. These characteristics are based on the success of Italian products in global markets, leveraging prestigious brands and high added value. This success can be attributed to the cultural, social and environmental values embodied by Italian products, which contribute to their recognition and protection through Geographical Indications (18% of the total product).

The Italian food industry is focused on a wide range of products, ranging from fresh to processed goods, with particular attention to typical regional products. The main products of the Italian food industry are:

- Wine

Italy is the world's leading wine producer. Italy's annual wine production is estimated to be around 47 million hectolitres (based on data from 2023), constituting a substantial segment of the nation's food industry. Exports account for approximately 20% of total production.

The primary wine-producing regions are Piedmont, Tuscany, Veneto, Sicily and Puglia.

- Pasta

Italy is the world's leading producer and exporter of pasta, with an annual output of approximately 3.5 million tonnes. Italian pasta is a leading product in the food industry, with a significant part of production destined for export (around 50%). The main producing regions are Campania, Puglia and Sicily.

- Olive oil

Italy is the world's second largest producer of olive oil after Spain, with an annual production of around 300,000 tonnes (data 2023). The main production regions are Puglia, Tuscany, Calabria and Sicily.

- Cheese:

Italy is known for its production of high-quality cheese, with an annual production of about 1.3 million tonnes of cheese (2023 data). Amongst the most representative cheeses are Parmigiano Reggiano, Grana Padano, Mozzarella di Bufala Campana and Gorgonzola.

- Bakery products (biscuits, cakes and snacks)

The bakery products industry in Italy produces around 3.2 million tonnes of bakery products every year, including biscuits, cakes and snacks, with a significant market share in exports.

- Vegetable preserves

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Italy produces around 3 million tonnes of canned vegetables, including tomatoes, vegetables in oil, and other processed vegetables. Tomatoes are the main crop used for canning, with around 70,000 hectares dedicated to this in Puglia and Campania.

- Meat and cured meats

Annual production: Italy is a major producer of meat and cured meats, with around 1.3 million tonnes of meat and cured meats processed every year, including the famous prosciutto, speck, salami, mortadella and salsiccia. The main regions producing cured meats include Emilia-Romagna, Piedmont and Tuscany.

- Coffee

Italy is one of the world's leading coffee consumers and roasters, with an annual production of 200,000 tonnes of roasted coffee. Espresso coffee is one of Italy's most exported specialities.

- Desserts and ice cream

The dessert and ice cream industry produces about 1.2 million tonnes per year. Italian ice cream, especially artisanal ice cream, is highly appreciated internationally.

- **Forestry:**

The Italian Forest area is 11 million hectares, equivalent to 37% of the total area of the national territory. The presence of the Mediterranean and the variety of the landscape, which ranges from the sea to high mountains, means that Italian forests are home to a great variety of plant ecosystems. However, there is a need for improvement in the management of forests, as well as in the accounting of ecosystem products and services. It should also be emphasised that the absorption of carbon by managed forests covers 10% of the national Kyoto target for the reduction of CO_2 emissions and that there is an active voluntary market for carbon sinks.

The wood industry is also important: more than 80, 000 companies are active in the processing sector, employing about 400,000 people, with an annual turnover of 40 billion euros, while the cellulose-based industry has an annual turnover of about 22 billion euros, more than 3,800 companies and over 20,000 employees. However, it should be noted that in such an important sector, 80% of the wood used is imported from other countries. Therefore, one of the primary objectives that the sector must set itself is to increase the degree of self-sufficiency in this area.

Solid biomass fuels including wood are the main source of renewable energy on a national scale. The bioenergy sector has also shown strong growth in recent years, becoming a very dynamic segment that includes biomass producers and traders, stove manufacturers, energy plant operators, etc., within the forest/wood sector. In addition to the wood products sector, it is also important to consider non-wood forest products and forest-related ecosystem services. The former includes a range of products such as mushrooms, truffles, herbs, cork, etc. that often have strong links to traditional knowledge, local economies and forest management practices.

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As far as ecosystem services are concerned, even if these are not, or are only marginally, included in official national accounting systems, they are increasingly recognised as an important component of forest ecosystems.

- **Marine bioeconomy:**

Italy boasts an extensive coastline of over 8,000 km, encompassing a vast maritime territory that is rich in marine resources, including food, energy and various materials. At present, activities related to the bioeconomy, such as fishing and aquaculture, the use of seaweed, microbes, enzymes, by-products and organic waste from fishing, and the processing of aquaculture products, biomonitoring and bioremediation of marine sedimentary systems, contribute approximately 15% of the turnover and jobs to the current Italian 'blue economy'. The value of the Italian 'blue economy' has been estimated at around 43 billion euros per year and 835,000 employees. Regarding employment, Italy is the second-largest European producer of fishing products and the fourth-largest producer of aquaculture products. In terms of production volume, Italy ranks eleventh for fishing and sixth for aquaculture. The quantities produced are also well below national demand, with around 75% of consumption being met by imports.

The potential for utilising aquaculture facilities for biomass production is currently underutilised but shows great promise for expansion.

- **Organic waste:**

Organic waste is an important part of the biomass available in Italy, especially in the bioeconomy, where these materials are used to produce energy, compost, biofuels and other valuable products. It is essential that these products are correctly treated and recycled. This is important not only to reduce the environmental impact, but also to stimulate the development of a circular economy.

Organic waste is a term used to describe a variety of materials, including food waste (waste from food processing activities), wet fraction of urban waste (kitchen waste, vegetable waste from gardening, etc.), agricultural residues (waste from cultivation, such as straw, marc, olive pomace), forest waste (wood, twigs, pruning), and waste from wastewater treatment (sewage sludge containing organic material).

According to data provided by ISPRA (the Italian Institute for Environmental Protection and Research), approximately 40% of municipal solid waste produced in Italy is organic. This resource can be recovered to produce compost, biogas, bioethanol and biofuels, thereby contributing to the reduction of CO_2 emissions and the transition to a low-carbon economy.

Organic waste is a key resource for the Italian bioeconomy. The valorisation of these materials is beneficial in several ways. Firstly, it reduces the amount of waste that ends up in landfills. Secondly, it contributes to reducing dependence on fossil sources, generating energy and products that are useful for other sectors.

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Supply-Side Barriers to Feedstock Utilisation

The development of Italy's bioeconomy is inevitably constrained by technical, economic and cultural limitations, which will be identified in this paragraph.

- **Economic Barriers:**

In the development of the bioeconomy, various economic factors must be taken into consideration when it comes to ensuring access to raw materials. Key amongst these are the costs of supply and logistics: the biomass present in the territory almost always has a predefined destination and the possibility of supplying it is in economic competition with existing channels. Concurrently, the financial burden of logistics is rising, largely due to escalating energy costs, particularly in scenarios where resources are limited or geographically distant from processing facilities. The strategic positioning of biorefineries near supply areas can offer cost benefits by reducing transportation expenses. However, this configuration may also present challenges, potentially competing with other local economic activities.

Another obstacle is the need for investment in research and development: it is often difficult for private companies to invest large sums of money without a guaranteed short-term economic return. Similarly, the costs of building biorefineries are often sustainable only if applied on a large scale. This should be considered a limiting economic factor for the development of the bioeconomy, thus making renewable raw materials uncompetitive compared to non-renewable sources.

Finally, it is important to consider that activities related to the bioeconomy can have significant social and environmental impacts. It is vital to methodically assess these factors to ensure that economic gains are not achieved at the expense of ecological sustainability and social well-being.

- **Technical and Structural Barriers**

The transition towards bioeconomy systems that make use of biomass requires the development and implementation of advanced technologies for the efficient conversion of biomass into finished products with high added value. However, the complexity of biotechnological processes and the need for specialised equipment represent significant challenges in this process, despite the considerable basic research supported at national and European level. In addition, there is a lack of adequate infrastructure, such as biorefineries and efficient transport networks, which limits the ability to process and distribute bio-based raw materials on a large scale.

A further structural barrier is the fragmentation of Italy's rural territory, which is characterised by small and niche productions, and related modest by-product volumes. The challenge lies in designing 'local' biorefineries on a small scale and distributed throughout the territory that can process limited quantities, and possibly not from a single input matrix.

Emerging Feedstocks in Italy

The raw materials for the development of the bioeconomy in Italy are diverse, ranging from agricultural residues to lignocellulosic biomass, and including algae and oil plants. Scientific research

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is crucial to overcome the technological and logistical challenges in the valorisation of these resources, with the aim of promoting a more circular and sustainable economy.

- **Lignocellulosic biomass**

Lignocellulosic biomass is composed of plant materials that can be used to produce second-generation biofuels, bioproducts and bioenergy. It includes agricultural residues, such as straw and pruning, and forestry resources. It is an important resource for Italy thanks to its availability, especially in rural and forest areas. The challenge is to acquire the skills to separate the various fractions in an economical and simple way in order to allocate them to different applications.

- **Algae**

The production of microalgae and macroalgae is attracting growing interest in Italy from both the research world and equipment producers. The main applications being looked at are the production of biofuels, bioplastics, vegetable proteins and other bioproducts. In Italy, research is focusing on the cultivation of marine algae, especially in Sicily and Calabria, as a source of renewable biomass, and on the production of microalgae in bioreactors using wastewater from other production processes.

- **Non-food oil plants**

Oil plants (e.g. camelina and jatropha) are promoted as raw materials for the production of vegetable oils, which can be converted into biofuels. These plants are interesting because they do not compete with food production and can grow on marginal land.

- **Insects:**

Insects, particularly black soldier flies (*Hermetia illucens*), crickets (*Acheta domesticus*) and cockroaches, are highly efficient at converting organic materials (such as food waste or agricultural waste) into proteins and fats, which can be used as food, animal feed or even for the production of bioproducts or biofuels.

Valorisation Pathways and Recommendations

- Short-Term Actions

In the short term, Italy can focus on implementing actions at a local level and optimising existing resources, exploiting technologies and resources that are already partially developed:

  - Optimisation of existing supply chains.
  - Investing in research to improve biomass management and conversion processes, starting from the plant matrices already present and widespread in the territory.
  - Encourage and support the involvement of small and medium-sized enterprises in the bioeconomy, for the adoption of green technologies.

- Medium-Term Actions

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In the medium term, Italy could focus on creating a circular bioeconomy, through the creation of new industrial supply chains and strengthening collaboration between the public and private sectors. Possible actions could be:

- Expand the production of second-generation biofuels and invest in the integration of pyrolysis and gasification technologies to obtain biofuels from agricultural and forestry residues.
- Adopt tax incentive policies for companies that invest in bioeconomic technologies and for those that promote the circular economy.
- Create ad hoc training programmes for companies and professionals involved in the bioeconomy.
- Incentivise small-scale 'local' biorefinery models that can be activated by non-industrial entities present in the territory.

- Long-Term Actions

In the long term, Italy could become a European leader in the bioeconomy, with an integrated and sustainable system that fully valorises biological resources, significantly reducing environmental impact and improving efficiency.

- Enhance the use of emerging biomass (such as algae, insects, etc.) for the production of biofuels, bioplastics and food.
- Support flagship projects for the commissioning of large-scale biorefineries with a national economic impact.

3.1.3.15 Latvia[529] [530] [531] [532] [533]

Latvia has a diverse biomass feedstock base, comprising forestry biomass, agricultural residues, bio waste and postconsumer wood, as well as dedicated perennial crops. The annual sustainable potential from forestry is estimated to be 7.72 million dry tonnes, with an estimated 2.9 million cubic metres per year of logging residues. According to BIC (2020) and Panoutsou & Singh (2016), the total amount of other sources is 4.81 million dry tonnes per year. Agriculture is responsible for the production of the largest residual streams.

[529] BEST-ACE Roadmap. (2024) BIOGAS BUSINESS ROADMAP - For bridging the market gap in Baltic Sea region. Available [online].

[530] Mapping Latvia's bio-based potential | Country-Report-Latvia-2020 | Bio-based Industries Consortium (BIC)

[531] LIBRA Latvian Bioeconomy Strategy 2030, (2018) Retrieved from https://www.zm.gov.lv/lv/media/1023/download?attachment

[532] Panoutsou, C., and Singh, A., Latvia Roadmap for lignocellulosic biomass and relevant policies for a bio-based economy in 2030. S2Biom. Available [online].

[533] RRF Latvia's recovery and resilience plan. (2025) https://commission.europa.eu/business-economy-euro/economic-recovery/recovery-and-resilience-facility/country-pages/latvias-recovery-and-resilience-plan_en#whats-in-the-plan

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Forestry-Based Biomass

According to the latest data from the Forest Resource Monitoring carried out in 2014, Latvia's total forest area is 3,260 thousand ha (more than half of the country's surface area). Of this, 1,510 thousand ha (46.3%) is state-owned, and 1,750 thousand ha (53.7%) is privately owned. The total forest stock is estimated at 668 million cubic metres, of which 355 million cubic metres are state-owned and 313 million cubic metres are privately-owned. According to BIC (2020), the most relevant tree species in Latvia are birch, pine and fir.

The growth rate of the forest stock is higher than the felling rate, indicating a steady expansion of the forest. In 2016, the total felled volume was 10.6 million cubic metres, with 48% of this volume being sourced from state-owned forests and 52% from privately-owned forests. This figure represents approximately 63% of the theoretical sustainable wood harvest per year. This indicates that an additional 7 million cubic metres of wood are theoretically available for the bioeconomy.

Agricultural-Based Biomass

In 2016, the total agricultural land area was 2.33 million ha, including both unmanaged and overgrown areas. The total utilised agricultural area is 1.93 million ha, of which 256 thousand ha remain unused. Furthermore, it should be noted that only 45% of the cultivated green mass from the 711 thousand hectares of agricultural grasslands is used for production.

Latvia's agricultural sector is predominantly focused on the production of cereals and dairy products. Cereals represent the most significant crop. In 2017, their production volume exceeded 2.5 million tonnes. It is important to note that rapeseed and potatoes also make relevant contributions to the overall value of the sector. In 2016/17, the production of potatoes and dry pulses was 4,916,000 and 1,254,000 tons, respectively. In the meat industry, pork is the largest contributor.

Aquatic biomass

Fishery activities in Latvia are mainly concentrated in the Baltic Sea and the Gulf of Riga. The recent decline in the catch of various fish species is a matter of concern. The most caught fish are herring, sprat and cod.

In 2014, the country had 160 aquaculture farms, the majority of which were small-scale. This is reflected by the production, which amounts to just 573 tonnes of fish per year.

Supply-Side Barriers to Feedstock Utilization

- **Economic Barriers**

Currently, the extraction and production of many products and other processes, installations, and infrastructure are oriented towards the use of fossil resources. Transitioning to bioresources is a complex process that requires significant financial and intellectual resources. It involves the development and acquisition of new products, installations and technologies, as well as the introduction of changes to manufacturing processes and infrastructure. Instruments that are not related to the market, but which are directed towards reducing consumption of fossil resources (including replacing them with renewable resources), are needed. Latvia is facing challenges due to

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inadequate funding for research and development, including investments from the private sector. This situation hinders the ability to address the development needs of the national economy and society, including those in the bioeconomy sectors.

- **Technical and Structural Barriers**

As stated in the Bioeconomy Strategy, the slow and fragmented development of technology transfer and innovation systems is hindering the growth of productivity and production, as well as the export of products with high added value in bioeconomy sectors.

Emerging feedstocks

It is important to note that a significant volume of residual streams and waste are currently being sent to low-value destinations. By integrating these streams into bio-based operations, their potential to be converted into applications with a higher value than their current disposal in the country could be realised. The Latvian State Forest Institute 'Silava' has provided an estimate of the quantities of agricultural residues. It is estimated that there are over 9 million tonnes of agricultural residues per year, with the majority arising from meadows and grazing, and from wheat cultivation. The corresponding number for generated municipal solid waste amounts to little over 850 thousand tonnes per year (2017).

- **Biomethane**

The Latvian Recovery and Resilience Facility specifically highlights the promotion of increased biomethane uptake. Lativa's reliance on Russian natural gas is due to the country's strategic location, with the gas grid passing through it. The Latvian Parliament is currently in the process of amending the Energy Law to incorporate provisions regarding the use of green components in fuels, such as biodiesel, and the development of gas infrastructure. These amendments aim to address the interconnection between the grid and suppliers, ensuring that suppliers are responsible for pipeline construction and grid connection expenses while retaining ownership rights over the build infrastructure. The growth in biogas production in Latvia is in line with regulatory developments, leading to an increase in production over the past year. This includes the initiation of biomethane exports to Estonia and liquefied natural gas (LNG) exports to Germany. Plans are underway to install three additional biogas plants in Latvia in 2024.

Valorisation Pathways and Recommendations

- Short-Term Actions

In order to eradicate unfair entrepreneurship in the traditional sectors of the bioeconomy, it is essential that different law enforcement authorities cooperate and form a joint action.

As per the latest recommendations, public procurements should be directed towards lower prices, as well as the priority areas for the development of the State and the latest, most efficient and most sustainable solutions.

- Mid-Term Actions

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The necessity for the efficient use of land should be emphasised when developing plans for spatial organisation. The key competitive advantage of rural territories is their land resources. In order to encourage population and employment growth in rural areas, it is recommended that the primary focus of state policy be the optimisation of land use for commercial activities.

In order to promote innovation, it is recommended that the capacity of national scientific institutions be substantially and purposefully strengthened in the production of bioeconomy products and in associated fields, e.g. technologies, packaging and design.

The current regulatory framework that hinders the rational and sustainable use of commercial forests must be revised. Appropriate amendments to the regulatory framework have the potential to increase the capital value of the forest by €440 million, and to raise its annual net potential for generating income by €12 million.

- Long-Term Actions

One of the key elements in the development of the bioeconomy is the human resources aspect. In comparison to numerous other EU countries, wages in Latvia are lower, and a significant proportion of the skilled workforce is employed outside the country. It is therefore challenging to attract and retain a skilled workforce in several sectors, including the bioeconomy sector. Attracting highly qualified teachers and creating a training infrastructure appropriate for the modern age are crucial to prepare specialists at international level in technological management and production management, as well as qualified employees.

In order to achieve the objectives of the bioeconomy strategy by 2030, investments to the tune of approximately 20 billion euros are required. A comprehensive strategy for promoting and attracting investments in the bioeconomy's development in Latvia should be formulated.

3.1.3.16 Lithuania[534]

Lithuania has a well-developed agricultural and forestry sector, providing a strong base for biomass production. However, despite the availability of feedstocks, several supply-side barriers limit their efficient utilisation and valorisation into high-value bio-based products.

Key Feedstocks in Lithuania

- **Agricultural Biomass**
  - Cereal Crops: Lithuania is a major producer of wheat, barley, and rye, generating significant amounts of straw and other agricultural residues. These by-products have potential for bioenergy, bio-based materials, and biochemical production.

[534] Vitunskienė, V., and Aleksandravičienė, A., Executive summary of the strategic concept paper for bioeconomy: Lithuania (2023) BIOEASTsUP H2020 Project

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  - Oilseeds: Rapeseed is a key crop used for vegetable oil and biofuel production, with further potential for bio-based chemical industries.
  - Dairy and Livestock Waste: Lithuania has a strong dairy industry, producing large amounts of manure and organic waste, which could be valorised through biogas and biofertilizers.
- **Forestry Biomass**
  - Forests cover approximately 33% of Lithuania's land, making forestry a crucial bioeconomic sector.
  - Wood processing and timber industries generate residues such as sawdust, bark, and wood chips, which could be used for bioenergy and advanced bio-based materials.
  - Despite a strong forestry sector, biomass utilization remains inefficient, with a significant portion exported rather than processed domestically.
- **Organic Waste and Residues**
  - Food Industry Waste: The food processing sector generates organic residues that could be repurposed for bio-based chemicals or energy.
  - Agricultural Waste: Crop residues, animal waste, and food processing by-products are underutilised, with limited circular economy initiatives in place.
- **Energy Crops and Bioenergy Feedstocks**
  - Lithuania has potential for energy crops, such as willow and miscanthus, which could be used for biofuel and bioenergy production.
  - Biogas potential: Agricultural waste, manure, and food waste could contribute to Lithuania's renewable energy mix, but biogas production remains underdeveloped.

Barriers to Feedstock Valorisation in Lithuania

- **Dominance of Primary Production with Low Valorisation:**
  - Lithuania's bioeconomy is still largely focused on primary biomass production rather than value-added processing.
  - Most agricultural and forestry biomass is exported as raw material instead of being processed domestically into high-value bio-based products.
- **Limited Biorefinery Infrastructure:**
  - The country lacks large-scale biorefineries capable of processing agricultural and forestry residues into biofuels, biochemicals, and bioplastics.
  - The bio-based chemical and material sector is underdeveloped, limiting opportunities for advanced bioeconomy industries.
- **Fragmented Biomass Supply Chains:**
  - The small-scale and decentralized nature of many Lithuanian farms makes it difficult to collect and process biomass efficiently.
  - Weak logistics and supply chain coordination hinder large-scale valorisation of bio-based feedstocks.
- **Regulatory and Policy Gaps:**

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- Lithuania lacks a comprehensive national bioeconomy strategy, leading to fragmented policies and weak support for bio-based industries.
- Insufficient government incentives for bioeconomy investments, particularly in advanced biorefineries and circular bioeconomy solutions.

Potential Valorisation Pathways

To overcome these barriers, Lithuania could adopt the following strategies:

- Developing Advanced Biorefineries: Investing in infrastructure to process agricultural and forestry residues into high-value bio-based products, such as bioplastics, biofuels, and bio-based chemicals.
- Enhancing Circular Bioeconomy Practices: Encouraging the reuse of agricultural and food industry waste in biogas production, organic fertilizers, and bioenergy.
- Improving Biomass Supply Chains: Strengthening cooperation between farmers, industry, and logistics providers to ensure efficient biomass collection and processing.
- Expanding Policy Support: Implementing national strategies, financial incentives, and subsidies to attract private investment in bio-based industries.

Lithuania has significant feedstock availability for the bioeconomy, but underdeveloped processing infrastructure, fragmented supply chains, and weak policy support limit its potential. By investing in value-added processing, strengthening supply chain logistics, and implementing targeted bioeconomy policies, Lithuania can enhance its role in the European bioeconomy while promoting sustainability and innovation.

3.1.3.17 Malta[535] [536] [537] [538]

Malta's status as an island nation is a key factor in understanding its climate dynamics. The island experiences seasonal variations in precipitation, with winter months often experiencing flooding and summer months typically experiencing drought. These natural conditions have a direct impact on the available biomass. The composition of the resource is primarily marine biomass, with a significant proportion being derived from waste originating from the fishing industry. Other sources include

[535] Attard, G., et al., Case study of potential production of renewable energy sources (RES) from livestock wastes in Mediterranean islands. Chemical Engineering Transactions 58 (2017) 553-558. Available in https://www.um.edu.mt/library/oar//handle/123456789/21838

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livestock manure, coproducts from the food industry, and, to a lesser extent, forestry-related materials.

Livestock waste and food industry coproducts

A 2017 publication evaluating the potential of livestock wastes in Mediterranean islands to produce renewable energy (e.g., biogas) used Malta as a case study. It was found that a correct ratio of organic wastes in the form of livestock manure and slurry and by-products originating from the food transformation industry in the making of alcoholic beverages and the processing of olives is suitable for the production of biogas after undergoing anaerobic co-digestion. The potential was estimated as 18 million of cubic meters. Despite the relative availability of these biomass types, beside for energy purposes, they seem not to be converted to value-added products.

Malta also produces approximately 15,000 tons of bluefin tuna every year and by-products are estimated to account for 55% of the harvest. Currently, the by-products are converted into fish meal and oil that are sold to the pet food industry and do not benefit bioeconomy sectors or on an anecdotal basis.

Wood waste

In 2015, a biomass pilot plant and research centre were established in Ta' Qali as part of the CRIM SAFRI research project. This initiative was co-financed by the European Regional Development Fund under the Italia-Malta Cross-Border Cooperation Programme 2007-2013. The objective of the project was to enhance the sustainability of SMEs in the building and construction sector by converting wood waste into energy. The construction wood waste, including sawdust and wood shavings, is converted into energy, which is then fed into the national energy grid.

Emerging biomass in Malta

Microalgae in Malta have attracted interest, as evidenced by studies evaluating their potential to boost crop production. These studies were performed by a research team at the Institute of Earth Systems at the University of Malta. Specifically, it is suggested that microalgal inputs could offer farmers a way to address several challenges, thereby enhancing resilience to biotic and abiotic stresses, especially those resulting from climate change, whilst also increasing crop yield.

The biodiversity of microalgae in the Maltese Islands remains understudied, as stated in a 2018 paper produced by a research team from Malta University. However, it is estimated to be both rich and versatile, holding great potential for a variety of applications. The salinity level, light intensity and other specific conditions present in the Mediterranean regions are conducive to the growth of certain microalgae species. If these conditions can be exploited, they have the potential to generate new opportunities in the bioeconomy.

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3.1.3.18 Poland[539] [540] [541] [542] [543] [544] [545] [546] [547] [548]

Poland's total area is 312,700 km², of which 51.2% is rural and 39.5% is intermediate. Approximately 31% of Poland's total area is covered by forests. Of the 14.5 million hectares of utilised agricultural area, 74.7% is arable land and 22.4% is permanent grassland and meadows. Poland has considerable potential for feedstock availability in the bio-based economy, with significant amounts of unused, underutilised and residual biomass from agriculture, livestock farming, forestry and the food processing industry. However, it should be noted that there are few biorefineries in the country and the majority relies on the use of agriculture-based feedstock. Most of the feedstock that is suitable for bio-based operations and valorisation into added-value products and services is either unused, incinerated, landfilled, or achieves relatively low value.

Agriculture-based biomass

Poland is a major player in the European Union's agricultural sector, ranking amongst the top producers. Polish agriculture is characterised by fragmentation and high specialisation at the regional and provincial levels.

Cereal crops, with an estimated grain production of 33 Mt in the 2020/21 season, are concentrated in the following regions: Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Łódzkie, Mazowieckie, Podlaskie, and Wielkopolskie. The predominant crop in these regions is wheat, followed by triticale, with barley, oats, and rye also cultivated. Maize is a relatively new crop for the country. Therefore, there is significant potential for the sustainable valorisation of lignocellulosic biomass for bio-based applications.

Poland is a major producer of oilseeds within the European Union, with rapeseed accounting for the vast majority of total oilseed production. The area dedicated to rapeseed cultivation and harvesting

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generates a production of approximately 2 million tonnes per year. The primary regions where rapeseed crops are cultivated are Dolnośląskie, Kujawsko-Pomorskie, Opolskie, Pomorskie, Wielkopolskie and Zachodniopomorskie. It is important to note that there is a domestic demand for rapeseed oil for biodiesel production.

Sugar beet is the most produced crop by tonnage (14-15Mt annually) and its cultivation is concentrated in Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Opolskie and Wielkopolskie. This feedstock is of interest for a number of applications, including the valorisation of waste from sugar processing and the use of sugars to accelerate fermentation processes.

Potato harvesting is a significant agricultural activity, contributing approximately 5-6 million metric tons annually. This important industry is present in various regions, including Lubelskie, Łódzkie, Małopolskie, Mazowieckie, Podkarpackie and Wielkopolskie.

Livestock farming side streams

Livestock farming in Poland is predominantly focused on poultry breeding, followed by pigs, meat cattle and dairy cattle. In 2023, the main poultry meat producers in the EU were Poland (representing 20.6% of EU production, with 2.7 million tonnes) and then Spain, Germany, France and Italy. Therefore, there is significant untapped potential for biogas energy derived from animal waste.

Forestry-based biomass

Poland has a large, forested area, covering approximately 31% of the total territory. According to data from the Polish Chamber of Commerce of the Wood Industry, the Polish wood sector generates approximately 2.5% of the national gross domestic product. According to the 2017 estimates, the total wood resource available is approximately 2.7 billion m^3, with coniferous species accounting for the largest share (72.8%), primarily pine. According to data from the Polish Chamber of Timber Industry, 90% of wood processing companies (7,300 entities) utilise no more than 5,000 m3 of wood per year. Between 2018 and 2021, the average energy resource represented by forest biomass in Poland increased from 351.8 TJ to 498.4 TJ. Wood biomass is a key resource for the development of bioenergy projects and investments, as well as for the recovery of aromatic volatile compounds and extraction of oils.

Biomass from food industry

The food industry is another key source of feedstock for bioeconomic processes. The Polish economy is predominantly comprised of the following subsectors: Meat production, particularly poultry, generates a by-product that could be utilised to produce new food and feed products, bioenergy, and beverages. The presence of four multinational brewing companies, accounting for almost 90% of the market share, underscores the significance of this sector. The by-products from these breweries could be used to feed bioenergy plants. The fruit and vegetable sector is dominated by apple orchards, contributing to the production of fruit. Following closely behind are sour cherries, plums and pears, as well as berries and strawberries. These products have the potential to be valorised for biochar production or biochemical extractions. The dairy sector, predominantly comprising cooperatives, generates substantial amounts of whey that could be utilised for food, feed

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and bioenergy purposes. Additionally, the cereals-based food, bakery and confectionary industries are significant contributors, as are the fish and aquaculture sectors, which encompass fish processing, canned fish and packaged fish meals.

Organic fraction of MSW

In 2020, 61% of MSW was collected separately (4.9 million tonnes out of 8.1 million tonnes generated). The biodegradable fraction, i.e. OFMSW, was the largest separately collected fraction by weight, with a collection of 1.6 million tonnes in 2020. As it is biodegradable, OFMSW can be treated biologically with anaerobic or aerobic treatments. The anaerobic treatment of OFMSW involves anaerobic digestion, with the production of biogas or biomethane. The aerobic treatment (composting) is carried out either directly on the organic component that is not destined for anaerobic digestion, or on the solid residue resulting from the digestate produced in the anaerobic phase, once it has been separated from the liquid component that will undergo a different aerobic treatment.

Supply-Side Barriers to Feedstock Utilisation

In order to fully unlock the potential for the sustainable bio-based valorisation of the available feedstock in Poland, it is essential that legal, socio-economic, structural and technical barriers are properly tackled and overcome.

- **Legal-administrative barriers**

The development of the bioeconomy in Poland is being hindered by several factors, including an unclear regulatory framework and the lack of a national bioeconomy strategy. This, in turn, is resulting in reduced investment in bio-based projects. The absence of well-defined, encouraging policy frameworks represents a significant hurdle to effective waste recovery and recycling procedures. To unlock the potential for a bio-based economy, it is essential to establish favourable framework conditions at local and regional levels.

- **Structural and socio-economic barriers**

There are several factors hindering Poland's growth potential, including low levels of investment and innovation, as well as structural challenges. The adoption of technology in businesses remains below the EU average, while SMEs demonstrate only a limited level of innovation. Several factors in the business environment are having a negative effect on private investment. The Polish energy mix is dominated by fossil fuels and was, until early 2023, heavily reliant on Russian imports. In order to effectively decarbonise its economy and improve energy security and affordability at the required pace to meet EU climate and energy targets, Poland should increase the deployment of renewable energy sources (RES). RES currently account for only around 11% of the country's energy mix. The current measures to decarbonise the economy are not well aligned with the EU's 2030 climate and energy targets. As outlined in the 2023 Country Report on Poland and the EU Commission Staff Working Document, Poland has been decarbonising at a substantially slower rate than other EU Member States.

The Polish economy continues to face challenges in accessing venture capital investment due to its limited availability. The lack of sufficient funding from high-risk funds has a negative impact on

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financing innovative projects, which in turn has a detrimental effect on reducing the technological gap and the development of modern sectors of the economy.

Polish agriculture is characterised by fragmentation and low yields. The combination of substandard soil quality and recurrent deficits in rainfall has a detrimental effect on agricultural productivity. In Poland, soil quality has a significant impact on agricultural productivity, with 62.5% of agricultural land classified as areas with natural constraints. This structural condition poses a significant challenge to the productivity of the land, the yield of crops and, consequently, the availability of agricultural feedstock.

In light of the challenges faced by Polish farms, including fragmentation, limited production scale and difficulties in adapting to customer demand, there is a clear need for effective tools to address these structural shortcomings. These include support for farmers to collaborate in producer groups and participation in quality schemes.

- **Technical Barriers**

The further modernisation of agriculture is crucial for enhancing the competitiveness of farms. As the agriculture sector accounts for 10.7% of Poland's greenhouse gas emissions, farmers also need practical tools to address these and other emissions stemming from intensive crop and livestock production. It is evident that the primary sector operators have a limited understanding of the benefits and gains associated with the green transition. It is crucial to promote and incentivise new bio-based value chains, given the current weakness in interlinkages across sectors.

It is vital to enhance the transfer of knowledge and technology from academia to industry. This process can be supported by the establishment of strategic business support organisations, such as bioeconomy clusters. These clusters serve as orchestrators of a bioeconomy ecosystem, bringing together key players from different sectors. This could help improve the low capacity to deliver high-quality secondary products, which is currently being experienced, by encouraging the adoption of innovative technologies.

Emerging Feedstocks in Poland

On 23 November 2021, the Cooperation Agreement for the Development of the Biogas and Biomethane Sector was signed in Warsaw. The objective of this initiative is to develop solutions that can stimulate the development of the Polish biomethane market, increasing the share of the biogas sector in the energy market. Furthermore, it is anticipated that the project will consolidate the position of domestic enterprises within the entire supply chain. The overarching aim of the Agreement is to develop regulations that will encourage investors to make decisions regarding the construction of installations for the production and purification of biogas or agricultural biogas, the production of biomethane and the expansion or reconstruction of existing gas networks in terms of enabling the injection of biomethane.

Statistics indicate that Poland has 301 biogas plants with a total capacity of 231 MW, of which half are agricultural, and one quarter are landfill gas and sewage gas.

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The availability of feedstock with potential for biogas production is significant, with a diverse range of streams available (agriculture-based biomass, livestock effluents, food industry by-products and the organic fraction of solid municipal waste). This supports the strong development of the sector in the forthcoming years.

- **Inland aquaculture**

Over the past decade, Poland's fish processing sector has undergone significant transformation, becoming one of the largest in Europe. From 2016 to 2020, the aquaculture sector experienced consistent annual growth, with a 5.6% average annual increase in production. In terms of volume, the largest segment is trout production, which annually provides almost half of the country's total aquaculture output, with rainbow trout being the dominant species. Climate change is having a significant impact on our resources and putting at risk the sustainability of our biological systems. Nevertheless, there are opportunities in Poland for the development of new technologies, such as hydroponic or integrated technologies (i.e. breeds + hydroponics). The country is also well placed to facilitate research and innovation, contributing to the development of aquaculture production and the promotion of aquaculture products as sustainable food products. The increase in national demand for aquaculture products, driven by the decline in catches of marine fish, is a key factor in this growth. The production of algae and algae-based products is negligible in the country. However, there are some examples of this technology in use at R&D facilities and on a small commercial scale.

The "Strategic Plan for the Development of Fish Farming in Poland for 2021-2027" includes several key objectives, including the following:

  - Increasing the current production volume of fish from inland aquaculture through the modernisation and development of aquaculture facilities
  - Increasing supplies from Polish aquaculture for domestic processing
  - Diversifying the activities of aquaculture micro and small enterprises
  - Developing aquaculture for the production of restocking and stocking material
  - Stepping up research and innovation programmes for the introduction of new fish species into aquaculture

Consequently, aquaculture-based biomass and fish and algae processing by-products can be a valuable feedstock for the development of bioeconomy projects and investments in bio-based new products.

Valorisation Pathways and Recommendations

- Short-Term Actions

The development of both conventional and emerging bioeconomy sectors requires a supportive policy ecosystem and, most importantly, a clear regulatory framework. This will ensure that requirements and advantages are visible and understandable to all the involved actors. Poland is currently lacking a national bioeconomy strategy and must strengthen its regulatory framework in order to stimulate bio-based projects and investments, which would take advantage of the significant and diverse domestic feedstock available. It is essential to implement policies that promote

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investments in R&D, facilitate access to financing for SMEs and offer economic incentives for the production of bio-based products. Adopting an integrated approach that addresses both economic and technical aspects is essential for Poland to fully leverage the potential of the bioeconomy. This will contribute to the country's environmental sustainability and economic growth.

- Medium-Term Actions

In order to fully exploit the economic potential of agricultural biomass, both for food and non-food uses, Poland should reconsider the management of biomass value chains. This should be done by means of overarching systemic management, with the aim of strengthening the relationship between the main segments of the agrifood sector, the biogas and biomethane sectors, and the production of bioproducts and bio-based carbon.

This transition will require the further development of the national and regional bioeconomy ecosystems. This will involve investing in the development of the necessary infrastructure (also reinforcing key actors such as bioeconomy clusters) as well as in training a qualified workforce that could support the growth of the sector.

In order to facilitate the transfer of technology from academia to businesses, it will be necessary to establish incentives for interlinkages across sectors, as well as dedicated training and funding programmes.

- Long-Term Actions

The creation of a solid bioeconomy ecosystem should be a key priority for Poland. This will involve funding demonstration and scaling-up plants, as well as attracting investments (domestic and foreign) in bio-based solutions and products. To achieve this, the necessary infrastructure will need to be provided to support the growth of flagship projects.

3.1.3.19 Portugal[549] [550] [551]

Portugal enjoys abundant biomass resources across forestry, agriculture, and fisheries. **Forests** cover approximately 3.4 million hectares (about 38% of mainland territory), consisting largely of maritime pine, cork oak, and eucalyptus plantations. This makes Portugal one of Europe's most forested Southern countries, with a unique dominance of cork oak montados and eucalyptus stands (the latter accounting for ~20% of forest area). These forests supply wood, cork, resin, and significant volumes of residues (branches, thinning wood, bark, etc.) that can be used as feedstock. However, the country also faces challenges like frequent wildfires in fire-prone forests,

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[550] Blue Bioeconomy Roadmap for Portugal | Blue and Green | CIIMAR

[551] APA – Agência Portuguesa do Ambiente (2022). Roteiro para a Neutralidade Carbónica 2050

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which threaten biomass availability and underscore the need for improved forest management and biomass mobilization for bioeconomy uses.

In the **agricultural sector**, about 42–43% of Portugal's land area is agricultural land, including arable fields, permanent crops (vineyards, olive groves, fruit orchards), and pastures. While Portugal's agriculture is relatively small in EU context, it generates substantial residual biomass, e.g. straw from cereals, pruning from vineyards and olives, bagasse from sugarcane, and livestock manure – that can be valorised. The country has large agro-food industries (wine, olive oil, fruit processing, dairy, etc.) which produce organic by-products amenable to bio-based conversion. Notably, Portugal is the world's leading cork producer; the cork industry (bark harvesting) yields not only high-value cork for materials but also cork dust and biomass residues that can be used for energy or bioproducts. Another traditional industry, wood pulp and paper (with major firms in Portugal), utilizes eucalyptus wood and generates co-products like black liquor and timber offcuts, which are important bioenergy resources.

Marine and fisheries biomass are also significant. With its long Atlantic coastline and large Exclusive Economic Zone, Portugal has abundant marine bioresources: fisheries produce fish waste and discards that can be converted to bio-products (e.g. fish oil for biodiesel or proteins for feed), and aquaculture is growing as a source of biomass (e.g. algae, shellfish). The country is actively exploring algae cultivation – macroalgae (seaweed) and microalgae – as an emerging feedstock that doesn't compete with land crops. Pilot projects in Portugal (often in EU partnerships) are testing integrated multi-trophic aquaculture (IMTA) systems and seaweed farms as sustainable income sources for coastal communities. These efforts tap into species like spirulina and Atlantic seaweeds for use in nutraceuticals, cosmetics, and biofuels.

Overall, biomass availability per year in Portugal is considerable relative to its size. One EU study estimated the sustainable lignocellulosic biomass potential (from agriculture, forestry and biowaste) at roughly 9.3 million dry tonnes per year (excluding primary forest harvest). This includes forest residues, cereal straws, pruning, and organic wastes – indicating that feedstock from all sources is significant and diversified. Indeed, Portugal's bioeconomy potential lies heavily in "side streams and residual streams from its large agri-food, forestry and fisheries industries," as well as specialty products like cork. The manufacturing of cork and even leather (from livestock by-products) offers further bio-based opportunities by valorising what would otherwise be waste.

Despite this resource wealth, utilization is uneven. A large share of Portugal's biomass is currently used for conventional purposes or exported with limited value addition. For instance, much agricultural residue remains underutilized or is burned on fields, and fish/seafood waste is only beginning to be tapped for byproducts. One positive trend is the push for bio-waste recycling: Portugal is implementing EU mandates for separate collection of organic waste, which will yield feedstock for biogas and biofertilizer production (e.g. via anaerobic digestion). Indeed, new biogas projects (often farm-based or municipal) are being launched to convert manure and organic effluents into renewable energy.

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In summary, Portugal's feedstock base is ample and diverse: from forestry (pulpwood, cork, pines), agriculture (crops and agro-industry residues), to blue biomass (fish, algae). The challenge ahead is to mobilize this biomass sustainably and efficiently. That means improving supply logistics (for example, aggregating biomass from many small forest owners), enhancing year-round availability (through energy crops or storage to counter seasonal swings), and ensuring sustainability (managing forests to reduce fire risks and protect biodiversity while harvesting residues).

Despite considerable biomass availability from forestry, agriculture, and fisheries, **multiple barriers** have constrained feedstock mobilization and valorisation in Portugal:

- **Economic barriers:** The profitability of residual biomass in Portugal remains low across all feedstock types. Forestry residues hold limited monetary value, so high costs for harvesting, collection and transport often outweigh the returnsieomsociety.org. Farmers similarly lack incentives to gather crop residues (e.g. straw, pruning) given the thin or undeveloped markets for these by-products, yet much of this remains unutilised. Emerging sources like marine algae are also affected by weak market demand, which discourages investment. Overall, the absence of strong price signals or subsidies fails to compensate for low profitability, leaving many biomass resources economically unattractive to mobilise.
- **Technical barriers:** Infrastructural limitations hinder the collection and processing of biomass from forestry, farms, marine cultivation and waste streams. Many rural and forested regions lack efficient systems for gathering and pre-treating residues. Marine biomass cultivation faces technological hurdles as well: deploying aquaculture structures along Portugal's rough Atlantic coast is challenging without robust engineering solutions. Similarly, the country is only beginning to implement widespread separate collection of organic waste; even in major cities like Porto, household bio-waste collection started as recently as 2018 and still covers only a fraction of residences. These gaps in equipment, storage capacity and processing infrastructure mean a significant portion of available feedstock cannot be reliably recovered or prepared for use.
- **Structural and logistical barriers:** Fragmented resource ownership and supply chain weaknesses further constrain feedstock mobilization. Over 90% of Portugal's forests are privately owned, mostly in very small parcels, and in the agricultural sector the pattern is similar, in the North, 86% of farms are under 5 ha. This highly fragmented landholding makes coordinated collection of residues inefficient and limits economies of scale. Biomass availability is also variable and seasonal (e.g. crop residues only after harvest, forest thinning post-fire season), causing supply fluctuations that complicate year-round facility operation. Additionally, newer biomass domains lack mature supply chains: the aquaculture/seaweed sector is nascent and underdeveloped, and organic waste valorisation streams are still being established (most municipalities have only recently begun source-separated bio-waste programs). Together, these structural issues, from dispersed feedstock sources and seasonal peaks to underdeveloped collection and logistics networks, create significant barriers to a stable, on-demand biomass supply in Portugal.

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Overall, these economic, technical and structural barriers significantly limit Portugal's ability to mobilize its abundant biomass sustainably. Portugal could markedly enhance the utilization of its biomass resources and accelerate its bioeconomy development.

3.1.3.20 Romania

Romania has abundant natural resources that contribute to its bioeconomy, particularly in agriculture, forestry, and bioenergy production. However, there are several supply-side barriers that hinder the efficient use of feedstock and the development of value-added bio-based industries.

Key Feedstocks in Romania

Romania's bioeconomy is primarily based on the following feedstocks:

- **Agricultural Biomass**
  - Cereal Crops: Romania is one of the EU's largest producers of wheat, maize, and barley. These crops generate significant amounts of agricultural residues, such as straw, which remain largely underutilized.
  - Oilseeds: Sunflower and rapeseed are key oilseed crops, with potential for biodiesel production and extraction of bio-based chemicals.
  - Sugar Beet: Used for sugar production but also has potential for bioethanol and bioplastic development.
- **Forestry Biomass**
  - Romania has 6.5 million hectares of forest, providing a strong base for timber, wood-based industries, and bioenergy production.
  - Large amounts of forestry residues, such as sawdust and wood chips, are available but are often inefficiently utilized.
  - Illegal logging and unsustainable practices pose risks to long-term feedstock availability.
- **Organic Waste and Residues**
  - Livestock Waste: Manure and other livestock residues could be used for biogas and organic fertilizers, but their valorisation remains limited.
  - Food Industry Waste: Romania's food processing sector generates organic waste that could be repurposed for bio-based chemicals or energy production.
- **Energy Crops and Bioenergy Feedstocks**
  - Romania has growing potential for energy crops, such as miscanthus and switchgrass, which could be used for biofuel and biogas production.
  - Biogas potential: Agricultural residues, food waste, and manure are underutilized resources that could contribute to Romania's renewable energy targets.

Barriers to Feedstock Valorisation in Romania

Despite its feedstock availability, Romania faces several barriers to effective valorisation:

- Fragmented Agricultural and Forestry Sectors

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  - A high proportion of small-scale farms makes feedstock collection and processing inefficient.
  - Limited cooperation between farmers, industries, and research institutions slows innovation.
- Lack of Infrastructure for Biomass Processing
  - Insufficient biorefineries and bio-based processing facilities hinder the transition to high-value bio-based products.
  - Most biomass is exported as raw material instead of being processed domestically.
- Inefficient Waste Management and Collection Systems
  - Agricultural and food industry residues are often discarded instead of being valorised.
  - The country lacks a circular economy framework to promote efficient use of biowaste.
- Policy and Regulatory Gaps
  - No dedicated national strategy to promote feedstock valorisation.
  - Bureaucratic barriers and weak incentives for investment in bio-based industries.

Potential Valorisation Pathways

To overcome these barriers, Romania could adopt the following strategies:

- Developing Biorefineries: Investment in biorefinery infrastructure to process agricultural residues into bio-based products such as bioplastics, bioethanol, and advanced biofuels.
- Enhancing Biomass Supply Chains: Improving logistics and cooperation between small farmers to facilitate large-scale biomass collection and processing.
- Promoting Circular Bioeconomy Practices: Encouraging waste valorisation through bioenergy projects and bio-based material development.
- Strengthening Policy Support: Implementing targeted subsidies and incentives to attract private investment in bioeconomy sectors.

Romania has significant feedstock availability for bio-based industries, but underdeveloped processing infrastructure, inefficient supply chains, and weak policy support limit its potential. Addressing these barriers through investment, policy coordination, and technological innovation will be essential for enhancing Romania's role in the EU bioeconomy.

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3.1.3.21 Slovakia[552] [553] [554] [555] [556] [557] [558] [559] [560] [561] [562] [563]

The key factor in enabling the expansion of the bioeconomy is the significant availability of feedstock in Slovakia. Biomass is a valuable resource with significant energy potential, promising bioproduct prospects and opportunities for organic farming. The identification of the most critical biomass origins in Slovakia is indicative of their capacity for resources and influence upon the bioeconomy. Slovakia has a promising and diverse range of biomass feedstock sources, including forest biomass, agricultural residues, waste biomass, and potential from energy crops and algae. However, to fully exploit these resources, Slovakia needs to invest in infrastructure, waste management, and research for improved biomass utilisation efficiency. Greater integration of biomass within the value chain through collaboration between agriculture, industry, and research institutions will also allow Slovakia to achieve a sustainable and competitive bioeconomy. In Slovakia, wood biomass is a key renewable energy source. The country has implemented sustainability criteria to ensure responsible biomass utilisation, emphasising the importance of origin verification, transportation efficiency, and energy conversion effectiveness. These measures are designed to balance energy needs with environmental conservation. Additionally, Slovakia is exploring the cultivation of short-rotation coppice poplar as a potential feedstock. This initiative reflects efforts to diversify biomass sources while considering social acceptance and environmental impact.

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Forest Biomass

Slovakia has an exceptionally high coverage of forests, amongst the highest in Europe, and is thus an important reservoir of biomass. Forest biomass is already widely used for energy production and heating purposes, and there is scope to develop its use in the manufacture of bio-based products (e.g. biofuels, bioplastics). Biomass from forest origin is derived predominantly from:

- **Wood residues**: wood chips, bark, and sawdust produced through logging and sawmilling.
- **Forest thinning**: Invasive tree species and dead or diseased trees are regularly removed to promote forest health.
- **Forest wood from forest operations**: Low-diameter branches and logs generated from regular forest upkeep.

Agricultural Biomass

Slovakia's agricultural sector provides a range of biomass feedstocks, including crop production residues. The residue can be used to produce energy in the form of biogas or bio-based chemicals and materials.

- **Cereal residues**: Barley, wheat, oat, and corn straw.
- **Vegetable residues**: Cabbage, potato, and other crop residues of vegetables.
- **Animal manures**: Livestock organic waste, which can be used for biogas production.

Waste Biomass

Slovakia generates a significant amount of organic waste from both households and industries. Waste biomass offers untapped potential for the bioeconomy. However, waste management systems and technology must be improved in order to be able to capture the maximum possible value from waste biomass.

- **Municipal solid waste**: Organic fraction of household waste.
- **Industrial organic waste**: Food processing, paper mill, and other by-products.
- **Food waste**: Fruit and vegetable peelings from regional farms and processing facilities.

Energy Crops Biomass

Dedicated energy crops provide a good potential source of biomass in Slovakia, particularly where land exists. Diversification of feedstock sources and promoting the use of renewable energy would result from the development of dedicated energy crops. They are planted specially for energy and material production:

- **Miscanthus**: A high biomass yielding, fast-growing grass.
- **Willow and poplar**: Both are quick-growing trees that give a good biomass yield.

Emerging Feedstocks in Slovakia for Developing Bioeconomy

Slovakia's bioeconomy is showing a growing interest in alternative and emerging feedstocks that have the potential to support sustainable bio-based industries. While traditional sources of biomass (wood, agricultural residues, and waste biomass) dominate the industry, emerging feedstocks are

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gaining attention due to their high productivity, sustainability potential, and new uses. The following is a review of the leading emerging feedstocks in Slovakia:

- **Giant Reed Grass** (*Miscanthus*): *Miscanthus* is a high-yielding, perennial bioenergy crop with the potential to produce significant amounts of biomass. There are also some challenges to consider, such as limited plantations due to the high cost of initial investments. To encourage farmers to produce on a large scale, policy incentives may be required. The product is used to produce bioenergy, bio-based products and animal bedding. The cultivation of this crop is performed on marginal lands, where there is less competition with food crops. The crop's high carbon sequestration rate has a beneficial effect on soil health.
- **Industrial Hemp** (*Cannabis sativa L.*): The use of hemp is gaining popularity in Slovakia due to its versatility and minimal environmental impact. There are regulatory challenges associated with its connection to THC-containing cannabis. There is a shortage of processing facilities that meet the necessary standards for high-value hemp products. The product is used in the manufacture of bioplastics, textiles, biofuels and construction materials (hempcrete). The crop is cultivated without the use of chemical pesticides or fertilisers, making it an environmentally sustainable option. The company provides biomass for the generation of bioenergy and CBD extracts for pharmaceutical applications.
- **Algae Biomass** (Microalgae & Macroalgae): Algae is a cutting-edge feedstock that has significant potential for use in the production of biofuels, animal feed, and biochemicals. The challenges to face are as follows: the high cost of production, the limited number of commercial plants in Slovakia, and the need for advanced bioreactor technology and investment in research. Algae can be cultivated on wastewater and industrial flue gas CO_2. This crop is capable of delivering a high yield per hectare in comparison to traditional crops. Furthermore, it is a rich source of lipids, proteins and bioactive compounds, making it suitable for a variety of industrial applications.
- **Biowaste and Circular Economy Feedstocks**: Slovakia is accelerating its efforts to utilise organic waste streams as feedstocks for bioproducts. The challenges are low rates of segregation of biodegradable waste in municipal waste collection systems and the requirement for investment in biorefinery technologies for the conversion of waste into high-value bioproducts. Municipal organic waste and food waste are used in the production of biogas and compost. The company is working to utilise brewery waste and used coffee grounds in the production of biofuels and biochar. Dairy waste (whey) and meat-processing by-products are used in the production of biochemicals.
- **Invasive Plant Species and Marginal Land Crops**: Some of the invasive and underutilised species are currently being assessed for their potential bio-based applications. It is vital to implement specific management practices to prevent the spread of invasive species. The demand for bioproducts derived from these crops is also growing. Japanese knotweed and amaranth are rich in bioactive compounds and have significant potential for use as bio-based extracts. Willow and Poplar (Short Rotation Coppice, SRC) are energy-rich biomass with high yield. Drought-tolerant crops, such as sorghum, are of interest due to their climate resilience.

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3.1.3.22 Slovenia[564] [565] [566] [567] [568]

Slovenia has an extensive biomass potential derived from forestry, agriculture, and food industries. However, several challenges hinder its effective utilisation.

Forestry-Based Biomass

Forestry is a dominant sector in Slovenia, with forests covering approximately 58% of the country's land area. Despite its strong production capacity, the sector faces significant challenges. The fragmented ownership structure, where the average forest holding is only 2.9 hectares, is an obstacle to large-scale industrial processing. In addition, a significant proportion of Slovenia's timber is exported as raw logs, with an estimated 1.3 million cubic metres leaving the country annually, rather than being processed domestically. The underutilisation of lower-quality hardwoods, particularly beech wood, represents a valuable opportunity for the development of bioplastics, coatings and bio-based chemicals. Furthermore, the logging of residues and bark, which have potential for biochemical extraction, remains largely unexploited. If harnessed effectively, these resources have the potential to be used in the production of tannins and lignin-based adhesives, thus enhancing Slovenia's bio-based industry.

Agriculture-Based Biomass

Agriculture is another significant source of biomass, though it is constrained by Slovenia's relatively small average farm size of seven hectares. The country produces an estimated 620,000 tons of manure annually in dry matter, but its potential for biogas production and soil fertilization remains underutilised. Similarly, crop residues, estimated at 700,000 tons per year, are not fully integrated into sustainable bioeconomic processes. In addition to these sources, fruit and vegetable waste, which amounts to approximately 100,000 tons of dry matter annually, could be further valorised for bioactive compounds and packaging materials. Furthermore, horticultural residues, estimated at 30,000 tons per year, have the potential to be converted into biodegradable mulches and fibres, thereby offering a sustainable alternative to conventional materials.

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Food Processing and Industrial Waste Biomass

The food processing and industrial sectors generate significant amounts of biomass, yet much of this remains unexploited. Dairy by-products, including whey, present significant opportunities for use in the production of biopharmaceuticals and biodegradable packaging materials. Furthermore, by-products from the brewing and winemaking industries could be redirected towards bioethanol production and the extraction of high-value polyphenols. In addition, slaughterhouse by-products have the potential to be transformed into bio-based chemicals and alternative animal feed sources, thus reducing reliance on conventional feedstocks.

Supply-Side Barriers to Feedstock Utilisation

The effective utilisation of biomass resources in Slovenia is hindered by multiple economic and technical challenges.

- **Economic Barriers**

The country's bioeconomy is constrained by a low level of domestic processing capacity. Slovenia's primary focus is on exporting large volumes of raw materials, rather than adding value through local processing and manufacturing. The prevalence of small-scale operations hinders the efficiency of biomass supply for industrial applications due to limitations in economies of scale. Furthermore, the sector's growth is restricted by the high logistics costs associated with biomass collection and transportation. Another significant barrier is the lack of biorefinery infrastructure, which limits the ability to process diverse feedstocks into high-value bio-based materials. Market incentives for bio-based industries are also insufficient, with inadequate subsidies for bio-based materials and bioenergy production, which discourages investment in the sector.

- **Technical and Structural Barriers**

Several technical and structural challenges are hindering the development of Slovenia's bioeconomy. There is a low level of awareness amongst SMEs and agricultural producers regarding the potential of bio-based opportunities. In addition, the current structure of research and industry collaboration is fragmented, which limits the effective transfer of technology from research institutions to commercial applications. Furthermore, the regulatory challenges associated with innovative bio-based products can hinder the commercialisation process, creating a sense of uncertainty for potential investors and industry innovators.

Emerging Feedstocks in Slovenia

In the context of Slovenia's strategic initiative to expand its bioeconomy, it is imperative to explore emerging feedstocks that have the potential to generate new avenues for sustainable biomass production and utilisation.

- **Oil Crops for Bio-Based Materials and Biofuels**

Oil crops represent a highly promising avenue to produce bio-based materials and biofuel. Rapeseed and sunflower have significant potential for biodiesel production, while lesser-known oil crops such as camelina and carinata offer high oil yields per hectare and can be used for biopolymers and

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aviation biofuels. The introduction of targeted incentives to encourage the cultivation of these crops could strengthen Slovenia's bioeconomy and reduce reliance on imported fossil fuels.

- **Algae as a Future Biomass Source**

Microalgae represent a promising emerging feedstock with a wide range of applications, including biofuels, pharmaceuticals, and biodegradable plastics. Microalgae are a sustainable alternative to conventional biomass sources due to their high content of lipids, proteins and bioactive compounds. However, challenges persist, particularly with regard to production costs and the absence of commercial-scale algae farms in Slovenia. Investment in algae cultivation infrastructure and the integration of algae-based solutions into wastewater treatment systems has the potential to offer a cost-effective means of increasing production.

Valorisation Pathways and Recommendations

- Short-Term Actions

In order to maximize the potential of agricultural residues, Slovenia should enhance subsidies for on-farm and industrial-scale biogas production. The establishment of regional biomass hubs has the potential to enhance logistics and reduce transport inefficiencies. Furthermore, the fostering of collaboration between SMEs has the potential to strengthen bioeconomy supply chains and innovation.

- Medium-Term Actions

Investment in small-scale modular biorefineries will facilitate the efficient processing of Slovenia's diverse biomass feedstocks. Strengthening public-private research partnerships will help commercialise new bio-based products. Furthermore, the establishment of a National Bioeconomy Hub has the potential to serve as a coordination centre for feedstock valorisation initiatives.

- Long-Term Actions

Slovenia should develop its first large-scale biorefinery to process forestry and agricultural residues into high-value bio-based products. Furthermore, integrating algae cultivation into wastewater treatment plants can provide an additional sustainable biomass source. The introduction of a national certification scheme for bio-based products is expected to stimulate market demand.

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3.1.3.23 Spain[569] [570] [571] [572] [573] [574] [575] [576] [577] [578] [579] [580] [581] [582]

Spain possesses significant biomass resources with the potential to support a robust bioeconomy. The country's extensive forest coverage, agricultural activities, and industrial processes provide substantial feedstock potential. However, numerous economic and supply-side barriers hinder effective utilisation of these resources. It is vital to understand the availability and characteristics of these resources if effective valorisation strategies are to be developed and a sustainable bioeconomy supported.

Forestry-Based Biomass

Spain has one of the largest forest areas in Europe, with forests and other wooded land covering 27.67 million hectares, which accounts for 55.6% of the country's total land area. Forests cover 18.27 million hectares, providing a forest area per capita of 0.39 hectares. In 2020, Spain had 8.15 million

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hectares of natural forest, covering 16% of its land area. However, in 2023, the country experienced a loss of 53,000 hectares of natural forest, equivalent to 19.2 Mt of CO_2 emissions. This underscores the importance of both resource availability, and the challenges associated with sustainable management.

The composition of Spanish forests is predominantly broadleaved (55%), followed by coniferous (37%), with mixed forests accounting for the remaining 8%. This diversity provides varied feedstock options for different bioeconomy applications. The total volume of wood in Spanish forests, as measured by the volume of wood over bark (VoB), is 927.76 million m³, placing Spain ninth in the European Union for total wood volume. This substantial inventory represents a significant potential resource for bio-based industries.

Spain's forest resources have shown remarkable growth over recent decades. Between 1970 and 2010, the forest area increased by 6.48 million hectares, and between 1990 and 2010, it grew by 31% (4.4 million hectares), representing an average increase of 210,000 hectares per year – the largest growth rate in Europe. This expansion is primarily attributed to natural regeneration on abandoned agricultural lands following the rural exodus since the 1960s, complemented by afforestation campaigns since the 1990s. This transition presents both opportunities and challenges for biomass mobilisation strategies.

A distinctive feature of Spain's forestry sector is the "Montes de Socios" (roughly translated as Partner Forests) system, which represents a collective private forest ownership model where multiple stakeholders share ownership of the land. This approach is designed to address challenges in managing forestry areas that were previously abandoned or had ambiguous ownership status. The initiative's key objectives are the preservation of forests as part of communities and the fostering of collaborative activities amongst stakeholders. The initiative promotes better forest management focused on multifunctionality and land stewardship. While this system has been successful in northern Spain, it is now being expanded to other regions of the country, presenting opportunities for coordinated biomass mobilisation.

Agriculture-Based Biomass

Spain's varied climate and geography support diverse agricultural activities that generate significant amounts of biomass waste. The transition from agricultural land to forest in recent decades, as indicated by the growth in forest area, suggests changes in land use patterns that may affect agricultural biomass availability. This rural exodus has led to the abandonment of agricultural lands, which have subsequently been regenerated into forests. This has potentially reduced certain types of agricultural biomass while increasing forest-based resources.

Agricultural residues from crop production, livestock manure, and pruning waste from Spain's extensive olive, vineyard, and fruit tree plantations represent potential feedstock sources for the bioeconomy. The area of forest available for the supply of wood and firewood, which is not included in protected areas, is 14.92 million hectares. This is equivalent to 82% of the forest area and 29% of the total national area. This suggests significant potential for sustainable harvesting from managed forest lands, complementing agricultural biomass sources.

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The challenge remains in developing efficient collection systems, processing infrastructure, and supply chains to effectively mobilise these diverse agricultural residues. Spain's historical context of rural depopulation may also impact the labour availability needed for biomass collection and processing in agricultural regions. This may require innovative approaches to resource mobilisation.

Food Processing and Industrial Waste Biomass

Spain's food processing industry is highly developed, with a particular strength in sectors such as olive oil production, winemaking, dairy, and meat processing. These industries generate significant amounts of by-products and waste streams that could serve as valuable bioeconomy feedstocks, though specific data on volumes and current utilisation rates is not provided in the available search results.

The wood processing industry in Spain is displaying interesting dynamics. The country is a significant player in the global trade of rough wood, with exports valued at $192 million (~€170 million) in 2023, marking a 12.4% increase compared to 2022, and imports valued at $108 million (~€95,5 million), reflecting an 11.2% rise over the same period. This bidirectional trade indicates the presence of specialised market requirements and potential inefficiencies in aligning domestic processing capabilities with available resources. The export of raw materials rather than processed products represents a missed opportunity for value addition within the Spanish economy.

Industrial and food processing waste streams represent opportunities for valorisation through biorefining processes to produce bioenergy, biochemicals, and biomaterials. The National Forestry Accounting Plan for 2021-2025 establishes a Forest Reference Level of -32.833 kt CO_2 eq., indicating Spain's commitment to sustainable forest management and carbon sequestration. This regulatory framework supports the sustainable use of forest resources as feedstocks while acknowledging their environmental value.

Supply-side Barriers to Feedstock Utilisation

In order to realise the full potential of the country's bioeconomy, it is essential to address the economic, technical and structural challenges currently hindering the effective mobilisation and utilisation of Spain's biomass resources.

- **Economic Barriers**

Despite the abundance of biomass resources, Spain's bioeconomy is facing significant economic challenges. The export data reveals that wood in the rough exports from Spain amounted to $192 million in 2023, while imports reached $108 million. This bidirectional trade pattern, involving substantial exports and imports of comparable raw materials, indicates potential inefficiencies within the domestic processing sector and untapped opportunities for local value addition. It is important to note that these exports only account for 0.045% of Spain's total exports in 2023, underscoring the relatively modest contribution of the forest sector to the national economy, despite the country's considerable forest resources.

The "Montes de Socios" system has the potential to be of significant benefit to the bio-based industry. By providing a reliable and sustainable source of biomass, the system can facilitate the continuous

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and responsible production of bioproducts and bioenergy. Furthermore, it is beneficial in terms of biodiversity conservation and climate change mitigation, with the added advantage of stimulating rural economic growth and employment generation in these areas. While this approach has clear benefits for collaborative forest management, it also introduces economic complexities related to coordinating multiple stakeholders and securing sufficient investment. These collective ownership structures may require additional financial support to develop economically viable business models for sustainable forest management and biomass utilisation. The initiative is encountering difficulties in defining the rights and obligations of landowners and in establishing the state's role in land management, which may lead to uncertainty for potential investors.

Rural depopulation, which has led to an increase in forest area through the abandonment of agricultural land, poses economic challenges for biomass mobilisation. The declining rural workforce has a direct impact on the availability of labour for biomass collection, processing, and related activities. Furthermore, the remaining small-scale operations frequently lack the economies of scale necessary for biomass supply chains to be viable for industrial applications, potentially resulting in inefficiency and cost.

The underinvestment in domestic processing capacity represents another significant economic barrier. Spain is missing opportunities to capture added value within its economy through the production of higher-value bio-based products, given the substantial volumes of rough wood being exported rather than processed domestically. This indicates a requirement for targeted investment in processing infrastructure that can efficiently utilise domestic biomass resources.

- **Technical and Structural Barriers**

Spain faces several technical and structural barriers to effective biomass utilisation. The country's approach to forest management, while comprehensive, introduces complexity through its regulatory framework. Law 43/2003 on Forests ensures the conservation of Spanish forests and promotes their restoration, improvement and sustainable management. The law is founded on principles of sustainable forest management, biodiversity conservation, and integration with international environmental objectives. While the regulatory framework provides a solid foundation for sustainable practices, it may create administrative burdens that smaller operators may find challenging to navigate.

The "Montes de Socios" initiative highlights the structural challenges in forest management. The programme is structured around three core steps: firstly, identifying the areas and the relevant stakeholders; secondly, developing pioneering examples of forest management; and thirdly, creating legal frameworks that define rights and duties. These steps emphasise the complexity of establishing effective governance structures for collective forest management, particularly in regions where ownership records may be unclear or outdated.

Spain's National Forestry Accounting Plan for 2021-2025 considers the entire forest area as managed for reporting and accounting purposes of greenhouse gas emissions and removals3. This comprehensive approach to forest carbon accounting creates additional administrative requirements

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for forest owners and operators, which may increase the complexity of biomass mobilisation efforts, particularly for smaller stakeholders with limited administrative capacity.

The distribution of biomass resources across a variety of geographical regions poses significant logistical challenges. The efficient collection, transportation, and processing of biomass requires well-coordinated supply chains, which may be difficult to establish in areas with poor infrastructure or dispersed resources. This geographical fragmentation, combined with the diverse types of biomasses available, necessitates tailored approaches to resource mobilisation rather than one-size-fits-all solutions.

In addition, insufficient technical knowledge creates obstacles to the effective utilisation of biomass. The transition to a bioeconomy requires specialised skills and knowledge in biomass processing, biorefining technologies, and bio-based product development. Addressing these knowledge gaps through education, training and knowledge transfer will be essential for overcoming technical barriers to biomass valorisation.

Emerging Feedstocks in Spain

Spain's diverse geography, climate, and industrial base provide opportunities for developing emerging feedstock sources that could complement traditional biomass resources and strengthen the country's bioeconomy.

- **Forest Management Innovations**

Spain's extensive forest resources, covering 55.6% of the national territory, present opportunities for innovative management approaches that could increase sustainable feedstock availability. The "Montes de Socios" model, which has been successful in northern Spain, represents an emerging approach to mobilising underutilised forest resources through collective management. By clarifying ownership and establishing collaborative governance structures, this model has the potential to unlock significant biomass potential from previously abandoned or poorly managed forests.

The National Forestry Accounting Plan demonstrates Spain's dedication to sustainable forest management, while also recognising the significance of ensuring a steady supply of wood. The plan notes that 82% of Spain's forest area (14.92 million hectares) is available for wood supply, indicating significant potential for sustainable harvesting. Innovative silvicultural techniques that enhance both wood production and ecosystem services could increase the availability of forestry biomass while maintaining environmental benefits.

Spain's forest sector has shown significant growth, with an expansion of 4.4 million hectares in forest area between 1990 and 2010. This trend indicates the possibility of increased managed forest areas, particularly through the afforestation of marginal agricultural lands. The development of dedicated energy forests or agroforestry systems on these lands has the potential to provide additional biomass feedstocks while delivering environmental benefits such as carbon sequestration and biodiversity conservation.

- **Agricultural Residues and By-Products**

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Spain's agricultural sector generates significant quantities of residues that are currently underutilised as bioeconomy feedstocks. The rural exodus that has contributed to forest expansion through abandoned agricultural lands suggests changing patterns of land use that could be strategically managed to optimise biomass production. Combining food production with biomass harvesting is a strategy that has the potential to enhance the return on investment from agricultural land.

The country's thriving olive oil, wine, and fruit production sectors generate substantial processing residues with considerable potential for valorisation. These residues could be used as feedstocks for biorefineries, recovering a wide range of high added-value compounds and producing a variety of products from bioenergy to high-value chemicals and materials. The establishment of efficient collection and processing systems for these agricultural residues would enhance their contribution to the bioeconomy while reducing waste management challenges.

- **Industrial Symbiosis and Urban Biomass**

Industrial symbiosis approaches, where waste from one industry becomes a resource for another, represent an emerging opportunity for increasing feedstock availability. Spain's diverse industrial base, including food processing, pulp and paper, and wood products sectors, generates various organic residues that could be redirected into biorefining processes. The development of these industrial symbiosis networks would increase resource efficiency while providing additional feedstock streams for the bioeconomy.

Urban biomass sources, including municipal solid waste organic fractions, wastewater treatment residues, and green waste from parks and gardens, represent additional feedstock potential. While not specifically mentioned in the search results, these urban biomass streams are often underutilised in many regions. The development of collection and processing systems for these urban biomass sources has the potential to supply feedstocks for bioenergy and bioproduct production, while also addressing waste management challenges in urban areas.

Valorisation Pathways and Recommendations

Following a thorough analysis of the challenges and opportunities that have been identified, the following recommendations have been made with a view to enhancing the mobilisation and valorisation of Spain's biomass resources for the purpose of strengthening the bioeconomy.

- Short-term Actions

Spain should prioritise the development of regional biomass hubs to improve collection logistics and reduce transportation costs for forest and agricultural residues. These hubs would serve as aggregation points for diverse biomass streams, enabling more efficient processing and utilisation. The expansion of the "Montes de Socios" model beyond the northern regions has the potential to enhance collaborative forest management and biomass mobilisation, particularly in areas where ownership is fragmented or where forests have been left unmanaged.

The introduction of financial incentives for the domestic processing of wood and agricultural residues would reduce raw material exports and increase value addition within Spain. Given the 12.4% increase in wood exports in 2023, targeted measures to encourage domestic processing could

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generate significant additional value for the Spanish economy. The development of training programmes for rural communities in biomass collection, processing, and utilisation would address labour shortages and create economic opportunities in rural areas experiencing depopulation.

Creation of a national database of biomass resources, including forestry, agricultural, and industrial waste streams, would facilitate better planning and investment in the bioeconomy sector. This database will provide essential information for potential investors, researchers, and policymakers, supporting strategic development of Spain's bioeconomy. Implementing pilot projects demonstrating innovative valorisation pathways for Spain's diverse biomass resources would build confidence and provide proof-of-concept for larger-scale investments.

- Medium-term Actions

Investing in small to medium-scale biorefineries adapted to Spain's specific feedstock availability would enhance domestic processing capacity and reduce the current practice of exporting raw materials. In order to ensure the efficient functioning of these biorefineries, it is vital that they are strategically located, thus minimising transportation costs and maximising access to diverse feedstock sources. Strengthening public-private research partnerships focused on valorising Spain's unique biomass resources, such as olive, vineyard, and forestry residues, would drive innovation and technological development.

The development of integrated supply chains that connect biomass producers with processors and end-users would improve system efficiency and reduce transaction costs. This would be of particular benefit to the "Montes de Socios" initiatives, which involve multiple stakeholders and require coordinated approaches to resource management. The creation of specialised financial instruments to support investment in bioeconomy projects, particularly for collective initiatives, would address capital constraints that currently limit sector growth.

The establishment of regional bioeconomy clusters that bring together producers, processors, researchers, and end-users would foster collaboration and innovation. These clusters will facilitate knowledge exchange and technology transfer, accelerating the development of Spain's bioeconomy. The development of standards and certification systems for sustainable biomass production is essential to ensure that increased mobilisation does not compromise environmental objectives. This is in alignment with Spain's commitment to sustainable forest management.

- Long-term Actions

Spain should develop large-scale biorefineries capable of processing multiple feedstock types, providing flexibility and resilience in the biomass supply chain. These facilities would act as anchors for the bioeconomy, creating demand for diverse biomass resources and producing a range of bio-based products. Integrating biomass valorisation into regional development plans, particularly for rural areas experiencing depopulation, has the potential to create sustainable economic opportunities while addressing demographic challenges.

The establishment of a national certification scheme for bio-based products would drive market demand and consumer awareness, creating pull factors for the bioeconomy. This would complement

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the push factors created by increased feedstock mobilisation, ensuring balanced development of the sector. The creation of international partnerships for knowledge exchange and technology transfer in advanced biomass processing would accelerate innovation and help Spain maintain competitiveness in the global bioeconomy.

The development of a comprehensive bioeconomy strategy that integrates forest, agricultural, and industrial policies would provide a coherent framework for the sustainable utilisation of biomass. This strategy should align with Spain's National Forestry Accounting Plan and other environmental commitments, ensuring that economic development goes together with environmental sustainability. Investing in research and development for emerging feedstocks and conversion technologies would position Spain at the forefront of bioeconomy innovation, creating opportunities for technology export and international leadership.

Finally, to overcome the current barriers, coordinated action is required across multiple fronts. These include improvements to logistics and supply chain infrastructure, the development of appropriate regulatory frameworks and financing mechanisms. Spain can transform its abundant biomass resources into sustainable economic opportunities, particularly for rural areas facing demographic challenges, by implementing the recommended short, medium, and long-term actions.

The transition to a robust bioeconomy is in line with Spain's environmental commitments, including sustainable forest management and carbon sequestration objectives outlined in the National Forestry Accounting Plan. By adopting integrated approaches that optimise both economic and environmental outcomes, Spain can establish itself as a leader in the European bioeconomy. This will create resilient and sustainable pathways for rural development and industrial innovation.

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3.1.3.24 Sweden[583] [584] [585] [586] [587] [588] [589] [590] [591] [592]

Forestry-Based Biomass

Sweden is part of the boreal forest, also known as the "taiga", which is the world's largest land biome. The woodland is usually made up of coniferous tree species, such as pine and spruce, and some broadleaf species, including poplar and birch. Forestry is the dominant sector in Sweden, with forests covering approximately 70% of the country's land area. Despite its strong production capacity and well-developed industrial industry, the sector faces different challenges. Sweden is a major player in global trade, particularly in the areas of pulp, paper and sawn wood products. In 2023, the export of products accounted for over 80% of total sales, with two thirds of these being sold within the EU. The recently introduced legislation pertaining to forests, particularly the Land-use, Land-use Change and Forestry (LULUCF) regulation, the European Union Deforestation Regulation (EUDR), and the Restoration Directive, introduces uncertainties regarding future biomass availability and potential utilisation, along with funding opportunities for biorefinery initiatives. Additionally, it imposes a substantial administrative burden on all forest owners. This has contributed to a lower level of interest in investing in forest-based businesses. New biorefinery initiatives are confronted with two significant challenges. Firstly, there is the prize of the biobased product competing with fossil products.

[583] Ali, S., et al., Recent advances in characterization and valorization of lignin and its value-added products: challenges and future perspectives. Biomass 4(3) (2024) 947-977; **https://doi.org/10.3390/biomass4030053**

[584] Bakratsas, G., et al., Single-cell protein production by Pleurotus ostreatus in submerged fermentation. Sustainable Food Technology 1(3) (2023) 377-389. **https://doi.org/10.1039/d2fb00058j**

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[586] SLU Riksskogstaxeringen. Forest statistics 2024 (Skogsdata 2024). Official Statistics of Sweden. Swedish University of Agricultural Sciences (SLU). Umeå 2024. Available [online].

[587] Swedish food strategy. Svenska livsmedelsstrategin (2017) Prop. 2016/2017:104. Retrieved from https://jordbruksverket.se/mat-och-drycker/livsmedelsstrategi-for-sverige/livsmedelsstrategin-och-vart-uppdrag

[588] Statistics Sweden 2024. Jordbruksmarkens användning 2024. Retrieved from https://jordbruksverket.se/om-jordbruksverket/jordbruksverkets-officiella-statistik/jordbruksverkets-statistikrapporter/statistik/2024-05-16-jordbruksmarkens-anvandning-2024.-preliminar-statistik

[589] Statistics Sweden 2025. Retrieved from https://www.scb.se/en/

[590] Svebio (2025). Visited 2025-03-17. https://www.svebio.se/om-bioenergi/biovarme/

[591] Swedish bioeconomy strategy. En hållbar bioekonomistrategi – för ett välmående fossilfritt samhälle (2023) SOU 2023:84. Retrieved from https://www.regeringen.se/contentassets/9690f67e83b8410192f1869d0d5da392/en-hallbar-bioekonomistrategi--for-ett-valmaende-fossilfritt-samhalle-sou-202384.pdf

[592] Skogsstyrelsen. Skogliga konsekvensanalyser 2022 - syntesrapport Regeringsuppdrag (2022). RAPPORT 2022/11. Retrieved from https://www.skogsstyrelsen.se/globalassets/om-oss/rapporter/rapporter-2022202120202019 2018/rapport-2022-11-skogliga-konsekvensanalyser-2022---syntesrapport.pdf

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Secondly, there is the opportunity to enter the raw material supply chain. It is understandable that existing pulp and paper industries and sawmills are naturally reluctant to invite new buyers.

Agriculture-Based Biomass

In Sweden, agricultural land constitutes 7% of the total land area, primarily located in the southern regions. The arable land area is 2.98 million hectares. There are two primary species: grain and fodder.

Aquatic biomass

Despite the extensive coastline in Sweden, the contribution from the blue bioeconomy remains modest, centring primarily on the utilisation of renewable aquatic biomass from marine and freshwater systems. This includes catches from commercial fishing, aquaculture involving the cultivation of animals and plants in water, and the harvesting of seaweed and algae from coastal areas. The blue industry's current contribution to food production is predominantly focused on the processing of imported fish, primarily from Norway. In Sweden, a negligible volume of fish is subject to processing or further processing. In 2022, the total catch in landed weight from commercial fishing in the sea was approximately 121,000 tonnes. According to the Swedish bioeconomy strategy (2023), more than 80,000 tonnes of this catch were landed directly abroad, primarily in Denmark.

Supply-Side Barriers to Feedstock Utilization

- **Economic Barriers**

Forestry is a co-production system, meaning several products are produced simultaneously, including saw logs, pulpwood and logging residues, as well as branches and tops left in the forest after harvesting operations. As a result of forest industry activities, a significant volume of by-products is available, including sawdust, bark and shavings. As you will be aware, these aggregated by-products are currently used primarily for the generation of power and heat in combined heat and power (CHP) plants. This is the most common form of heating in Sweden.

As a result of harvesting operations, large volumes of logging residues are available, but these are scattered over the land. In terms of area, thinning is the most prevalent forestry practice, accounting for approximately 290,000 hectares per year. This is followed by pre-commercial thinning, which occurs across approximately 250,000 hectares annually, and final felling, which makes up about 240,000 hectares per year. The economically viable logging residues are primarily derived from final fillings of spruce-dominated stands. There is a significant untapped resource of forest logging residues, primarily located in the northern part of Sweden. However, most of this potential remains unused due to the higher costs associated with harvesting, transport and storage, which exceed the prices for sawdust and bark. Its primary function is in the field of combustion.

Uncertainty surrounding long-term regulations on forest biomass and the low taxation on fossil CO_2 are two factors hindering the development of new, more efficient ways of harvesting and refining this biomass.

- **Technical and structural barriers**

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The costs of harvesting, transporting, storing and handling the biomass are key factors in determining overall biorefining costs. It is therefore vital to develop local forest biomass supply systems that can efficiently supply biorefineries with sufficient raw material that meets their specific quality and seasonal demands. The cost of long-distance road transport for biomass is a significant challenge for supply chains. For instance, logging residues are typically sourced within a 100-kilometre radius from the end consumer. It is also important to consider the willingness of existing biomass suppliers to sell. In Sweden, a few large forestry companies have a dominant market position. For several decades, there has been a strong focus on business relations and trust between the woody biomass sellers and buyers. Therefore, new facilities demanding biomass may encounter difficulties in competing for and sourcing available biomass.

- **Emerging Feedstocks in Sweden**

As Sweden seeks to expand its bioeconomy, it is crucial to valorise side streams from existing bio-based industries and explore underutilised feedstocks that could provide new opportunities.

  - Lignin

Lignin has historically been considered a low-value byproduct in the pulp and paper industry. However, recent advancements in valorisation are transforming lignin into a sustainable and versatile feedstock for producing high-value biofuels, bioplastics, and specialty chemicals. Several Swedish companies and research groups are exploring different routes of valorising lignin.

  - Single-cell protein (SCP)

Research on how to valorise fibre sludge, a low-cost industrial by-product from the pulp and paper industry, by producing single-cell protein derived from microorganisms could be a solution to high societal protein demand. Fibre sludge has been demonstrated to be a highly effective feedstock for SCP production, achieving levels of productivity and protein content that are comparable to those achieved in glucose fermentations.

  - High value compounds from logging residues

There is a potential to increase the extraction of logging residues (treetops and branches) in clear felling from today's level of 9 TWh to 24 TWh until 2035. The potential has been assessed in accordance with the ecological restrictions stipulated by the Swedish Forest Agency, while economic and technical restrictions have not been taken into consideration. Given these conditions, most of this potential is located in the northernmost part of Sweden. Using more forest residues to generate heat and electricity will make more sawdust available for new biorefining operations.

Several studies have been conducted on the procurement of logging residues, and it has been determined that these residues have the potential to be used as a feedstock in the production of high-value compounds. Logging residues, and especially needles, contain high concentrations of valuable compounds that can be used to produce a range of added-value products. These include pharmaceuticals, cosmetic ingredients, platform and specialty chemicals, dietary supplements, biopolymers, bioplastics, foams and emulsions, and coatings.

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- New crops for increased self sufficiency

The Swedish Food Strategy, published in 2017, sets out a comprehensive plan to enhance Swedish food production and ensure that by 2030, the Swedish food chain will be globally competitive, innovative, sustainable and attractive.

Sweden is committed to increasing its food self-sufficiency. Research and cultivation trials are performed to test and develop new crops and new food products. One example of a product available on the market is oat rice, which has properties like rice. Cultivation trials of various legumes, which are rich in protein, are underway in southern Sweden. The objective of these trials is to replace imported food and feed with domestic produce.

Valorisation Pathways and Recommendations

- Short-Term Actions

It is vital to educate entrepreneurs on the most effective methods of harvesting and collecting logging residues. The next stage is to establish volume-adapted functional systems for the extraction of logging residues.

The establishment of additional regional biomass hubs will enhance logistics and reduce transport inefficiencies. Furthermore, the fostering of collaborations between SMEs has the potential to strengthen bioeconomy supply chains and innovation.

- Medium-Term Actions

New industrial actors seeking biomass fractions must establish novel supply chains and collaborate with forest owners. It seems improbable that existing forest industry will allow them to enter the current supply chain.

- Long-Term Actions

The proposal for a Swedish bioeconomy strategy outlines a vision to promote a fossil-free society. This will be achieved by replacing fossil-based raw materials, products and systems with bio-based alternatives, together with a high degree of electrification and circular business models. By 2040, Sweden's bioeconomy will be more resource-efficient, resilient and competitive throughout the country. The proposed strategy is comprised of 17 specific actions, including revenue guarantees for the domestic production of liquid renewable fuels and intermediates, a plan for industrial wood construction and increased wood utilisation, and policy instruments to promote bio-based solutions.

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3.1.3.25 UK[593] [594] [595]

Emerging UK bio-based feedstocks are pivotal in transitioning toward sustainable biomanufacturing, with research and innovation focusing on diverse sources such as lignocellulosic biomass, biogenic waste streams, and renewable agricultural residues. Strategic initiatives emphasise scaling bio-based feedstocks to replace fossil-derived inputs, supported by collaborations between academia and industry to enhance circularity and reduce carbon emissions. The UK Biomass Strategy highlighted the integration of these feedstocks into high-value applications, including bio-based chemicals and materials, while addressing challenges in sustainable sourcing and processing to ensure compatibility with net-zero targets. Whilst the Bioeconomy Strategy has been superseded by the Industrial Strategy, funded frameworks aim to standardise feedstock use and accelerate commercial adoption, positioning the UK as a leader in global bioeconomy innovation

Forestry Resources

The UK's forestry sector contributes virgin wood and processing residues for bioenergy and bioproducts. In 2018, approximately 4.1 million tonnes of virgin wood (softwood and hardwood) was used for energy recovery, with softwood accounting for 3.4Mt and hardwood 0.7Mt. While domestic softwood harvesting reached 76% of potential supply, an additional 2.0Mt could be sustainably harvested annually. Forestry residues, including sawmill by-products, are increasingly utilized in biomass power generation, though competition with traditional timber industries influences availability.

Agricultural Feedstocks

Agricultural biomass plays a pivotal role in advancing the UK's biobased industries, driven by regional initiatives and national strategies to transition toward a circular bioeconomy. Food and feed crops are grown on arable land as part of a crop rotation and can be suitable for human and/or animal consumption. Non-food crops are obtained from non-edible biomass, such as perennial energy crops and short rotation forestry (SRF). Perennial energy crops are frequently grown for bioenergy production and include lignocellulosic grasses such as Miscanthus and SRC species, like willow or poplar which do not need to be replanted annually offer a stable biomass supply. In 2023, 133,000 hectares of UK agricultural land were dedicated to bioenergy crops, including maize (73,000 ha) for anaerobic digestion and wheat/sugar beet (45,000 ha and 2,600 ha, respectively) for biofuels.

[593] UK Dedicated Biomass – Statistics 2019 – Tolvik Consulting

[594] House of Commons: Seeing the wood for the trees: the contribution of the forestry and timber sectors to biodiversity and net zero goals: Government Response to the Committee's Fifth Report of Session 2022–23. Available at: https://committees.parliament.uk/publications/42599/documents/211731/default/

[595] Unlocking the UK's biomass resources as a feedstock for Chemical Manufacturing – UK RI – Innovate UK KTN

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Miscanthus (8,800 ha) and short rotation coppice (3,800 ha) provide lignocellulosic biomass for heat and power.

Livestock farming generates 90 million tonnes of manure and slurry annually, a key low-cost feedstock for biogas.

Waste Streams

Post-consumer and industrial waste streams are critical for circular bioeconomy strategies:

- **Food Waste**: Approximately 16 million tonnes of post-farm gate food waste is generated annually, half from households, with growing diversion to anaerobic digestion.
- **Municipal and Industrial Waste**: Biogenic fractions of MSW (e.g., paper, organic waste) and agro-industrial residues (e.g., distillery by-products, spent grains) are increasingly valorised. Regulatory pressures to reduce landfill disposal (e.g., UK's 2030 biodegradable waste target) are expanding accessible volumes.

Fisheries and Aquaculture

While fisheries and aquaculture sectors are not major contributors to biomass feedstock in the UK, limited by-products (e.g., fish processing waste, shellfish shells) are explored for niche applications such as chitin extraction or algae cultivation. Macroalgae (seaweed) farming remains underdeveloped but holds potential for biorefinery integration, particularly in coastal regions.

Challenges and Opportunities

The UK's bio-based feedstock landscape faces constraints, including competition for land (food vs. energy crops), fragmented supply chains, and reliance on imports for lignocellulosic biomass. However, emerging technologies (e.g. thermochemical conversion) and policy frameworks prioritizing sustainability and carbon capture (e.g., bioenergy with CCS) are driving diversification. Strategic mapping of regional biomass resources could enhance sector resilience.

Priority uses for biomass emphasize hard-to-decarbonise sectors, with strict sustainability criteria governing large-scale applications. While forestry and agriculture dominate current supply, waste valorisation and marine biomass represent underutilized niches critical for long-term bioeconomy growth.

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3.2 Supply Side Barriers: Production Costs, Capacity, Profitability, Competition And Lack Of Supporting Business Models, R&D&I Ecosystem For Scale-Up/Commercialisation

3.2.1 Belgium[596]

Labour productivity in bioeconomy sectors

Figure 10 illustrates the labour productivity of the Flemish bioeconomy sectors, in comparison to the productivity of the bioeconomy sectors in our neighbouring countries and the EU average in 2017.

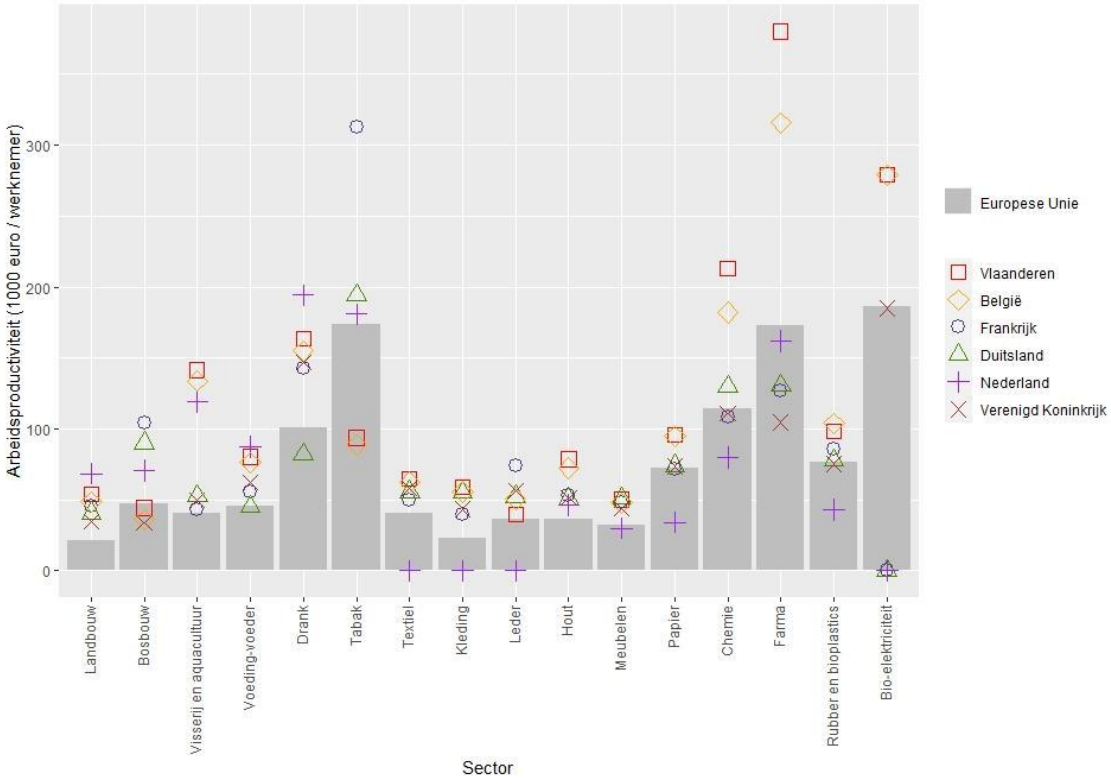


Figure 10 – Labour Productivity of the Flemish Bioeconomy Sectors Compared to Our Neighbouring Countries and the EU Average (2017).
(Source: MonBio – 2022)

Overall, Flemish bioeconomy sectors demonstrate high labour productivity; in absolute terms, the Flemish bio-based pharmaceutical industry is particularly competitive. In relative terms, sectors such as fisheries, food and beverage, bio-based textiles, clothing, wood, furniture, paper, chemicals,

[596] MonBio - 2022: Bioeconomy monitoring study- Specifieke opdracht in het kader van de opvolging van de Vlaamse bio-economie

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pharmaceuticals, rubber and plastics, and bioelectricity all perform significantly better than the European average and often outperform those in neighbouring countries.

In terms of agricultural output, Flanders is the second-largest producer after the Netherlands. The Flemish bioeconomy demonstrates notable strength in terms of labour productivity.

Figure 11 displays the relative labour productivity for Flanders and neighbouring countries, normalized against the European average. A value of 1 represents the EU average, 0.5 is half the EU average, and 2 is twice the EU average.

Labour productivity in fisheries in Flanders is almost 3.5 times higher than the European average, and Flanders also outperforms its neighbouring countries in this sector. Flanders demonstrates a minimum of double the labour productivity of the European average in the bio-based clothing, agriculture, bio-based pharmaceutical and wood sectors.

While neighbouring countries also demonstrate strong performance in bio-based clothing, agriculture, and wood, Flanders is a clear standout in the bio-based pharmaceutical sector. In the field of agriculture, however, the Netherlands has consistently demonstrated its pre-eminence. In the field of tobacco production, labour productivity in Flanders is the only sector where it falls below the European average.

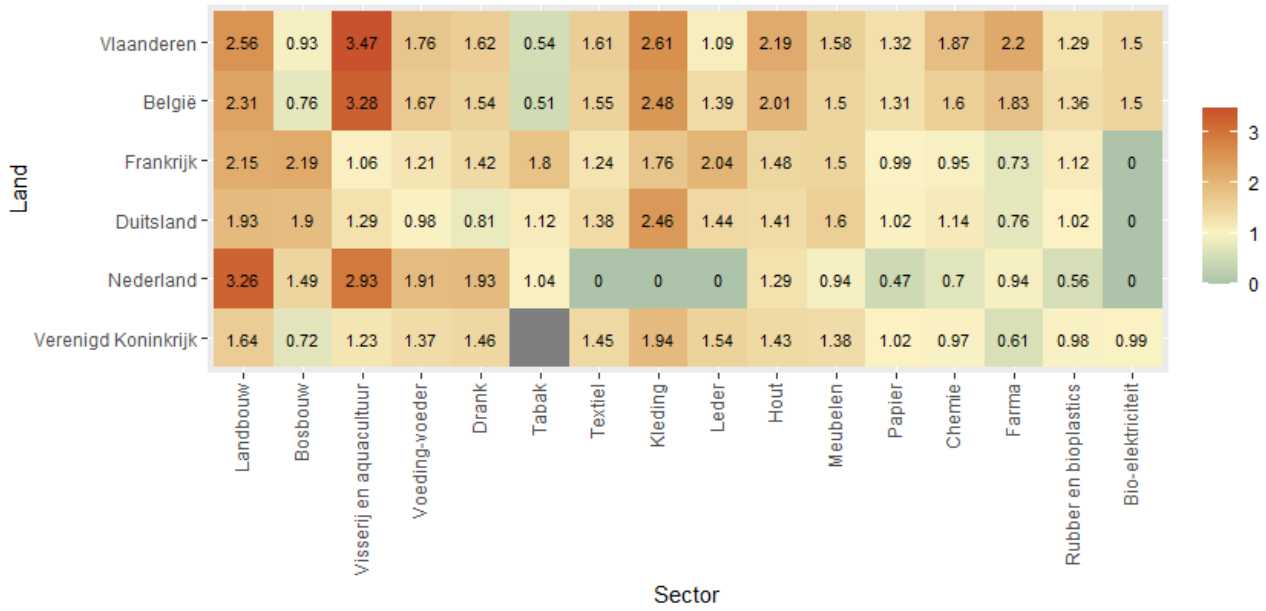


Figure 11 – Relative Labour Productivity of the Bioeconomy Sectors in Flanders, Belgium, and Our Neighbouring Countries Compared to the EU Average (EU Average = 1) (2017)
(Source: MonBio – 2022)

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3.2.2 *Bulgaria*[597] [598] [599] [600] [601]

Bulgaria's bioeconomy is still in the early stages of development and is facing multiple supply-side barriers that limit its ability to scale up and commercialise bio-based industries. These barriers include high production costs, low profitability, limited production capacity, competitive pressures from conventional fossil-based products, and a lack of well-developed business models. Furthermore, while Bulgaria's research and innovation (R&I) ecosystem is showing signs of improvement, there are still challenges to be addressed in order to ensure the commercialisation of bio-based technologies. It is vital that these obstacles are addressed if the country is to unlock its bioeconomic potential and align with EU sustainability and climate objectives.

Production Costs and Profitability Constraints

One of the key challenges that Bulgaria's bioeconomy faces is the high cost of production, which is attributable to the high cost of raw materials, the inefficiency of supply chains, and high energy costs. Bulgaria's bioeconomy industries face challenges in comparison to their Western European counterparts, primarily due to fragmented supply chains, which can lead to increased production expenses. The predominance of small-scale farms and processing facilities further contributes to these inefficiencies, as achieving economies of scale is difficult. The cost of producing bio-based materials is significantly higher than that of traditional fossil-based products. This makes it difficult for bio-based alternatives to compete in price-sensitive markets.

Profitability is another critical issue, as bio-based businesses often operate with low margins due to high initial investment costs and lengthy return-on-investment periods. Investors are reluctant to fund bio-based start-ups or large-scale biorefinery projects due to concerns over long-term market stability. The availability of EU and national funding has eased some of the pressure, but the process of securing financial support remains complex and bureaucratic. Many bioeconomy ventures encounter difficulties in achieving commercial viability without subsidies or direct governmental support.

[597] Kaneva, K., et al. Executive summary of the strategic concept paper for bioeconomy: Bulgaria (2023) BIOEASTsUP H2020 Project

[598] Republic of Bulgaria, Ministry of Energy & Ministry of the Environment and Water. (2021). Integrated Energy and Climate Plan of the Republic of Bulgaria 2021–2030

[599] Adjarova, L., et al., National Bioeconomy Dossier: Bulgaria. WWF Bulgaria (2020) Bio-Based Industries Joint Undertaking (BBI-JU), Horizon 2020

[600] Kotseva-Tikova, M., Benefitting from the development of the bioeconomy: the case of Bulgaria. Regional Formation and Development Studies, 38(3) (2022) 25-33. **https://doi.org/10.15181/rfds.v38i3.2442**

[601] Bulgarian Industrial Association, Thracian University, & Stakeholders Working Group of Stara Zagora Region. Strategy for Development of the Bioeconomy in Stara Zagora Region (2021). BE-Rural, Horizon 2020

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Production Capacity Limitations

The absence of substantial production facilities considerably restricts Bulgaria's potential for cultivating a robust bioeconomy. While there are several small biogas plants and biofuel production units, there are no large-scale industrial biorefineries capable of processing diverse biomass sources into high-value bio-based chemicals, bioplastics, or advanced biofuels. The limited availability of advanced processing technologies has a detrimental effect on the efficiency of biomass utilisation.

Bulgaria's wood processing and pulp industries have considerable potential for contributing to the bioeconomy, particularly in the production of lignocellulosic biofuels and bio-based materials. However, the majority of the country's forestry biomass remains underutilised due to the following factors: outdated processing technologies and logistical challenges in transporting raw materials from remote areas to processing facilities. In order to enhance the production capacity of Bulgaria, there is an essential requirement for substantial investments to be made in the modernisation of production infrastructure and the establishment of an integrated biomass supply network.

Competitive Pressures and Market Challenges

Bulgaria's bio-based industries face strong competition from established bioeconomy leaders such as Germany, the Netherlands and Scandinavian countries, which have heavily invested in biorefinery technologies and bio-based supply chains. The absence of domestic processing capacity means that a significant proportion of Bulgaria's biomass is exported in its raw state, rather than being processed into higher-value bio-based products. This situation creates a disadvantage for local producers, as they are unable to fully capitalise on the economic benefits of biomass valorisation.

Furthermore, fossil-based alternatives continue to dominate the market, as they are generally cheaper and more widely available. In the absence of robust policy measures, including carbon pricing, mandatory bio-based procurement policies, or subsidies for bio-based products, many Bulgarian companies face challenges in maintaining competitiveness. Consumer awareness of and demand for bio-based products remains low, which limits market opportunities for domestic producers.

Lack of Supporting Business Models

Bulgaria's bioeconomy is currently lacking well-developed business models that integrate raw material suppliers, processors, and end-users into cohesive value chains. In contrast to the bioeconomy clusters in Western European countries, which facilitate industrial cooperation and knowledge exchange, Bulgaria has yet to establish strong bio-based industry networks. Many companies are reluctant to invest in bio-based ventures due to the lack of long-term supply contracts and stable demand.

Furthermore, there is a lack of incentives for businesses to transition from conventional production to bio-based manufacturing. Although a select number of EU-funded initiatives have provided support for pilot projects, the majority of companies encounter challenges in scaling up due to limitations in financing and regulatory uncertainties.

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Weak R&I Ecosystem for Scale-Up and Commercialization

Despite Bulgaria's strong academic research base in biotechnology and bio-based sciences, the commercialisation of bio-based innovations remains challenging. Research institutions and universities conduct valuable studies on biomass utilisation, bio-based materials and biofuels. However, the translation of these findings into commercial applications is often hindered by limited industry collaboration and insufficient funding for demonstration projects.

Bulgaria's research institutions and companies are facing limitations in their capacity to develop large-scale pilot projects due to a comparatively lower level of EU bioeconomy funding secured in comparison with Western Europe. There is also a lack of dedicated innovation hubs that provide tailored support for bio-based start-ups and small businesses. Although there are general business incubators, they frequently lack sector-specific expertise in bio-based industries. This can make it challenging for entrepreneurs to navigate the complex regulatory and financial landscape.

Addressing Supply-Side Barriers

In order to overcome these challenges, Bulgaria must implement targeted policy measures to support the growth of its bioeconomy. Key recommendations include investing in the modernisation of biomass processing infrastructure, providing financial incentives for biorefineries and bio-based start-ups, and fostering collaboration between academia and industry to enhance technology transfer. The development of bioeconomy clusters and the strengthening of supply chain integration will also be crucial in reducing production costs and improving market competitiveness.

Furthermore, it is essential that Bulgaria raises consumer awareness of bio-based products and implements supportive regulations, such as bio-based procurement policies, carbon pricing mechanisms, and subsidies for bio-based materials. If these measures are implemented effectively, Bulgaria has the potential to establish itself as a regional leader in the field of sustainable bioeconomy development. The country's abundant biomass resources could be utilised to drive economic growth and environmental sustainability.

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3.2.3 *Croatia*[602] [603] [604] [605] [606] [607] [608]

The Croatian bioeconomy sector faces fundamental supply-side barriers that limit its ability to scale up and compete internationally. The impact of these barriers on production costs, processing capacity, profitability, market competition and the overall business ecosystem must be given full consideration.

High Production Costs and Limited Economies of Scale

The production costs of bio-based industries in Croatia are considerably higher than those in established EU bioeconomy hubs. Key factors contributing to high costs include:

- **Outdated agricultural and forestry practices** that reduce efficiency and increase input costs.
- **High energy and water consumption** in biomass processing, making domestic production less competitive.
- **Limited mechanisation and precision agriculture adoption**, leading to lower yields and higher labour costs.

Insufficient Production Capacity

- **Croatia lacks large-scale processing plants** for advanced bio-based products such as bioplastics, biofuels, and bio-based chemicals.
- **Low integration of circular bioeconomy principles** prevents the full utilisation of agricultural and forestry residues.

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- **Limited access to specialised technology and infrastructure** impedes the scalability of bio-based enterprises.

Market Competitiveness and Business Model Challenges

- **Bio-based products face stiff competition from fossil-based alternatives** that benefit from lower production costs and mature supply chains.
- **Lack of structured public-private partnerships** limits funding opportunities and knowledge transfer.
- **Weak commercialisation of research outputs** hinders the development of innovative business models and scalable production processes.

In order to address the challenges currently being experienced, it is essential that Croatia **invests in modern bio-based processing infrastructure, incentivises private-sector engagement, and enhances R&I collaboration. This will allow the commercialisation of bioeconomy innovations to be fostered**.

3.2.4 Cyprus[609] [610] [611] [612] [613] [614] [615]

Cyprus faces significant supply-side barriers that hinder the growth and commercialisation of its bioeconomy. These challenges include high production costs, limited production capacity, low profitability, competition from fossil-based alternatives, and a weak R&I ecosystem. The absence of adequate business models is further hindering the development of bio-based industries in the country. Addressing these barriers is crucial for enhancing Cyprus' bioeconomy and aligning with EU Green Deal objectives.

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Production Costs and Profitability Constraints

One of the primary obstacles hindering the advancement of the bioeconomy in Cyprus is the significant expense associated with production. The country's small-scale agricultural sector, coupled with the high cost of inputs such as water and fertilisers, makes bio-based production expensive. The reliance on imports for many raw materials, including biomass-processing equipment, is a further cost factor. In contrast to larger EU nations that have well-established bio-based supply chains, Cyprus faces challenges related to logistics and infrastructure, which contribute to higher production costs.

The bioeconomy sector continues to experience low profitability, primarily due to limited economies of scale and the substantial initial capital investments required for bio-based ventures. The lack of large-scale biorefineries has resulted in many bio-based products being produced at pilot scale. This has had a negative impact on their competitiveness when compared to conventional fossil-based alternatives. Furthermore, Cyprus's heavy reliance on fossil fuels, which account for over 90% of its energy mix, results in an unfavourable economic environment for bio-based energy and products.

Production Capacity Limitations

Cyprus lacks the industrial-scale processing facilities required to transform raw biomass into high-value bio-based products. The majority of biomass produced on the island, including agricultural residues and organic waste, remains underutilised due to a lack of infrastructure for collection and conversion. Cyprus has made significant progress in the field of biogas production, with several small-scale plants now in operation. However, the island still lacks large-scale industrial biorefineries capable of processing diverse biomass sources into bio-based chemicals, biofuels, or biodegradable plastics.

The limited availability of advanced processing technologies further restricts the efficiency of biomass utilisation. Cyprus has the potential to exploit biomass from agriculture, food processing waste, and algae, but the necessary infrastructure and expertise are lacking. The country has an extensive coastline, which presents a significant opportunity for the development of algae-based bioeconomy projects. However, the commercialisation of algae processing is currently hindered by technological and financial constraints.

Competitive Pressures and Market Challenges

Cyprus' bio-based industries face strong competition from conventional fossil-based products, which are often cheaper and more readily available. The country's small domestic market size and reliance on imports make it difficult for locally produced bio-based alternatives to compete. In the absence of robust policy measures, such as subsidies for bio-based materials or carbon pricing on fossil-based products, bio-based industries face significant challenges in establishing a strong market presence.

Additionally, Cyprus lacks well-established bioeconomy clusters that could foster industrial collaboration and knowledge exchange. Although certain EU-funded initiatives have provided backing for pilot projects, the absence of integrated supply chains and stable demand for bio-based products is hindering the sector's growth. In addition, the general public has limited awareness of

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bio-based alternatives, which is having a negative effect on market penetration and investor confidence in the sector.

Lack of Supporting Business Models

The bioeconomy sector in Cyprus is currently lacking well-developed business models that integrate raw material suppliers, processors, and end-users into a cohesive value chain. In contrast to countries such as Germany and Finland, where industrial symbiosis supports bio-based industries, Cyprus has yet to develop strong networks linking different actors in the bioeconomy. Many companies are reluctant to invest in bio-based ventures due to the lack of long-term supply contracts and clear market demand.

Additionally, the financial landscape in Cyprus does not favour bio-based start-ups, as investors perceive these ventures as high-risk due to long payback periods and market uncertainties. Although financial assistance is available from both EU and national funding programmes, companies seeking to expand their bio-based production still face significant challenges in obtaining the necessary financing.

Weak R&I Ecosystem for Scale-Up and Commercialization

Despite the existence of well-developed research institutions specialising in biotechnology and bio-based sciences, Cyprus experiences challenges in translating research innovations into commercial applications. There is a significant gap between academia and industry, with limited collaboration between universities and businesses in bioeconomy-related fields. Research projects frequently encounter difficulties in progressing beyond the pilot stage, often due to insufficient funding for demonstration plants and commercialisation initiatives.

The country also lags in securing EU bioeconomy funding compared to other Mediterranean nations, which limits opportunities for R&D expansion. There is a lack of dedicated innovation hubs supporting bio-based start-ups, and general business incubators often lack sector-specific expertise in bio-based industries. Cyprus risks falling behind in the global bioeconomy transition if it does not receive adequate support for the scaling up of bio-based technologies.

Addressing Supply-Side Barriers

To overcome these challenges, Cyprus must implement targeted policy measures to support bioeconomy growth. Key recommendations include:

- **Investment in Infrastructure**: Developing biorefinery capacity and biomass collection networks to improve the efficiency of biomass utilisation.
- **Financial Incentives**: Providing grants, tax breaks, and subsidies for bio-based start-ups and biorefineries to reduce the financial risks associated with entering the sector.
- **Market Development**: Implementing bio-based procurement policies and carbon pricing mechanisms to create a competitive advantage for bio-based products.
- **R&I Strengthening**: Enhancing collaboration between universities and industry to facilitate technology transfer and support commercialisation.

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- **Public Awareness Campaigns**: Educating consumers and businesses on the benefits of bio-based products to stimulate demand and market growth.

If these measures are effectively implemented, Cyprus could leverage its biomass resources to develop a competitive and sustainable bioeconomy, contributing to EU climate and energy goals while fostering economic growth.

3.2.5 Czechia[616] [617] [618] [619] [620] [621] [622] [623]

The Czech Republic has ambitious plans for its bioeconomy, but there are several supply-side barriers that limit the competitiveness and commercialisation of emerging feedstocks. Here's a structured breakdown of the main issues across production, economics, and innovation ecosystems:

High Production Costs

- **Low Economies of Scale**: The majority of biomass valorisation projects (e.g. insect protein, algae, bioplastics) are still in pilot or small-scale phases, resulting in high per-unit costs.
- **High Input Costs**: Specialised crops (e.g. hemp, algae) require investments in processing, harvesting equipment, or controlled growing conditions (greenhouses, photobioreactors). For instance: Algae cultivation in controlled environments can be costly both initially and in the long term, and bio-based packaging materials are often unable to compete with fossil-based alternatives in terms of price.
- **Logistics Costs**: The transportation of bulky, low-density biomass (e.g. straw or manure) to processing sites can be costly and logistically challenging.

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Limited Production Capacity

- **Fragmented Supply Chains**: Feedstocks are often dispersed across small farms, and there is an absence of aggregation or centralized pre-processing infrastructure.
- **Seasonal Availability**: Crop residues and certain agricultural by-products are only available during certain seasons, which limits continuous supply for biorefineries.
- **Lack of Specialisation**: However, the adoption of non-traditional biomass crops such as industrial hemp and energy crops remains limited due to various factors, including uncertainty, a lack of expertise, and the absence of contractual agreements with processors.

Low Profitability

- **Uncertain Market Demand**: Markets for many bio-based products (e.g. biofertilisers, bio-based chemicals) are still in development, so the revenue potential is uncertain.
- **High upfront investment, slow adoption, and long return periods** discourage private sector investment.
- **Incentives Favor Energy Use**: In some cases, incentives such as subsidies for biomass burning or biogas have been found to skew markets towards lower-value uses rather than advanced bioproducts.

Competition with Established Industries

- **Fossil-Based Alternatives**: Petrochemical plastics, synthetic fertilisers and fossil fuels remain cheaper, well-established and supported by global supply chains.
- **Competing Biomass Uses**: For instance, straw is also used for animal bedding, mushroom production, or direct combustion, which makes it expensive or unavailable for bio-based product developers.
- **Land-Use Competition**: The incentivisation of feedstock crops may result in competition with food production or other land uses, particularly in regions with limited arable land.

Lack of Supporting Business Models

- **Few Aggregators or Cooperatives**: There are limited models for pooling biomass supply, negotiating contracts, or offering risk-sharing between farmers and processors.
- **Missing Value Chain Actors**: Many insects, aquatic biomass and lignocellulosic waste are not linked to mid-tier processors or logistics services, meaning that there is a lack of connection between raw materials and product manufacturers.
- **Start-ups Face Scaling Barriers**: Many bioeconomy start-ups lack the business development skills, private capital access, or incubation support required to progress from lab to market.

Weak R& I Ecosystem for Scale-Up and Commercialization

- **R&D Fragmentation**: While institutions such as the Czech University of Life Sciences and Mendel University are engaged in pioneering research, mechanisms for technology transfer are underdeveloped.

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- **Limited Demonstration Projects**: There is a paucity of pilot plants or demonstration sites showcasing economically viable bio-based product pathways.
- **Funding Gaps**: Early-stage R&D is supported (e.g., Horizon, TAČR), but funding for scale-up and commercialisation is scarce, especially from private investors.
- **Lack of Tech Readiness Support**: Many innovations are unable to progress beyond TRL 4-6 due to a lack of mentoring, infrastructure, or regulatory clarity for field deployment.

3.2.6 *Estonia*[624] [625] [626] [627] [628] [629] [630] [631] [632] [633] [634]

The bioeconomy of Estonia is facing systemic supply-side challenges that limit its transition to a high-value, circular model. While Estonia has a considerable amount of biomass resources, there are several supply-side barriers that are hindering the full development of its bioeconomy. The barriers to entry in this sector include production costs, capacity limitations, profitability constraints, competitive pressures and the nascent stage of supporting business models.

The current situation is such that Estonia's bioeconomy is characterised by a lower added value per employee compared to the European Union average. This suggests potential inefficiencies or a focus on lower-value processing activities. The primary output from agricultural bioresources is food and animal products, with limited industrial utilisation for higher-value products such as chemicals, pharmaceuticals, or textiles. The underutilisation of advanced processing is a key factor contributing to the sector's lower profitability and constrained growth potential.

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High Production Costs and Low Profitability.

Estonia's bio-based industries are facing considerable challenges due to high production and operational costs, which are reducing their competitiveness in comparison to well-established fossil-based alternatives. A key factor is the fragmented and dispersed biomass supply chain, exacerbated by underdeveloped collection infrastructure. This results in increased logistics costs, estimated at 30% of forestry residue loss during harvesting, and hinders economies of scale due to small average farm sizes (40 hectares) and fragmented forest ownership, in turn raising per-unit processing costs.

The export-oriented raw material economy has been identified as a potential contributor to logistics inefficiencies. Capital-intensive investments in bioenergy solutions by agricultural firms have further strained profitability without delivering short-term returns, as seen in financial assessments of Estonian agricultural companies. The limited domestic value addition is a further complicating factor. A significant proportion of raw biomass, such as the 90% of wooden house components are exported unprocessed, which limits local industries of value-added opportunities. For instance, Estonia's timber chemical processing sector is outperformed by countries such as Finland, primarily due to a persistent reliance on less sophisticated mechanical valorisation techniques.

Advanced processing technologies, especially those necessary for the extraction and purification of high-value components such as lignin, are currently costly and complex. Estonia still relies heavily on imported technologies to implement them. Collectively, these factors have a detrimental effect on the potential for profitable scaling of bio-based production. Furthermore, energy costs remain high due to the country's reliance on oil shale, with fossil fuels accounting for 77% of total energy supply. This has the effect of inflating operational expenses for bio-based ventures, further widening the gap in competitiveness with fossil-based industries.

Due to structural and economic limitations, the Estonian bioeconomy currently generates a value-added output of €23,000–25,000 per employee. This figure is significantly below the EU average of €61,000. In order to enhance profitability, there is a need for a shift towards domestic value retention through investment in advanced processing technologies, better aggregation of biomass, and strategic reforms in energy sourcing.

Limited Production Capacity and Infrastructure.

Estonia is currently lacking large-scale biorefineries for advanced biomaterials. The existing infrastructure and investment in biorefineries and other advanced processing facilities are still in the development phase, which limits the capacity for advanced processing and the creation of high-value bio-based products. While Fibenol's lignin plant processes 90% of hardwood into high-value products, most biomass is still used for low-value energy generation (e.g. wood pellets). Key feedstocks are currently underutilised, thus demonstrating a significant lack of systemic valorisation for biogas or biochemical applications.:

- 3.65 million dry tonnes/year of lignocellulosic biomass from forestry residues.
- 85,000 tonnes/year of manure and 450,000 tonnes/year of wood processing residues.
- Only 5% of municipal biowaste is segregated for circular applications, missing nutrient recovery opportunities.

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The lack of modular biorefineries in rural regions such as Järvamaa and Raplamaa, where SME innovation rates are 40% below the national average, hinders the possibility of decentralised, cost-effective processing.

Competitive Pressures and Market Challenges.

Bio-based products are facing strong competition from fossil-based imports, which currently dominate 90% of the domestic bioplastics and biochemical markets. Consumer demand for bio-alternatives is growing, but higher price premiums and limited awareness are constraining this market. There is currently a limited level of public understanding of bio-based alternatives, which means that demand for these products is not growing as quickly as it could. Meanwhile, the small domestic market of Estonia is not conducive to private investment in niche bioproducts. The timber sector is a prime example of this imbalance: despite forests covering 51% of land, 40% of forestry exports are raw materials, while high-value engineered wood products are imported.

Lack of Supporting Business Models.

The development of a thriving bioeconomy requires robust and innovative business models that can support the entire value chain, from biomass sourcing to the production and marketing of bio-based products. At present, there may be a lack of established business models that are tailored to the specific opportunities and challenges of the Estonian bioeconomy, particularly in emerging areas beyond the traditional agriculture and forestry. The bioeconomy of Estonia is currently lacking integrated value chains that link farmers, processors and end-users. For instance, 95% of municipal biowaste is not segregated, which represents a missed opportunity for circular nutrient recovery. Similarly, crop residues and food processing by-products are rarely repurposed for bio-based chemicals or fertilisers. Industrial symbiosis models, which are commonplace in Nordic peers, are rare due to the following reasons:

- **Weak SME collaboration**: It is interesting to note that only 5% of start-ups in the bioeconomy participate in EU-funded networks.
- **Financing gaps**: It is estimated that **less than 5% of national R&D funding** supports bio-based ventures, and venture capital access is limited. The absence of **long-term supply contracts** or guaranteed offtake agreements is a further deterrent to investment in bio-based innovations.
- **Regulatory barriers**: Legislation that defines "waste" and "by-products" in outdated terms is a barrier to the development of circular business models. Concurrently, the integration of renewable energy into the grid is delayed by grid constraints.

Weak R&D&I Ecosystem for scale-up.

A robust innovation ecosystem is pivotal for translating research and development into commercially viable bioeconomy ventures. This necessitates effective collaboration between research institutions, industry, and government, as well as access to funding for piloting, scaling up, and commercialisation. Despite the robust academic research in this field (e.g., Estonian University of Life Sciences), there remains a significant gap between research and industry application, thus conforming to an **inadequate technology transfer**. Since 2015, **only two bioeconomy projects**

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have been funded under the NUTIKAS programme, reflecting weak ties between academia and industry. Key gaps include:

- **Limited demo-scale facilities**: not many demo-scale facilities due to many innovations at or below TRL 4-5.
- **Sector-specific expertise**: Central Estonia's workforce has 15% fewer STEM graduates than the national average, which is hindering biorefinery operations.
- **Fragmented policy support**: Bioeconomy strategies are divided across ministries, with no harmonised methodology for sustainable biomass allocation.

Addressing Supply-Side Barriers:

To overcome these challenges, Estonia requires a multifaceted approach and should prioritise the following actions:

- **Infrastructure investments**: The development of regional biomass hubs and commercial modular biorefineries is recommended in order to reduce logistics costs and valorise underused residues.
- **Financial incentives**: Introducing tax incentives for SMEs in the bio-based sector, along with guarantees for private loans, is a key strategy to de-risk in scaling innovative initiatives.
- **Market creation**: It is recommended that bio-based procurement be mandated in public contracts, and that carbon pricing be enforced to provide businesses with a competitive advantage over their fossil fuel-based competitors. To create a competitive business environment, it is crucial to foster forestry entrepreneurship, support the development of new value chains, and encourage collaboration between different sectors
- **R&D&I strengthening**: The establishment of a national bioeconomy innovation hub is recommended, with the aim of aligning academia, industry and policymakers. The focus of this initiative should be on lignin valorisation and marine biomass, with examples of this biomass including red seaweed. Initiatives such as the SWEETWOODS project, which is focused on producing high-purity lignin and wood sugars, could facilitate this process.
- **Policy integration**: The harmonisation of bioeconomy strategies across ministries, the enforcement of cascading biomass utilisation principles, and the updating of waste legislation to promote circularity are three key areas of focus.
- **Circular business models**: Collaboration across the whole value chain is promoted, from biomass producers to end-product manufacturers, and innovative circular business models are developed and the concept of industrial symbiosis implemented within Järvamaa clusters, leveraging agroresidues to produce biogas and several bio-based products.
- **Education, skills and awareness**: The integration of curricula on the subject of a circular bioeconomy into universities and the launching of public campaigns designed to stimulate market demand are recommended, thus contributing to the further development and acceptance of the circular bioeconomy.

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By addressing these barriers, Estonia has the potential to transform its bioeconomy into a competitive, high-value sector, reducing fossil dependency and advancing EU Green Deal objectives.

3.2.7 France

France is a leader in the bioeconomy, particularly in regions such as Grand Est and Haut-de-France. However, actors in different sectors continue to face technical challenges that are common to other countries. The following is a summary of the challenges encountered in each sector:

Bio-based molecules:

- Scalability: scaling microbial fermentation or enzymatic synthesis can be challenging.
- Process efficiency:
  - Complexity of enzyme immobilisation.
  - Contamination-proneness of biotech processes.
- Digital transformation:
  - Limited use of AI for optimisation of strains via bioengineering.
  - Limited use of AI for the prediction of structure/activity relationship.
- Environmental performance: downstream processing generates significant amount of waste or can be energy intensive.

Bio-based materials:

- Scalability: difficulties in producing high-quality biopolymers at industrial scale (e.g., PHA production that depends on in situ PHA synthesis of microbes).
- Product development: limited performance of bio-based materials compared to their fossil-based counterparts, for instance insufficient mechanical and barrier properties of biopolymers compared to traditional plastics, relatively poor thermal resistance of various bio-based materials.
- Environmental performance:
  - Difficult recycling of bio-based materials and especially composite materials (issues with adhesives that may hinder the recycling process, difficulties to separate the different materials).
  - Some materials have poor end-of-life management options such as biopolymers with poor biodegradability under natural conditions.

Food & Feed

- Scalability: lab-to-industrial scale-up of certain novel food processes is challenging such as cultured meat, far from being cost-effective as of today.
- Product development:
  - Need for optimisation of characterisation and functionalisation of plant-based proteins.

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    - Flavour, texture, and nutritional properties of alternative proteins sometimes inferior as traditional proteins.
    - Need to facilitate the emergence and culture of novel plant varieties (e.g., lentils, faba beans).
- Circularity & Waste: cascade valorisation of agri-food side streams.
- Digital transformation: opportunity for integration of AI in precision agriculture and food traceability.

Bioresources:

- Scalability:
    - Reliable, year-round supply of bioresources that are seasonal.
    - Algal biomass production suffers from high energy costs and harvesting inefficiencies.
- Product development: tailoring biomass characteristics (e.g., lignin content) for downstream use.
- Process efficiency: lack of cost-effective pre-treatment technologies and high energy use in biomass fractionation.
- Circularity: opportunity for better integration with urban or industrial biowaste streams.

Bioenergy:

- Process efficiency:
    - Low energy conversion efficiency, especially in second-generation biofuels.
    - Enzyme and microbial robustness in lignocellulosic ethanol production.
- Digital transformation: smart grid integration and predictive control of biogas systems.
- Circularity & waste: limited valorisation of digestate from anaerobic digestion.
- Environmental performance: potential land-use change and feedstock competition with food (priority usage of biomass).

Cross-sector challenges:

- Process efficiency: adaptation of processes to the variability of biomass (e.g., quality, moisture content).
- Digital transformation: limited use of digital twins or AI-driven optimisation.
- Environmental performance: lack of data or standard method to evaluate the environmental performance and allow a benchmark.

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3.2.8 Greece[635] [636] [637] [638] [639] [640] [641] [642] [643] [644] [645] [646] [647] [648] [649]

Greece's bioeconomy has significant untapped potential, but the large-scale commercial deployment of its resources is being hindered by several supply-side barriers. These challenges include high production costs, limited production capacity, low profitability, competition from fossil-based alternatives, a lack of supporting business models, and weaknesses in the R&I ecosystem necessary for scaling up and commercialisation. Addressing these barriers is crucial to fostering a sustainable and competitive bio-based economy in Greece, aligning with EU Green Deal objectives and the Greek National Bioeconomy Roadmap 2025.

Production Costs and Profitability Constraints

One of the primary challenges currently being faced by Greece's bioeconomy is high production costs, which are the result of expensive raw material procurement, inefficient supply chains and high

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energy prices. In contrast to bioeconomy leaders such as Germany and Finland, Greece has not developed large-scale biorefineries, resulting in costly and fragmented production processes. The country's small-scale farming system (average farm size of 4.8 hectares compared to 14.3 hectares in the EU) further exacerbates inefficiencies, increasing costs per unit of bio-based feedstock. Profitability margins remain low, discouraging businesses from investing in bio-based ventures. The absence of economies of scale and the lack of secure long-term feedstock contracts can create financial risks for investors. At present, the majority of biomass is used for low-value energy applications rather than high-value bioplastics, biochemicals or advanced biofuels, which limits potential profit margins. Additionally, the high taxation on biofuels (24%) acts as a deterrent to investment in bio-based energy projects. In the absence of tax incentives or subsidies, Greek bio-based industries face challenges in competing with more cost-effective fossil-based alternatives. Furthermore, the unpredictability of feedstock availability, stemming from climate change and the volatility of agricultural yields, introduces additional risks for investors and businesses.

Production Capacity Limitations

Greece's limited industrial capacity for processing biomass into high-value products remains a significant constraint. The country lacks large-scale biorefineries, with the result that most raw biomass is exported without value addition. Consequently, Greece imports substantial quantities of bio-based chemicals, biofuels and biomaterials that could otherwise be produced domestically. In addition, infrastructure bottlenecks in storage, transport, and logistics prevent the efficient handling of biomass. The fragmented nature of Greece's agricultural landscape, coupled with the challenges posed by inadequate regional connectivity, contributes to higher transportation costs. This, in turn, results in biomass being less competitive than imported fossil-based raw materials. Greece must invest in bioeconomy-specific processing facilities and integrated supply chains if it is to effectively scale up bio-based production. Western Macedonia, a region undergoing post-lignite transition, has the potential to become a bioeconomy hub, but investment in biorefinery infrastructure and biomass collection networks remains low. The absence of adequate feedstock processing infrastructure results in the inefficient utilisation of agricultural residues, including wheat straw, corn husks and pruning waste. These residues have the potential to support a thriving bio-based energy sector.

Competitive Pressures and Market Challenges

Greek bio-based industries face intense competition from well-established European bioeconomy leaders such as Germany, the Netherlands, and Scandinavia. These countries have well-developed bioeconomy clusters, advanced biorefineries, and strong market demand for bio-based products. The dominance of low-cost fossil-based alternatives in the markets for plastics, chemicals and energy further limits the competitiveness of bio-based products. Additionally, Greek SMEs encounter challenges in accessing international bio-based value chains due to inadequate distribution networks, high production costs, and a lack of branding for bio-based innovations. This hinders Greek bio-based start-ups from accessing global markets, which limits their potential for growth. To address this, regulatory interventions such as mandatory bio-based procurement targets and carbon pricing mechanisms could help reduce the price difference between bio-based and fossil-based

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products, creating a more level playing field. However, Greece has yet to implement strong bioeconomy-specific policy measures to stimulate demand for bio-based alternatives.

Lack of Supporting Business Models

The Greek bioeconomy sector is currently lacking integrated business models that connect biomass producers, processors, and end-users in a stable value chain. Furthermore, financial instruments for bioeconomy investment remain weak. Greek bio-based enterprises face challenges in accessing venture capital, green bonds, and government-backed subsidies, which hinders their ability to secure funding for biorefineries, bio-based start-ups, and the scaling up of new technologies. The lack of long-term biomass supply contracts creates uncertainty for bio-based manufacturers, discouraging investment in processing facilities. The development of cooperative business models that ensure a stable supply of feedstock and shared financial risk has the potential to enhance market confidence and stimulate investment in bio-based production.

Weak R&I Ecosystem for Scale-Up and Commercialisation

Despite a robust academic and research foundation in bioeconomy, Greece faces challenges in successfully translating R&D into commercial outcomes. Greek universities and research institutes, including CERTH and the Agricultural University of Athens, are engaged in bio-based research. However, there is room for improvement in terms of technology transfer mechanisms. The absence of pilot-scale demonstration plants and industrial partnerships is hindering the commercialisation of new bio-based technologies. While countries like Finland and Germany have dedicated funding for bio-based innovation hubs, Greece lacks structured innovation centres that bridge the gap between research and industry. Securing funding for the commercialisation of bio-based technology is a challenge for Greek SMEs and start-ups. The reason for this is that most available financing focuses on traditional energy and industrial sectors rather than bio-based innovations. The lack of sector-specific business incubators and accelerators has a negative impact on the scaling up of bioeconomy start-ups.

Policy Recommendations to Overcome Supply-Side Barriers

In order to address these critical supply-side barriers, Greece must implement targeted policy interventions, investment strategies, and regulatory reforms. Key recommendations include:

- **Investment in Biorefinery Infrastructure**:
  - Establish regional biomass processing hubs to convert agricultural residues into high-value bio-based products.
  - Provide CAPEX and OPEX subsidies for biomass-to-energy plants and biorefineries to lower production costs.
  - Financial Incentives for Bio-Based Industries:
  - Reduce taxation on biofuels and bio-based products to encourage investment.
  - Introduce low-interest loans and grants for bio-based start-ups and SMEs.
- **Regulatory Support for Bio-Based Products**:
  - Implement mandatory bio-based procurement policies in public sector supply chains.
  - Introduce carbon pricing to make bio-based alternatives more competitive.

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- **Enhancement of Research-Industry Collaboration**:
  - Establish dedicated bioeconomy innovation hubs linked to Greek research institutions.
  - Increase EU Horizon Europe funding participation to support bio-based technology commercialization.
- **Development of Bio-Based Market Networks**:
  - Foster bioeconomy clusters similar to Germany and Finland, bringing together farmers, processors, and manufacturers.
  - Support export-oriented bio-based value chains to integrate Greek bio-based products into European and global markets.

Greece has significant bioeconomy potential, but barriers on the supply side are hindering large-scale commercialisation. In order to overcome challenges such as high production costs, limited infrastructure, and weak business models, targeted investments, regulatory incentives, and stronger industry-research collaboration are required. Greece can unlock its bioeconomy potential, reduce its dependence on fossil fuels and achieve sustainable economic growth in alignment with the EU Green Deal by implementing strategic policy measures and fostering a competitive bio-based market.

3.2.9 Hungary[650] [651] [652] [653] [654] [655] [656]

The development and commercialisation of bio-based products in Hungary is being hindered by several supply-side barriers. These include high production costs, limited production capacity, low profitability, competition with established industries and weaknesses in the R&I ecosystem. These factors limit the scalability of bio-based industries and hinder their commercial success.

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High Production Costs and Limited Financial Incentives

A key challenge to the bioeconomy's development in Hungary is the high cost of bio-based production. The following factors have been identified as contributing to this issue:

- **High input costs**: the cost of raw materials, such as biomass feedstocks, remains high due to inefficient harvesting, collection and processing systems.
- **Expensive processing technologies**: Advanced technologies for biorefining, bioplastics and biofuel production require significant capital investment.
- **Lack of subsidies and financial incentives**: Government support programmes primarily support traditional agriculture and fossil-based industries, so financial support for bio-based innovations is limited.
- **Expensive logistics and supply chains**: The transportation of biomass feedstock from rural areas to processing plants has been shown to increase production costs.

Limited production capacities

Hungary does not currently have the necessary industrial capacity to expand bio-based production. The primary issues are as follows:

- **Inadequate biorefinery infrastructure**: The country has few bioprocessing plants, and most bio-based products are produced on a small scale.
- **Low investment in scaling up technologies**: The transition from pilot projects to large-scale production is hindered by a lack of capital investment and supporting policies.
- **Limited labour and expertise**: There is a shortage of skilled labour in the bioeconomy sector in the areas of bioprocessing, industrial biotechnology and green chemistry.

Profitability and Market Uncertainty

The profitability of bio-based businesses in Hungary is constrained by:

- **Low market demand for bio-based products**: Consumer awareness of sustainable alternatives is limited, as is their willingness to pay premium prices for them.
- **Unstable revenue streams**: Many bio-based industries lack long-term purchase agreements and contracts with buyers.
- **Price competition from fossil-based alternatives**: Bio-based products often find it difficult to compete with cheaper petroleum-based materials.

Competition with Conventional Industries

The bio-based sector in Hungary faces intense competition from well-established fossil-based industries and traditional agriculture:

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- **Strong presence of conventional chemical and energy industries**: Hungary's energy and chemical sectors continue to favour fossil-based solutions due to existing investments and infrastructure.
- **Subsidies for fossil-based fuels and materials**: Government policies continue to provide financial advantages to conventional industries, making it challenging for bio-based businesses to compete.
- **Lack of regulatory support for bio-based alternatives**: Policy incentives promoting the transition from fossil-based to bio-based products are limited.

Weaknesses in the R&I Ecosystem

The bioeconomy sector in Hungary is facing challenges in research, innovation, and technology transfer:

- **Limited collaboration between academia and industry**: Universities and research institutions tend to operate in isolation from commercial enterprises, which can result in a delay in the application of innovations.
- **Insufficient funding for R&D projects**: As of 2021, Hungary invests less in bioeconomy R&D than Western European countries, which limits the development of breakthrough technologies.
- **Slow technology transfer and commercialisation**: Research findings are not always translated into market-ready solutions. This is partly due to a lack of incubator programmes and venture capital investments.

The supply-side barriers in Hungary's bioeconomy sector include high production costs, limited industrial capacity, low profitability, competition from fossil-based industries, and weaknesses in the R&I ecosystem. To address these challenges, it is essential that the government provides increased support, that there is investment in infrastructure, that market development strategies are implemented and that there is improved collaboration between academia and industry.

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3.2.10 Italy[657] [658] [659] [660]

Production Costs, Capacity, Profitability, Competition

The production costs of bio-based technologies are generally high, particularly during the start-up phase. This is due to the significant investments required for the development of new technologies and infrastructures, as well as for the acquisition of biological raw materials. These raw materials are often not as competitive in terms of pricing as traditional resources. In terms of capacity, many Italian companies, especially small and medium-sized enterprises, have limited resources with which to implement large-scale production processes. This, in turn, limits their competitiveness when compared to larger or international industrial companies. Furthermore, the sector is experiencing intense competition from new international players in the bioeconomy sector, who are leveraging economies of scale and diversified resources. Regarding business models, Italian companies are closely linked to traditional agri-food production. This cultural context presents a challenge when it comes to adopting innovative approaches necessary to fully realise the potential of the bioeconomy. In order to overcome these obstacles, there is a need for collaborative strategies, access to financing, and adaptation to new market and technological dynamics.

Production Costs and Profitability Constraints

Two of the primary economic factors hindering the development of the bioeconomy in Italy are production costs and profitability constraints. As previously stated, production costs in the bioeconomy sector tend to be higher than in traditional sectors, which limits the development of new business initiatives. The cost of organic raw materials often exceeds that of fossil fuels. Bio-based production is not yet scalable enough to generate economies of scale, resulting in a production price that is uncompetitive.

The financial viability and economic sustainability of bioeconomic projects can certainly be enhanced by the implementation of stable and dedicated policy support measures, in addition to substantial investment in new productive initiatives.

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Production Capacity Limitations

The bioeconomy's production capacity in Italy is limited primarily due to the prevalence of small and medium-sized enterprises. These enterprises often lack the scale to achieve economies of scale and compete on a global stage. The sector's growth is hindered by two key issues. Firstly, there is a lack of modern and adequate infrastructure for biomass processing. Secondly, there is a scarcity of advanced technologies accessible to companies. In addition, the restricted availability of local biological resources, coupled with the substantial costs incurred by companies when transitioning to bio-based models, serves to compound these challenges. The abovementioned factors have a combined effect of reducing the production capacity of companies, thereby diminishing their competitiveness and economic sustainability.

Competitive Pressures and Market Challenges

The main market challenges in transitioning to a bio-based industry pertain to various aspects related to demand, competitiveness, regulations and consumer awareness. To date, demand for bio-based products remains limited, primarily due to cost considerations and a lack of awareness or interest amongst consumers and companies. Many consumers and industrial sectors are still tied to conventional consumption and production models, based on fossil resources, and have not yet fully adopted more sustainable models. This poses a significant challenge for the entry of bio-based products into the market.

Italian companies operating in the bioeconomy sector face significant competition from global competitors, who often possess greater economies of scale, access to substantial capital and abundant natural resources. It is important to note that international competitiveness can limit growth opportunities for Italian companies.

The bioeconomy is still perceived by many companies and consumers as an emerging and not yet fully consolidated sector.

Need for pilot and demonstration plants for R&D transfer

The absence of pilot and demonstration plants in Italy has the potential to hinder the development of the bioeconomy, thereby limiting experimentation, the adoption of innovative technologies and the transfer of knowledge to the productive fabric. Investing in this infrastructure is crucial to bridge the gap between research, innovation and industrial production. Large companies can manage this in-house with their own resources, but for widespread diffusion in the Italian production sector, technology transfer centres accessible to all are needed.

Addressing Supply-Side Barriers

In order to overcome the supply-side barriers in Italy's bioeconomy, an integrated approach is required. Firstly, investment is required in research and development, as well as pilot and demonstration plants, to test and validate new technologies. In order to achieve this, it is essential that national and European policies provide support for the sector through the provision of incentives, subsidies and a stable regulatory framework, with a view to reducing uncertainty and stimulating investment. Public-private collaboration is essential to address technological and financial

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challenges, while SMEs need targeted funding programmes and training to compete in the sector. It is vital to increase access to funding and investment so that companies can invest in innovation.

Concurrently, there is an opportunity to enhance the management of raw materials, with a particular emphasis on sustainable agricultural practices and the utilisation of all secondary biomass. A coordinated effort is required to accelerate the transition to a competitive and sustainable bioeconomic model.

3.2.11 Latvia[661] [662] [663] [664] [665]

Production Costs and Profitability Constraints

The value of primary production per hectare of agricultural land in Latvia is amongst the lowest in the EU. This indicates a considerable potential for increasing the production of bioresources. In comparison to the highly developed countries of the EU, Latvia's productivity level shows a marked improvement, which is primarily the result of high total factor productivity and significant differences in the quality of production resources (human and capital). In 2020, Latvia's productivity level was 51.7% of the EU average. Furthermore, Latvia's economy is heavily reliant on non-renewable fossil resources, a factor that has implications for economic, environmental and national security. Considering this, the bioeconomy strategy aims to reduce Latvia's reliance on fossil fuels and transition to the use of bioresources.

Production Capacity Limitations

There is a critical lack of well-remunerated employment opportunities in Latvia, indicating a shortage of skilled workers. Migration has had a significant impact on the population dynamics of the region, with a net decrease of 270,000 inhabitants from 2000 to 2016. Notably, the majority of these individuals are within the younger demographic.

The EU regulation regarding LULUCF poses a significant threat to the development of Latvia's forestry sector and the maintenance of the current level of activity in forest management until 2030.

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The pulp and paper product subsector is relatively small in Latvia. In February 2025, Fibenol, a producer of biomaterials based in Estonia, announced its intention to seek funding for the construction of a state-of-the-art €700 million biorefinery in Latvia. Should this initiative be successful, it will result in a significant increase in production capacity.

Competitive Pressures and Market Challenges

Numerous prominent companies have identified a profitable business model and are successfully operating within the bioeconomy sector in Latvia. It is evident that the primary focus of these companies does not necessarily lie in generating higher levels of added value in Latvia. Consequently, the most efficient utilisation of land resources from a socio-economic standpoint is not a central concern. Furthermore, it is possible that they will be interested in maintaining the current status quo. If the bioeconomy market attracts new participants, this will result in increased competition for bioresources, which will not benefit current market participants. In light of the pivotal role that development plays in the context of fostering the nation's bioeconomy, the prevailing circumstances are poised to present certain challenges.

In the wake of Russia's full-scale invasion of Ukraine in February 2022, there has been a rapid acceleration in the efforts to free the energy sector from its reliance on Russian resources. As a result, in early 2023, the import of Russian fossil fuels was prohibited. Instead, there has been an increase in the import of liquefied fossil gas from the Klaipeda plant in Lithuania. This plant has supplied gas to Latvia since 2015.

In response to the EU's imposition of sanctions on Russia, Moscow has taken measures to restrict the import of dairy and fishery products from Latvia, amongst other actions. In 2014, Latvia's exports to its neighbour decreased by 25% compared to the previous year.

Lack of Supporting Business Models

The private sector in agriculture and forestry is characterised by a fragmented structure of undertakings and inefficient production. This is significantly below the average level achieved in the EU Member States. In order to change it, it is necessary: 1) To alter the conventional structure of manufacturing by centring on products with higher added value; 2) To produce functional and niche products; 3) To substitute imports with domestic products; 4) To implement energy performance measures; 5) To ensure balanced development and succession of all sections of the value chain, including the promotion of private investments for the processing of biomass.

Weak R&I Ecosystem for Scale-Up and Commercialisation

Latvia's bioeconomy sectors, along with the national economy and society, are being hindered in their development due to insufficient funding for research and development, including investments from the private sector. In recent years, scientific institutions in the bioeconomy sector have implemented a few key activities to promote the development of the sector. The foundation of these activities is the coordinated management of research institutions within the framework of the Strategic Association for Bioeconomy Research.

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3.2.12 Lithuania[666] [667]

Lithuania has a well-developed agricultural and forestry sector, providing a strong foundation for its bioeconomy. However, the country still struggles with high production costs, limited processing capacity, weak market demand, and an underdeveloped innovation ecosystem. Lithuania's approach to biomass export is similar to that of Romania. The decision not to process biomass into high-value bio-based products is likely to limit the sector's profitability.

The absence of adequate business models and insufficient policy incentives further hinders bioeconomic growth. Additionally, there is a lack of developed biorefinery infrastructure and a need for stronger research-industry collaboration to facilitate the scaling up of bio-based innovations. Competition from Western European bioeconomy industries is another challenge, as Lithuania strives to match their level of technological advancement.

However, recent analyses highlight that Lithuania has significant potential in bioenergy production, particularly in biogas and biofuels. The country has a growing bioenergy sector, with increasing investments in biomass-based heating systems, biogas plants, and biofuel production. Lithuania's strategic focus on renewable energy and climate neutrality creates an opportunity to integrate bio-based solutions into the energy mix.

High Production Costs and Limited Profitability

There are several cost-related challenges hindering the development of Lithuania's bioeconomy, including:

- **High operational costs**: Limited investment in modern processing facilities leads to inefficient production methods, raising costs.
- **Expensive feedstock logistics**: Lithuania has a fragmented agricultural and forestry sector, making it costly to collect and transport biomass.
- **Limited domestic processing capacity**: A large share of raw biomass (e.g., timber, agricultural residues) is exported rather than processed into high-value bio-based products.
- **Energy and raw material price volatility**: Fluctuating costs of inputs affect the profitability of bio-based industries, especially in biofuel production.

Profitability remains low due to:

[666] Vitunskienė, V., and Aleksandravičienė, A., Executive summary of the strategic concept paper for bioeconomy: Lithuania (2023) BIOEASTsUP H2020 Project

[667] Aleksandravičienė, A., et al., The strategic concept for the Lithuanian bioeconomy: insights for niche bioenergy sectors (2023) **https://doi.org/10.12688/openreseurope.16085.2**

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- **Weak value-added production**: The bioeconomy is still heavily reliant on primary production (e.g., raw timber, unprocessed crops), with limited conversion into bio-based chemicals, bioplastics, and advanced biofuels.
- **Lack of market incentives**: Bio-based products are often more expensive than fossil-based alternatives, and government support (such as subsidies or green procurement policies) is insufficient to drive demand.

Despite these challenges, Lithuania has shown progress in the bioenergy sector, with biofuels and biogas becoming increasingly competitive due to EU climate policies. The use of bio-based heating solutions is also gaining traction, especially in rural areas.

Potential solutions: In order to enhance the bioprocessing infrastructure, optimise logistics efficiency, and establish financial incentives for the adoption of bio-based products.

Limited Production Capacity and Competition

Lithuania's industrial capacity is not sufficient to develop high-value bio-based products, leading to:

- **Underdeveloped biorefinery infrastructure**: The country has few advanced biorefineries capable of producing biofuels, bio-based chemicals, and innovative biomaterials.
- **Competition from foreign bio-based industries**: More developed bioeconomy sectors in Western Europe produce bio-based products at a lower cost and higher quality, limiting Lithuania's market competitiveness.
- **Dependence on raw biomass exports**: Lithuania exports large amounts of raw materials (e.g., wood, grain), missing opportunities for domestic value-added processing.

However, Lithuania's bioenergy sector is becoming a strong competitor in the Baltic region. The country has implemented several initiatives to promote sustainable biomass use, particularly for district heating and electricity generation. This shift has the potential to pave the way for broader bioeconomy development, including biorefineries and bio-based industrial applications.

Potential solutions: The objective is to attract foreign and domestic investment in bioprocessing industries, and to establish specialised bioeconomy hubs.

Lack of Supporting Business Models

The Lithuanian bioeconomy sector is currently lacking well-developed business models, resulting in:

- **Low private sector engagement**: Many companies perceive bio-based industries as risky due to high investment costs and uncertain returns.
- **Weak industrial cooperation**: There is limited collaboration between agriculture, forestry, and manufacturing sectors to create integrated bio-based value chains.
- **Regulatory and financial barriers**: Bureaucratic hurdles and insufficient government incentives discourage investment in bio-based projects.

Lithuania is beginning to address these challenges by integrating bio-based solutions into national climate and energy strategies. Nevertheless, there remains a requirement for more robust incentives and a more comprehensive business support framework.

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Possible solutions:

- Developing public-private partnerships to share investment risks.
- Establishing bioeconomic clusters to connect farmers, processors, and manufacturers.
- Introducing tax incentives for businesses investing in bio-based innovation.

Weak R&I Ecosystem for Scale-Up and Commercialisation

Lithuania has a growing but still underdeveloped research and innovation ecosystem for bioeconomy development, with barriers such as:

- **Low R&D investment**: Lithuania spends a relatively low percentage of GDP on bioeconomy research, limiting innovation in bio-based materials and technologies.
- **Lack of industry-academia collaboration**: Research institutions produce bioeconomy-related knowledge, but technology transfer to businesses is weak.
- **Limited commercialisation pathways**: Start-ups and SMEs struggle to scale up due to insufficient funding and support mechanisms.

However, Lithuania has identified bioeconomy as a strategic priority in its innovation policies. The government is exploring new ways to integrate bio-based industries into research funding programmes, particularly in the areas of renewable energy and bio-based materials.

Possible solutions:

- Increasing R&D funding through EU programs (e.g., Horizon Europe, European Innovation Council).
- Creating bioeconomy innovation hubs to facilitate knowledge exchange between researchers and businesses.
- Establishing government grants and venture capital incentives for start-ups in the bioeconomy sector.

Lithuania's bioeconomy has considerable potential but faces serious supply-side challenges due to high production costs, limited infrastructure, low profitability, and weak business models. Additionally, the R&I ecosystem is not yet fully developed, which makes it difficult to scale up and commercialise bio-based innovations. However, Lithuania has made notable progress in the bioenergy sector, particularly in biofuels and biogas, which could serve as a foundation for broader bioeconomic growth. Lithuania can create synergies with other bio-based industries by leveraging its advancements in biomass-based energy. In order to address these barriers, investment in biorefineries, improved business models, stronger policy incentives and enhanced industry-research collaboration is required. This will boost Lithuania's competitiveness in the EU bioeconomy.

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3.2.13 Malta[668] [669] [670] [671] [672] [673]

Despite growing policy attention and EU support, Malta's bioeconomy faces persistent supply-side barriers that hinder commercial expansion and innovation. The challenges being faced by the industry at the present time are many and varied. These include high production costs, limited processing capacity, modest profitability, intense competition from conventional products, fragmented business models, and a research and innovation ecosystem which has yet to be fully developed. Overcoming these constraints is imperative for Malta to align with the EU Green Deal objectives and unlock the potential of its bioeconomy.

Production Costs and Profitability Constraints

The bioeconomy of Malta faces challenges due to its production costs being high. This is a consequence of the bioeconomy's small-scale nature, fragmented land holdings, and heavy reliance on imported inputs, especially to produce livestock and dairy products. Fragmented supply chains and limited economies of scale further drive-up costs and make it challenging for Maltese manufacturers to compete on price in international markets. Profitability remains low, with agricultural incomes and productivity per worker significantly below the EU average.

To address these challenges, Malta should **focus on value-added products and niche markets**. The country's efforts in this regard will be rewarded as it is in a position to command premium prices, while also enhancing sector sustainability, by leveraging EU quality labels and certifications.

Production Capacity Limitations

The limited land area and high population density of Malta restrict the development of large-scale bio-based processing infrastructure. Investment in essential processing and grading facilities is currently underway, though at a comparatively modest scale in relation to larger EU countries. The agri-food and aquaculture sectors show considerable potential for future investment. However, in order to meet market demands and support sustainable expansion, there is a need for investment in infrastructure and technology.

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[668] Commission recommendations for Malta's CAP Strategic Plan (2020) | European Commission

[669] Ministry for Agriculture, Fisheries and Animal Rights - Draft of Malta's Strategy for Resilient Food Systems (2024) Government of Malta [online].

[670] ShapingBio. Bioeconomy Country File: Malta (2022). Retrieved from [online].

[671] Circular Economy Country Profile 2024 - Malta | ETC-CE Report 2024/Malta | European Topic Centre – Circular economy and resource use | European Environment Agency

[672] The European Agricultural Fund for Rural Development | Malta – Rural Development Programme (2014-2022) | Retrieved from [online].

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Securing access to EU funds and implementing strategic policies to ensure effective land use and support digitalisation are essential to overcoming these capacity constraints.

Competitive Pressures and Market Challenges

Maltese bio-based products face strong competition from conventional and imported alternatives, which are often more cost-effective and better distributed. The sector's small-scale and fragmented structure has the effect of limiting bargaining power and market reach. Malta's reliance on imports for essential inputs, such as animal feed, continues to impact the country's competitiveness.

The **emergence of new markets for upcycled and waste-derived products** presents opportunities for business, however awareness amongst consumers and demand for bio-based alternatives remains limited. To increase demand for and differentiate Maltese bio-based products, the **implementation of educational campaigns and market development initiatives** is recommended.

Lack of Supporting Business Models

In the Maltese bioeconomy, business models are frequently characterised by fragmentation, with a lack of integration across the value chain. Small and micro-farm holdings are predominant, with limited collaboration amongst producers and insufficient economies of scale. To improve commercial capabilities, access new markets, and adopt digital tools for sales and distribution, producer organisations need to be strengthened.

Empowering producer organisations and encouraging cooperation are vital for developing robust, scalable business strategies.

Weak R&I Ecosystem for Scale-Up and Commercialisation

Malta's R&I ecosystem for bioeconomy is still in its early stages of development, with limited collaboration between academia, industry and government. Innovation and skills gaps, particularly amongst older farm managers, are hindering investment in new technologies and practices. Research and innovation are recognised as strategic priorities, but implementation is hindered by fragmented networks, inadequate public-private collaboration and underutilisation of EU funding opportunities.

To bridge the gap between research and commercialisation, targeted investment in R&I, knowledge transfer, and the development of innovation networks is required.

Malta's bioeconomy shows great potential, but systemic supply-side barriers are currently holding it back. To build a competitive, resilient bio-based sector that aligns with EU green growth ambitions, it is imperative to enhance infrastructure, professionalise producer organisations, incentivise sustainable markets and strengthen the R&I-commercialisation bridge. In order to ensure a prosperous bioeconomic future for Malta, it is essential to enhance collaboration, target investment and focus on value-added and niche markets.

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3.2.14 Poland[674]

In addition to the issues related to the availability and utilisation of feedstock for bio-based projects and investments, the development of the bioeconomy in Poland is currently limited by the coexistence of other barriers. The challenges faced in this area include a lack of awareness regarding the advantages of bio-based applications from the valorisation of biomass. This is also due to the lack of a structured R&D ecosystem that could support the acceleration of bio-based value chains. Moreover, high production costs, coupled with limited production capacity, result in low profitability and high complexity in scaling up and commercialising our products. Overcoming these barriers is vital for Poland to align with the Green Deal objectives, as well as with the Strategy for Sustainable Development of Rural Areas, the Roadmap for the Circular Economy in Poland, the Plan for Rural Areas and the National Energy and Climate Plan for the years 2021-2030.

Bio-based business models, R&I ecosystem

The definition and diffusion of bio-based business models is crucial to demonstrate to the productive system what could be replicated in a sustainable way (economically, socially and of course, environmentally). Achieving this requires awareness of all potential players. However, this is not possible without a structured, interconnected and well-positioned bioeconomy ecosystem, with strategic actors such as bioeconomy clusters acting as orchestrators. It is vital that technology transfer from academia to the production sector is strengthened, and that links between primary producers, industry and the service industry are created and enhanced. Identifying and promoting business models which create value for all stakeholders, including farmers and foresters, will be also essential.

In order to establish a sustainable bio-based industry, it is essential to establish new value systems that span the boundaries between the various and distinctive industrial and academic sectors, with a view to creating synergies in the areas of feedstock, technology and market.

Production Costs and Profitability Constraints

At present, the price of bio-based applications exceeds that of fossil-based solutions, which is a limiting factor in the development of bioeconomy-related investments. Companies are facing challenges due to high production costs, which are a result of two main factors. Firstly, there has been a significant increase in energy prices. Secondly, there has been a considerable rise in the costs of raw materials. When this challenge is coupled with a rural economy that is characterised by low profitability and a lack of cost-efficient supply chains, as is the case in Poland, the complexity of designing and activating bioeconomy projects becomes evident. The lack of interlinkages between

[674] Mapping Poland's bio-based potential | Country-Report-Poland-2023 | Bio-based Industries Consortium (BIC)

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sectors is proving to be a challenge in the establishment of bio-based value chains. Additionally, the perceived low profitability of the business is deterring investment interest.

Dedicated funding instruments for bioeconomy-related projects and investments could be a starting point for addressing this issue. However, it is essential to clearly demonstrate the return on investment and the profitability of bio-based operations in the medium and long term to stakeholders, banks and investors.

Production Capacity Limitations

Despite the availability of feedstock and the presence of research centres specialising in bio-based materials, environment and life sciences, Poland's bio-based production capacity remains constrained. It is evident that companies are not yet fully cognisant of the advantages associated with the bioeconomy. The absence of interconnected, cross-sectoral value chains and scalable, fair business models further complicates the situation.

Poland has abundant residual biomass available from a variety of sources, including crops (cereals, sugar beet and rape), forestry, the OFMSW and the food industry (meat, beverages, dairy and bakery products). Some ongoing or completed BBI/ CBE JU projects can serve as examples to further increase utilisation and demonstrate the potential of these streams in Poland, including LIGNOFLAG, OPTISOCHEM, EXCORNSEED, AGRIMAX, PROMINENT, SWEETWOODS, EXILVA, PERCAL, NEWFERT, URBIOFIN, GREENPROTEIN, PULP2VALUE, and PRO ENRICH.

However, in order to demonstrate the scalability and technical and economic viability of bio-based investments, innovations around TRL 4 – 8 need to seek support of scale-up infrastructures and industrial-scale biorefineries. The existing bio-based applications are predominantly related to agrifood feedstock, with limited exploration of other, more lucrative end products that offer higher profitability.

Competitive Pressures and Market Challenges

Poland boasts several advantages in terms of attracting potential investors but also faces certain barriers.

The lack of clarity in the regulatory framework and the suboptimal interlinkages within the value chain have a negative impact on the ability to achieve the optimum market positioning at EU and global level. The market share of bio-based products remains modest, primarily due to their current lack of competitiveness in terms of production costs for companies and pricing for consumers. Poland is an emerging innovator and is facing competition from neighbouring countries with stronger performance records.

Despite being one of the fastest growing sectors in Poland, biotechnology is still an emerging sector. The availability of highly qualified professionals and the competitive nature of labour costs in Poland are key reasons why the country attracts investors in this field. Another fast-growing market in Poland is the dietary supplements sector, which encompasses vitamins, minerals, herbal teas and other related products.

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Addressing Supply-Side Barriers

To successfully overcome the challenges presented by the supply side, it is essential that **Poland implements a comprehensive and well-defined regulatory framework**. This is because uncertainty has been proven to have a significant negative impact on investment development and attraction. The availability of a national bioeconomy strategy and related regulations would create more favourable framework conditions for the acceleration of the bioeconomy.

Strengthening bioeconomy clusters and links between universities and companies, and across sectors (farmers, industries and services), will be crucial to mobilising all the actors capable of providing the resources and skills needed for a biotransition.

The definition of replicable, scalable and sustainable business models could provide key stakeholders with a clear indication of the technically feasible and economically viable options available.

3.2.15 Portugal[675] [676] [677] [678] [679]

Supply-Side Barriers (Production Costs, Capacity, Profitability, Competition, R&D&I Ecosystem):

- **High production costs and weak cost-competitiveness:** Bio-based production in Portugal faces high input costs (feedstocks, energy, etc.) and lacks economies of scale. Bio-based chemicals can cost 20–50% more to produce than petrochemical equivalents due to smaller manufacturing scales, expensive feedstocks, and energy-intensive processes. These factors, coupled with cheap fossil-based alternatives, render many bio-based products economically unattractive, undermining the competitiveness of domestic bio-based industries.
- **Limited scale-up infrastructure and capacity:** There is a shortage of pilot plants, demonstration facilities, and commercial biorefineries to bridge the gap between lab innovations and industrial production. As a result, promising bio-based technologies struggle

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[677] ZERO – Associação Sistema Terrestre Sustentável.. A Biomassa em Portugal: Impactes e Políticas Públicas (2021).

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[679] Corticeiro, S., et al., Assessing Forestry Needs and Challenges in Portugal: Insights from the Sector Interested Parties. Forests 16(3) (2025) 501 2025, **https://doi.org/10.3390/f16030501**

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to scale up within Portugal. Notably, the country is only now constructing its first large-scale advanced biorefinery, a €400 million project to produce renewable diesel and SAF, set to begin operation in 2026, underscoring the historically limited biorefining capacity. The lack of such infrastructure has slowed the commercialization of new bio-based processes and left much biomass processing to occur abroad.

- **Low profitability and value-addition of biomass resources:** A significant share of Portugal's biomass is utilized in low-value applications or exported as raw or minimally processed commodities, yielding slim profit margins. For example, Portugal produced about 815,000 tonnes of wood pellets in 2021, yet over 510,000 tonnes (>60%) were exported to be burned in power stations in Northern Europe. Wood pellets consumed roughly 20% of the country's pine wood harvest that year but accounted for only ~3% of the export value of pine-derived products, reflecting how much of the biomass is sold in bulk at low prices. This emphasis on low-value exports, combined with a small domestic market for advanced bio-based products, limits the profitability of bio-based ventures and disincentivizes local investors. Indeed, the wood pellet industry has only survived with substantial public subsidies (over €100 million since 2008) and still struggles financially as feedstock costs rise, illustrating the tenuous economics of Portugal's bioresource utilization.
- **Fragmented R&D and innovation ecosystem:** Gaps in research, development, and innovation capacity impede the advancement of bio-based industries. Portugal's R&D investment remains relatively low – only 1.69% of GDP in 2021, compared to the EU average of 2.26%, and the country's patent output per capita is very modest (30 EPO patent applications per million inhabitants vs 151 for the EU). This indicates a lag in innovation and technology development. Moreover, coordination between academia and industry is weak. There are few dedicated bioeconomy clusters or structured support networks, which hinders knowledge transfer and scale-up of new technologies. According to EU analyses, a lack of cooperation amongst biomass suppliers, researchers, and processors, along with hurdles in academia-industry partnerships, has been a notable barrier to commercialising bio-based innovations. Limited financing for new production facilities and a shortage of skilled workers in bioprocessing further constrain the innovation ecosystem. These factors have slowed the diffusion of R&D results into viable business models and commercial products in Portugal's bioeconomy.

On the other hand, **Portugal** can leverage several strengths to overcome these barriers:

- **Abundant and diverse biomass resources:** Portugal possesses substantial bioresource potential, with over 85% of its territory covered by vegetation (forests, agricultural land, and other biomass-producing areas)mdpi.com. The country's forestry sector (eucalyptus and pine forests) and by-products from agriculture and fisheries provide a strong raw material base for a bioeconomy. These ample feedstocks, if mobilised sustainably, give Portugal a solid foundation to expand bio-based production domestically.
- **Robust innovation hotspots and expertise:** Despite the challenges, Portugal has a growing innovation ecosystem in relevant fields. The country is gaining recognition as a

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budding biotech and bio-based innovation hub, with multiple universities and research institutes (e.g. in Lisbon, Porto, and Braga) active in biotechnology, bioengineering, and marine bio-resources. It also has niche excellence in the blue bioeconomy (marine and aquatic biomass) through initiatives like the BlueBio Alliance and the B2E CoLAB, capitalising on Portugal's long coastline and marine research capacity. A rising cohort of highly trained scientists and engineers, reflected in the increasing tertiary education rate (44% of young adults) and bioeconomy-focused R&D units, is available to drive innovation. This human capital and know-how position Portugal to develop higher-value bioproducts and improve process efficiencies, provided they are integrated into industry.

- **Emerging policy support and investment momentum:** Recent developments show a stronger commitment to bolstering the bio-based sector. The government's new Sustainable Bioeconomy Strategy 2030 action plan signal a strategic vision and have started to address previous policy gaps. With increased public and private financing, and clearer policy incentives, Portugal is poised to scale up its bio-based industries. The combination of strategic direction and new investments is creating an environment where the above supply-side barriers can be progressively reduced, allowing Portugal's bioeconomy to realize more of its considerable potential.

3.2.16 Romania[680] [681] [682] [683]

Romania's bioeconomy shows great promise, but high production costs, limited processing capacity, weak profitability, and an absence of appropriate business models are hindering its development. Additionally, the R&I ecosystem for scaling up bio-based industries is underdeveloped, creating further barriers to commercialisation.

High Production Costs and Limited Profitability

Romanian bio-based industries face high costs related to:

- **Low technological investment**: Many bioeconomic sectors rely on outdated technologies, leading to inefficient production and higher costs.

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[681] Voicilas, D.M., et al., Executive summary of the strategic concept paper for bioeconomy: Romania (2023) BIOEASTsUP H2020 Project

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- **Expensive logistics and supply chain inefficiencies**: The decentralised agricultural sector results in high collection and transportation costs for feedstocks such as crop residues and forestry biomass.
- **Lack of large-scale biorefineries**: Most bio-based industries operate on a small scale, preventing economies of scale and keeping production costs high.
- **Energy and raw material costs**: Rising energy prices and competition for feedstocks (e.g., between food and bioenergy production) reduce profit margins.

Profitability remains low due to:

- **Limited access to high-value bio-based markets**: Most biomass is exported as raw material instead of being processed into profitable bio-based products.
- **Insufficient demand for bio-based products**: Low consumer awareness and lack of incentives for bio-based alternatives reduce market opportunities.

Limited Production Capacity and Competition

- **Low investment in bioprocessing facilities**: Romania has few biorefineries and lacks infrastructure for producing advanced bio-based materials such as bioplastics and biofuels.
- **Dominance of traditional industries**: The agri-food and forestry sectors prioritise conventional production over bio-based innovation.
- **Competition from imported bio-based products**: Romania struggles to compete with more technologically advanced bioeconomy sectors in Western Europe, where higher-quality bio-based materials are produced at lower costs.

Lack of Supporting Business Models

Romania's bioeconomy suffers from weak business models, leading to:

- **Limited private sector engagement**: Many companies view bio-based industries as high-risk due to uncertain returns on investment.
- **Fragmented industry collaboration**: Weak links between agriculture, forestry, and industrial sectors hinder integrated bio-based value chains.
- **Regulatory uncertainty**: The absence of a clear bioeconomy strategy and policy incentives discourages long-term business investments.

Potential solutions:

- Public-private partnerships to attract investment.
- Support for bioeconomic clusters and cooperatives to enhance supply chain coordination.
- Tax incentives and subsidies for bio-based production and circular economy initiatives.

Weak R&I Ecosystem for Scaling Up

Romania's R&I ecosystem for bioeconomy development is underfunded and fragmented, facing challenges such as:

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- **Low R&D investment**: Romania spends a low percentage of GDP on research, limiting innovation in bio-based technologies.
- **Lack of collaboration between academia and industry**: Universities conduct bioeconomy research, but commercialisation pathways are weak.
- **Insufficient technology transfer mechanisms**: Start-ups and SMEs struggle to scale up due to a lack of funding and support.

Opportunities for improvement:

- Increased funding for bioeconomy R&D projects through EU programs (e.g., Horizon Europe).
- Establishing bioeconomy innovation hubs to connect researchers and businesses.
- Encouraging venture capital and start-up investment in bio-based industries.

Romania's bioeconomy faces significant supply-side barriers due to high production costs, limited processing capacity, low profitability, weak business models, and an underdeveloped R&I ecosystem. In order to address these challenges, it is essential to implement policy measures, make substantial investments in infrastructure, and foster enhanced industry collaboration. These measures are crucial for the scaling up of bio-based industries in Romania and for the further enhancement of the country's role in the EU bioeconomy.

3.2.17 Slovakia[684] [685] [686] [687] [688] [689] [690] [691]

While Slovakia aims to exploit the potential of its bioeconomy, new feedstocks such as agricultural residues, forest wood, short-rotation coppice, and food processing wastes represent underutilised

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and yet valuable resources. Despite their potential, several supply-side challenges hinder their effective mobilisation and commercialisation. These include high production costs, limited processing capacities, non-viability, and intense competition with conventional uses such as combustion or export. Additionally, the absence of sustainable business models, ineffective policy coordination, and deficiencies in the R&I ecosystem further hinder the expansion process. Breaking down these barriers is essential to maximise the valorisation of feedstock, stimulate rural economies and enable Slovakia to transition to a circular and climate-resilient bioeconomy. Slovakia has promising feedstock resources (e.g. wood biomass, agricultural residues, energy crops), but several structural and systemic barriers are hindering the full development of the bioeconomy.

High Production Costs

Split ownership of land is a factor that contributes to logistics costs, particularly in faraway or hilly regions where biomass harvesting is inefficient. Moreover, most farms and forest enterprises are small or medium-sized and therefore have limited investment capacity in relation to the procurement, drying, storage, or processing machinery. The input costs for very specialist crops such as short-rotation coppice or hemp remain high, especially in the absence of established value chains that are able to absorb the biomass at stable and certain prices.

Limited Production Capacity & Infrastructure

- **Underdeveloped biorefinery and bioprocessing infrastructure**: Slovakia lacks regional hubs for biomass valorisation (e.g. advanced biogas, biochar, or bioplastics).
- **Low logistics integration**: There's limited coordination between feedstock producers and processing facilities, resulting in high transport costs and feedstock losses.
- **Storage and handling deficits**, especially for perishable or seasonal materials (e.g. grape pomace, grass cuttings, manure) that require rapid conversion.

Profitability Challenges

- **Low return on investment**: Current market prices for raw biomass (especially for energy use) are often too low to incentivise collection or diversification.
- **Feed-in tariffs and incentives** have been reduced or are inconsistent, especially in the bioenergy sector, weakening investor confidence.
- **Emerging markets** (e.g. for compostables, bio-based packaging, soil amendments) are still small or underdeveloped domestically, limiting revenue streams.

Competition and Market Constraints

Agricultural residues and forestry by-products are still mostly used for heating or combustion, which competes with higher-value uses such as biomaterials or green chemicals. In many cases, the cost of imported fossil-based and synthetic alternatives is lower than that of local bio-based products, which can negatively impact investment in the development of domestic feedstock. Export-focused models (particularly for wood and cereals) result in a significant amount of biomass being exported without any added value being retained within the country.

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Lack of Supporting Business Models

- **Missing links in the value chain**: Farmers, processors, and technology providers often work in silos; business models to connect them (e.g. cooperatives, contract schemes, mobile bioprocessing units) are rare.
- **Limited incentives for diversification**: Many farmers and forestry managers are focused on traditional markets, and there is little risk-sharing support to encourage experimentation with emerging biomass crops or technologies.
- **Policy uncertainty: Inconsistent support for bio-based innovations** leads to a lack of long-term planning or blended finance schemes for SMEs.

R&I Ecosystem for Scale-Up and Commercialisation

- **Good research base** (e.g. National Agricultural and Food Centre – NPPC, Slovak University of Agriculture), but tech transfer is weak.
- **Innovation gaps**: There is a disconnect between pilot projects and market-ready solutions. Most biomass innovations remain at lab or demo scale.
- **Few testbeds or pilot plants for biomass processing—entrepreneurs struggle to validate, certify, or industrialise their innovations**.
- **Lack of innovation brokers and facilitators to bridge research, start-ups, and rural biomass producers.**
- **Low participation in EU funding for bioeconomy pilots** compared to Western EU countries.

Risk Aversion and Lack of Entrepreneurial Mindset in the Bioeconomy

Many farmers and forest owners are understandably cautious about investing in unproven biomass markets, especially where returns are uncertain or delayed. Bioeconomy entrepreneurship (e.g. creating start-ups in bioplastics or biochemicals) is still underdeveloped, with most innovation occurring in urban or academic circles rather than in rural production regions. There is a cultural and generational gap when it comes to adopting novel feedstock-based business models or engaging in cooperative ventures.

Low Uptake of Precision and Digital Technologies

The use of emerging feedstocks often requires enhanced monitoring, planning, and traceability (e.g. harvest timing, moisture content, origin verification for sustainability claims). Digital solutions such as GIS biomass mapping, remote sensing for land use, or blockchain for traceability are not yet widely adopted by feedstock producers. The digital divide between research institutions and rural stakeholders limits the uptake of tech-based solutions that could reduce costs or improve margins.

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3.2.18 Slovenia[692] [693] [694] [695] [696] [697]

Production Costs, Capacity, Profitability, Competition, and Business Models

The development of Slovenia's bioeconomy is significantly constrained by various supply-side barriers that limit its ability to scale up and commercialise innovative bio-based products. These barriers include high production costs, limited production capacity, low profitability, competitive pressures, and a lack of supporting business models. Additionally, the weak R&I ecosystem makes it difficult for companies to transition from pilot-scale projects to full commercial production. Addressing these challenges is essential to unlocking Slovenia's full bioeconomic potential and aligning with EU Green Deal objectives.

Production Costs and Profitability Constraints

One of the most pressing issues for Slovenia's bioeconomy is high production costs, which stem from several factors, including the high cost of raw material procurement, limited economies of scale, and high energy costs. In contrast to larger European countries that have well-established bioeconomy industries, Slovenia lacks cost-efficient supply chains that could reduce input costs. The predominance of small-scale farms and fragmented forestry operations has been identified as a key factor contributing to increased unit costs, thereby reducing the competitiveness of bio-based products when compared to conventional fossil-based alternatives.

Additionally, the low profitability margins that characterise the sector make it difficult for Slovenian businesses to invest in long-term bio-based ventures. Securing financing for biorefinery infrastructure is a challenge for many companies, as investors perceive bioeconomy projects as high-risk due to uncertain market demand and long return-on-investment periods. Many bio-based initiatives encounter challenges in achieving commercial viability without financial incentives such as tax breaks, grants, or subsidies.

[692] Juvancic, L., et al., Executive summary of the strategic concept paper for bioeconomy: Slovenia (2023) BIOEASTsUP H2020 Project

[693] CCIS – Association of Chemical Industries of Slovenia, National Bioeconomy Dossier: Slovenia (2020) | Central European Leaders of Bioeconomy Network | CELEBIO

[694] Juvancic, L., et al., Strategic concept paper for Bioeconomy in Slovenia: from a patchwork of good practices to an integrated, sustainable and robust bioeconomy system. Open Resource Europe 3 (2023) 167 **https://doi.org/10.12688/openreseurope.16181.1**

[695] Virant, G., et al., Country Report: Slovenia (2020) BIOEASTsUP H2020 Project

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[697] Juvancic, L., Bridging gaps in Bioeconomy: from forestry and agriculture biomass to innovative technological solutions (2021). Bridge2Bio. Ministrstvo za Kmetijstvo, Gozdarstvo in Prehrano, Slovenia.

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Production Capacity Limitations

Slovenia's bioeconomy is hindered by a shortage of large-scale production facilities, which restricts its capacity to manufacture bio-based products at competitive prices. The absence of industrial-scale biorefineries means that much of Slovenia's biomass is either exported raw or remains underutilised. While some SMEs have attempted to integrate biomass valorisation technologies, they often lack the resources to scale up beyond pilot projects. In addition, the focus of existing processing facilities is predominantly on low-value biomass applications, such as energy generation, rather than on the production of high-value bio-based chemicals, bioplastics, or advanced biofuels.

Competitive Pressures and Market Challenges

Slovenian bio-based industries face intense competition from well-established bioeconomy leaders such as Germany, the Netherlands, and Scandinavia, which have already invested heavily in biorefinery technology and bio-based supply chains. Furthermore, the cost-effectiveness of fossil-based alternatives poses a significant challenge to the market presence of bio-based products, unless policy interventions such as carbon pricing or mandatory bio-based procurement targets are implemented. Furthermore, a number of Slovenian SMEs are not equipped with the necessary marketing and distribution networks, which restricts their ability to participate in global bio-based value chains.

Lack of Supporting Business Models

The absence of integrated business models is also hindering the commercialisation of Slovenia's bioeconomy. In contrast to Germany or Finland, where bioeconomy clusters are known to promote industrial symbiosis, Slovenia currently lacks robust bioeconomy networks that could facilitate collaboration between raw material suppliers, processors, and end-users. In the absence of a well-defined supply chain and stable market demand, many companies are hesitant to invest in bio-based ventures. The absence of contractual agreements for biomass supply also introduces an element of uncertainty, making long-term business planning challenging.

Weak R&I Ecosystem for Scale-Up and Commercialisation

Despite Slovenia's strong research base in bio-based technologies, its technology transfer and commercialisation ecosystem is underdeveloped. While universities and research institutions are active in bio-based research, their findings often do not translate into market-ready products due to limited industry collaboration and lack of funding for demonstration projects. Slovenia is lagging behind Western Europe in securing EU bioeconomy funding, which is limiting the development of large-scale pilot plants that could facilitate commercialisation.

Furthermore, the country lacks dedicated innovation hubs that support start-ups and SMEs in bioeconomy-related fields. While there are general business incubators, they often lack sector-specific expertise in bio-based industries. Slovenia risks falling behind in the global bioeconomy transition if it does not receive adequate financial support for the scaling up of bio-based technologies.

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Addressing Supply-Side Barriers

In order to overcome these challenges, **Slovenia should implement targeted policy measures**, such as investment incentives for biorefineries, subsidies for bio-based product development, and funding for commercialisation projects. **The development of bioeconomy clusters** that integrate farmers, processors and industrial end-users will be essential for creating cost-effective supply chains. Furthermore, it is recommended that **collaboration between universities and industry in research and innovation be strengthened**. This would result in an improvement in the commercial viability of Slovenia's bio-based innovations.

3.2.19 Spain[698] [699] [700] [701] [702] [703]

Notable advances in policy and strategy have been made in Spain, but the bioeconomy is still facing supply-side barriers that limit its potential for commercial growth. These include elevated production costs, limited processing capacity, modest profitability, fierce market competition from conventional alternatives, fragmented business models, and a nascent R&D&I ecosystem for scale-up and industrial deployment. Overcoming these constraints is vital for Spain to fully align with EU Green Deal objectives and realise its bioeconomic ambitions.

Production Costs and Profitability Constraints

Spain's bioeconomy is hindered by high production costs rooted in fragmented supply chains, small-scale operations, and limited domestic availability of specialised bioprocessing inputs. For instance, in the agri-food sector, organic producers struggle with fragmented markets and elevated prices, exacerbated by limited consumer awareness and sales infrastructure.

Profitability remains low across many sub-sectors. In the *Dehesa* agroforestry system of Extremadura, livestock farming continues to be economically marginal, with low input intensity

[698] Horrillo, A., et al., Understanding the barriers and exploring the possibilities of the organic livestock sector in Dehesa agroforestry systems: a multi-actor approach for effective diagnosis. Renewable Agriculture and Food Systems 35(6) (2019) 663-667. https://doi.org/10.1017/S1742170519000334

[699] Lainez, M., et al., Spanish strategy on bioeconomy: towards a knowledge based sustainable innovation. New Biotechnology 40 (2018) 87-95 http://dx.doi.org/10.1016/j.nbt.2017.05.006

[700] Macías Aragonés, M., et al., Digital Innovation hubs as a tool for boosting biomass valorisation in regional bioeconomies: Andalusian and South-East Irish case studies. Journal of Open Innovation: Technology, Market, and Complexity 6(4) (2020) 115. https://doi.org/10.3390/joitmc6040115

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[702] Ferreira, V., et al., The bioeconomy in Spain as a new economic paradigm: the role of key sectors with different approaches. Environment, Development and Sustainability 26 (2024) 3369-3393. https://doi.org/10.1007/s10668-022-02830-5

[703] López-Castro, J.A., and Parrilla-González, J.A., Marketing strategies for olive oil: a supply-side perspective from Spain. Businesses 4(4) (2024) 553-565 https://doi.org/10.3390/businesses4040033

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translating into modest returns. Despite its potential, organic conversion is hindered by limited technical support and high certification costs. The high initial investment requirements for the research, development and innovation, and demonstration phases, have a significant impact on the entry and expansion of bio-based businesses, making it a challenging environment in which to operate.

Production Capacity Limitations

Spain lacks adequate biorefinery infrastructure to scale biomass conversion into higher-value products. While regional initiatives, such as those in Andalusia, show promise, they remain regionally fragmented and underdeveloped. Digital Innovation Hubs (DIHs) have been established to support biomass valorisation, but their reach and industrial integration are still limited.

The Spanish forestry sector is abundant in biomass resources, particularly in rural areas that are otherwise underutilised. However, the development of processing infrastructure necessary for a forest-based bioeconomy has been slow. Forest owners often lack the organisational and technical capacity to implement scalable business models.

Competitive Pressures and Market Challenges

Spanish bio-based products face intense competition from fossil-based counterparts, which are generally cheaper and more widely distributed. The absence of carbon pricing mechanisms and inadequate consumer incentives have constrained the market adoption of sustainable alternatives. The key issue facing the Spanish bioeconomy is the additional cost of using these processes compared to traditional ones with higher GHG emissions.

Furthermore, product development in the bio-based materials sector is constrained by performance gaps when compared to fossil-based products. Spain has been slow to address the challenges of recycling and biodegradability, particularly in the context of composite bio-based materials.

Lack of Supporting Business Models

The commercialisation of bio-based products in Spain is being hindered by the lack of integrated and sustainable business models. Many ventures lack long-term contracts, stable biomass supply chains, and secure revenue models. In the olive oil industry, a key bio-based subsector, firms must undergo structural transformation to become more professionalised and market-oriented in order to overcome entrenched marketing barriers.

While certain platforms facilitate direct-to-consumer sales for organic products, most SMEs lack access to digital tools or e-commerce expertise, which limits scalability and customer outreach.

Weak R&D&I Ecosystem for Scale-Up and Commercialisation

Despite the presence of well-established academic institutions in Spain, the transition from research to market remains limited. Many bio-based start-ups encounter obstacles when seeking financial investment, incubation support and demonstration-scale development. The national innovation system is currently facing challenges due to fragmented governance and weak public-private collaboration, particularly amongst SMEs. Collaboration and knowledge transfer are essential for the

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development of the bioeconomy. However, Spain still lacks a robust innovation ecosystem and effective coordination between regions and the central government.

Additionally, while Spain's bioeconomy strategy emphasises innovation, implementation gaps persist at regional levels, and the country underperforms in leveraging EU funding opportunities. The Spanish Bioeconomy Strategy, implemented at the end of 2015, has not yet fully evolved or achieved the desired impact. This is due to insufficient implementation and limited stakeholder engagement.

Spain's bioeconomy shows great potential but is restricted by systemic supply-side barriers. In order to ensure a competitive bio-based sector that is aligned with EU green growth ambitions, it is imperative to **enhance production infrastructure, professionalise SMEs, incentivise sustainable markets and strengthen the R&D&I-commercialisation bridge**. With the purpose of unlocking Spain's bioeconomic potential, it is essential that there is greater collaboration between public administration, industry and academia. This will require improved regulatory frameworks and targeted investment.

3.2.20 Sweden[704] [705] [706] [707] [708] [709]

Production Costs and Profitability Constraints

In 2024, the price of timber increased by 30 percent and the pulpwood price by 18 percent compared to 2023, causing an increase in timber prices across all regions of the country.

The primary challenge is to ensure a reliable and cost-effective long-term supply of raw materials. Other large forest nations face even greater supply issues, and there is a forecast for a further decrease in supply. It is anticipated that the global importance of Swedish forestry products will increase as a result.

Concurrently, the implementation of EU initiatives, including LULUCF and the Nature Restoration Act, carries the potential to exert a negative influence on Swedish supply. A further development that has come to light is that large forest owners in Sweden are either already reducing their supply or

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[705] Pyrocell (2025). Setra group. Visited 2025-03-20. https://www.setragroup.com/en/pyrocell/

[706] RISE (2025). Visited 2025-03-20. https://www.ri.se/en/expertise-areas/biorefinery

[707] Skogsindustrierna (2024). Så går det för skogsindustrin nr 3 2024. Retrieved from https://www.skogsindustrierna.se/siteassets/bilder-och-dokument/sa-gar-det-for-skogsindustrin/2024/sa-gar-det-for-skogsindustrin_3_2024.pdf

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[709] Sunpine (2025). Visited 2025-03-20. https://www.sunpine.se/en/

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plan to do so in order to comply with the new policies. This may have a negative effect on the supply side of forest biomass.

Production Capacity Limitations

Sweden has a number of large-scale production facilities for traditional bio-based products, as well as some for new bio-based products, such as biofuels. Examples of companies with production facilities in Sweden include Sunpine and Pyrocell. It is evident that other bio-based products have encountered difficulties in successfully reaching the market. One initiative to address this issue is a large research facility at RISE -the Swedish Research Institute-, for scaling up waste streams from the forestry industry and other industries into new innovative products.

Competitive Pressures and Market Challenges

The outcome of the US presidential election, along with the potential for import tariffs, is contributing to market concerns in both the short and long term. This applies to general tariffs on the entire global market, including those applied by the US (10–20%), China (60%) and Mexico and Canada (25%). The global trade of forest industry products may be subject to adjustments in the event of the introduction of increased tariffs in the US.

Furthermore, the cost-effectiveness of fossil-based alternatives poses a significant challenge to the market presence of bio-based products, unless policy interventions such as carbon pricing or mandatory bio-based procurement targets are implemented.

The debate surrounding the optimal approach for managing forests, whether through the management of carbon sinks or other strategies, has created a significant degree of uncertainty, a factor that is likely to be unfavourable to the market.

Lack of Supporting Business Models

The market for new bio-based products, including chemicals, plastics, rubber and aviation fuel, is encountering difficulties in securing long-term contractual agreements for biomass supply and in integrating these products into existing production processes.

It is also important to note the challenge of adjusting the business model to incorporate the forest owner in new ways. Switching from fossil fuels to bioenergy will change the power balance between buyers and producers. This is especially true in the context of new business models that encourage carbon sequestration instead of substitution.

Weak R&I Ecosystem for Scale-Up and Commercialization

Sweden has a strong research base in bioeconomy and bio-based technologies, but there are still challenges around technology transfer and commercialisation for both existing large and new entities. The former faces challenges due to significant investment costs, while the latter is confronted with competition from affordable fossil fuels. Several attempts have been made to scale up from demonstration to industrial scale, but these have not been successful. The primary reasons for this are as follows: the absence of long-term and stable policies, which makes it difficult to attract financing; market uncertainty; and fluctuations in oil price.

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To facilitate Swedish industry's transition, the government has commissioned the Swedish Energy Agency to lead the Industrial Transition. This initiative will support industry by providing funding for innovative climate-related projects. Sweden is well-positioned to provide technical solutions and serve as a source of inspiration for other countries undergoing their own transitions. The Industrial Transition is a key component of the EU's strategic initiative, Next Generation EU, which aims to foster a healthier, greener, and more digitally-oriented Europe.

Addressing Supply-Side Barriers

To address these challenges, Sweden must understand the total impact of the EU's new legislation on the supply of raw materials and adjust accordingly. It is vital that **policies continue to promote active and sustainable forest management**. They should also **focus on the possibilities of substituting products and energy based on fossil fuels with bio-based alternatives**. **Securing funding for the expansion of new biorefinery pathways and products** will be a key priority.

3.2.21 UK[710]

The UK bio-based industry faces some supply chain barriers, including fragmented integration between the agricultural, chemical, and waste management sectors. This complicates feedstock availability and scalability. Seasonal variability and geographic concentration of biomass sources disrupt consistent supply, while misaligned policies (such as regulatory frameworks that favour incumbent industries) create competitive disadvantages for bio-based alternatives. Disconnects between government strategies can result in challenges in aligning research priorities with market needs. The issue is further compounded by difficulties in establishing collaborations between upstream waste generators (e.g., food industries) and downstream users (e.g., chemical manufacturers), which has a detrimental effect on valorisation opportunities for biological waste streams. Regulatory inconsistencies, including life cycle assessment standards and end-of-life labelling, further impact market confidence and consumer adoption. In order to address these barriers, there is a need for coordinated policy reforms, targeted financial incentives and multidisciplinary partnerships. This will enhance supply chain resilience and align bio-based materials with circular economy objectives.

Production Costs

Bio-based industries face elevated production costs due to seasonal variability in biomass feedstock availability, geographic concentration of resources, and competition for sustainable feedstocks. High biomass costs in the UK, coupled with energy-intensive processing requirements, hinder cost-

[710]Lloyd, C., and Dey, P., Supply chain integration in the UK bioenergy industry: findings from a pilot study. Journal of Cleaner Production 79 (2014) 41-52. https://doi.org/10.1016/j.jclepro.2014.05.080

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competitiveness with fossil-derived alternatives. Certifications for sustainability and environmental compliance further inflate operational expenses.

Production Capacity

Limited infrastructure for biomass conversion and inconsistent feedstock supply chains restricts scalable production. Pilot studies highlight imbalances in supply chain integration, particularly in logistics planning and inventory management, which exacerbate capacity constraints[i]. While the UK has technical expertise in pretreatment technologies, underinvestment in open-access demonstration facilities delays industrial-scale deployment.

Profitability Challenges

Bio-based sectors can target low-margin markets (e.g., bulk chemicals, plastics), where price sensitivity undermines profitability. Uncertain demand and fragmented policy frameworks reduce investor confidence, limiting opportunities for economies of scale. Additionally, competition with bioenergy for feedstocks creates market distortions, further pressuring margins.

Competition and Market Dynamics

Domestic bio-based industries face competition from international markets with lower feedstock and labour costs. Internally, conflicting departmental priorities (e.g., Defra's ecological focus vs. DSIT's innovation-driven approach) create regulatory misalignment, disadvantaging bio-based materials in policy incentives. The lack of a cohesive bioeconomy strategy also stifles market differentiation and export potential.

Scale-up and Commercialisation Ecosystem

The UK's commercialisation ecosystem is hindered by insufficient collaboration between academia, SMEs, and large industrial players. While government initiatives like the aim to bridge this gap, fragmented R&D investments and regulatory barriers slow technology transfer. Start-ups struggle to secure funding without proven scalability, perpetuating reliance on incremental rather than disruptive innovations.

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4 EMERGING TECHNOLOGIES IN BIO-BASED INDUSTRY

The European Union is steadfast in its commitment to the promotion of a green and circular economy, a strategic direction that has been articulated with clarity in the European Green Deal[711]. This ambitious initiative acknowledges the pivotal function of bio-based products, derived from renewable biological resources, in substituting fossil-intensive alternatives, with the potential to reduce up to 2.5 billion tonnes of CO_2 equivalent per year by 2030[712]. These bio-based solutions frequently demonstrate superior environmental and technical performance, contributing significantly to Europe's objective of achieving climate neutrality by 2050 and reducing its reliance on finite fossil resources. The development and deployment of these innovative bio-based products and processes will be supported by dedicated research and innovation funding at EU level, thereby enhancing their economic, social and environmental benefits. This strategic focus aims not only to promote technological advances but also to create new market opportunities and jobs, particularly in innovative sectors and in rural and coastal regions where bioresource production is concentrated[713].

The transition to a robust bioeconomy demands continuous advances in scientific knowledge, innovation and enabling technologies to establish sustainable bio-based processes and transform natural resources into valuable goods and services. The bioeconomy, which encompasses both manufacturing and service industries, extends to the production of biopharmaceuticals, bioplastics, composite materials, biofuels, bio-based chemicals and high-value food products, coupled with the application of biological knowledge such as bioinformatics. The evolution of this economic paradigm is influenced by a multitude of global drivers, including environmental pressures such as climate change and biodiversity loss, the volatility of fossil fuel prices, and the expanding global population[714]. Europe's commitment to this transition is evident in the establishment of initiatives such as the Circular Bio-based Europe Joint Undertaking (CBE JU), which aims to accelerate the market uptake of innovative bio-based solutions while ensuring their environmental performance through the development of new biorefining technologies[715] [716].

[711] Bio-based products and processes | Bioeconomy | European Commission

[712] Philippidis, G., et al., The development of bio-based industry in the European Union: a prospective integrated modelling assessment. Ecological Economics 219 (2024) 108156. **https://doi.org/10.1016/j.ecolecon.2024.108156**

[713] Thormann, L., et al., Opportunities and challenges of the European Green Deal for the chemistry industry: an approach measuring innovations in bioeconomy. Resources 10(9) (2021) 91. **https://doi.org/10.3390/resources10090091**

[714] Kardung, M., et al., Development of the circular bioeconomy: drivers and indicators. Sustainability 13(1) (2021) 413. **https://doi.org/10.3390/su13010413**

[715] Home | Circular Bio-based Europe Joint Undertaking (CBE JU)

[716] Johnson, C., et al., The bio-based industries joint undertaking as a catalyst for a green transition in Europe under the European Green Deal. EFB Bioeconomy Journal 1 (2021) 100014. **https://doi.org/10.1016/j.bioeco.2021.100014**

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Nevertheless, Europe's endeavours to establish itself as a global leader in the bioeconomy are encountering mounting international competition. While the EU has a robust foundation in bioeconomy research and innovation, with substantial revenue and employment in the sector, there are concerns about its capacity to preserve its competitive edge against regions such as Asia and Brazil, which are also allocating considerable resources to the sector[717] [718]. In order to unlock the full potential of the European bioeconomy, it is essential to address the challenges related to securing funding for the scale-up and commercialisation of novel technologies, navigating complex regulatory frameworks and promoting greater market uptake of bio-based products. While the current approach has yielded some successes, it needs to be strengthened to fully leverage the opportunities offered by the bioeconomy and support European businesses in achieving the EU's environmental, climate and competitiveness goals.

4.1 BIOTECHNOLOGY ADVANCEMENTS

4.1.1 Third- and fourth-generation bioethanol: sustainable feedstocks and production

The European biofuel and bioenergy industry is under growing pressure to achieve sustainable energy production while meeting ambitious carbon neutrality targets. This transition involves a shift from first-generation bioethanol, which is produced from sugar and starch crops, and second-generation bioethanol, which is derived from lignocellulosic biomass, towards more advanced and sustainable alternatives. Third-generation bioethanol, derived from microalgae and cyanobacteria, and fourth-generation bioethanol, which uses genetic engineering to improve production, are emerging as solutions that address the limitations of their predecessors[719] [720].

Algae are considered to be one of the most promising sources for third-generation bioethanol due to their high photosynthetic efficiency, ability to grow on non-arable land, and high sugar content suitable for fermentation. They offer several advantages, including high energy content and the ability to grow without competing with food crops, use brackish water and consume CO_2. Research efforts in Europe are increasingly focused on harnessing the potential of algae for bioethanol

[717]Spekreijse, J., et al., Bio-based value chains for chemicals, plastics and pharmaceuticals – A comparison of bio-based and fossil-based value chains, Publications Office, 2021, https://data.europa.eu/doi/10.2760/712499

[718]Philippidis, G., et al., Exploring economy-wide sustainable conditions for EU bio-chemical additives. Ecological Economics 210 (2023) 107857. https://doi.org/10.1016/j.ecolecon.2023.107857

[719]Aron, N.S.M., et al., Sustainability of the four generations of biofuels – a review. International Journal of Energy Research 44(2) (2020) 9266-9282. https://doi.org/10.1002/er.5557

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production.[721] [722]. ExxonMobil, in collaboration with Synthetic Genomics, is actively researching advanced biofuels from algae with the objective of achieving the technical capability to produce significant volumes by 2025[723].

Fourth generation bioethanol embodies a forward-thinking approach that employs genetic engineering to enhance the characteristics of organisms utilised in biofuel production. This approach involves enhancing the utilisation of diverse sugars, boosting lipid synthesis, and improving photosynthesis and carbon fixation. Genetic engineering is being used to improve the accumulation of carbohydrates in species such as *Chlamydomonas reinhardtii*, with a view to enhancing ethanol yields[724]. Metabolic engineering studies are underway to develop cell factories capable of producing superior biofuel options such as butanol and isobutanol at high titre[725] [726]. Furthermore, the application of CRISPR/Cas9-mediated genome engineering in microbial cells is being explored with a view to revolutionising biofuel production by optimising cells for upscaling and improving tolerance[727] [728].

The transition from the first to the fourth generation of bioethanol in Europe demonstrates a growing trend towards the use of more sustainable feedstocks that do not compete with food production. This evolution is underpinned by an increasing reliance on advanced biotechnological methods, such as genetic and metabolic engineering, to improve the efficiency and sustainability of bioethanol production. While European research into third and fourth generation bioethanol, in particular using algae and genetically modified organisms, is vibrant and promising, the commercial deployment of

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[722]Villacreses-Freire, D., et al., Advanced metabolic engineering approaches and renewable energy to improve environmental benefits of algal biofuels: LCA of large-scale biobutanol production with Cyanobacteria Synechocystics PCC6803. BioEnergy Research 15 (2022) 1515-1530. **https://doi.org/10.1007/s12155-021-10323-y**

[723]ExxonMobil, Advanced biofuels and algae research: targeting the technical capability to produce 10,000 barrels per day by 2025 (2018) Visited: 25-05-03. Retrieved from Advanced biofuels and algae research | ExxonMobil Benelux

[724]Chatuverdi, V., et al., Genetic engineering for enhancement of biofuel production in microalgae. In: Verma, P. (ed.) Biorefineries: A step towards renewable and clean energy. Clean Energy Production Technologies (2020). Springer, Singapore. **https://doi.org/10.1007/978-981-15-9593-6_21**

[725]Zhang, W., et al., Isobutanol tolerance and production of *Saccharomyces cerevisiae* can be improved by engineering its TATA-binding protein Spt15. Letters in Applied Microbiology 73(6) (2021) 694-707. **https://doi.org/10.1111/lam.13555**

[726]Meliawati, M., et al., Engineering the carbon and redox metabolism of *Paenibacillus polymyxa* for efficient isobutanol production. Microbial Biotechnology 17(3) (2024) e14438. **https://doi.org/10.1111/1751-7915.14438**

[727]Javed, M.R., et al., Current situation of biofuel production and its enhancement by CRISPR/Cas9-mediated genome engineering of microbial cells. Microbiological Research 219 (2019) 1-11. **https://doi.org/10.1016/j.micres.2018.10.010**

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these advanced technologies continues to face hurdles related to achieving cost effectiveness and facilitating large-scale industrial implementation.

4.1.2 Synthetic Biology in bio-based material development

Synthetic biology represents an emerging and rapidly evolving field within the European bioeconomy. This interdisciplinary approach employs engineering principles to the creation and design of novel, complex biological components and systems, such as microorganisms and plants, and the optimisation of existing metabolic pathways to produce tailored bio-based materials and sustainable products with enhanced functionalities and innovative solutions across multiple industries[729]. Consequently, new opportunities to produce advanced biofuels, renewable chemicals, biodegradable plastics, bioelectricity systems, self-healing materials and even healthcare products are emerging, which address pressing challenges in health, biotechnology and sustainability[730] [731].

The applications of synthetic biology extend to the development of a wide range of bio-based materials. Researchers are exploring the potential of engineered organisms to commercially produce pharmaceuticals and industrial products, such as biofuels, PHAs and PLA, which serve as substitutes for fossil-based materials[732] [733] [734]. Additionally, synthetic biology enables the design of entirely new biosynthetic pathways and highly specialised microorganisms with precision for fermentation processes and biosynthesis processes, allowing for the efficient production of organic acids and biogenic alcohols, as evidenced by the engineering of *Escherichia coli* to produce biofuels,

[729] Dixon, T.A., et al., Sensing the future of bio-informational engineering. Natural Communications 12 (2021) 388. https://doi.org/10.1038/s41467-020-20764-2

[730] Rutz, B., Synthetic biology and patents: a European perspective. EMBO Reports 10 (2009) S14-S17. https://doi.org/10.1038/embor.2009.131

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[732] Liu, Z., et al., Yeast synthetic biology advances biofuel production. Current Opinion in Microbiology 65 (2022) 33-39. https://doi.org/10.1016/j.mib.2021.10.010

[733] Mezzina, M.P., et al., Engineering native and synthetic pathways in *Pseudomonas putida* for the production of tailored polyhydroxyalkanoates. Biotechnology Journal 16(3) (2020) 2000165. https://doi.org/10.1002/biot.202000165

[734] Joseph, T.M., et al., 3D printing of polylactic acid: recent advances and opportunities. The International Journal of Advanced Manufacturing Technology 125 (2023) 1015-1035. https://doi.org/10.1007/s00170-022-10795-y

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bio-based intermediates and bio-based products from glucose via redesigned pathways[735] [736] [737]. This is achieved through the employment of advanced tools such as CRISPR-Cas9 gene editing, light-responsive proteins, and DNA nanotechnology (such as microarray-based and yeast-based methods[738]), which facilitate the creation of programmable biomaterials with complex, hierarchical structures. These innovations contribute to enhanced sustainability, efficiency and precision in biomanufacturing. Moreover, they facilitate the development of new living systems and the optimisation of existing ones. In addition, synthetic biology is instrumental in facilitating the transition towards circular economies by reducing waste and minimising environmental impact. The following European projects are examples of initiatives that explore the potential of synthetic biology in the development of bio-based products: SYBORG and S2B[739] [740]. The former's objectives were to develop innovative methods for CO_2 fixation by integrating synthetic biology and chemistry. This was achieved using reductive carboxylation mechanisms — a novel and highly efficient enzymatic CO_2-fixation reaction — the design of artificial synthetic CO_2-fixation pathways, and their integration into model organisms, including *Methylobacterium extorquens* and *Escherichia coli*. The latter is centred on the development of innovative, scalable technology for the direct production of butanol from solar energy and atmospheric CO_2. This is achieved by utilising photosynthetic microbes that have been engineered into solid-state photosynthetic cell factories.

Synthetic biology is opening new possibilities for the creation of novel bio-based materials and chemicals. Synthetic biology is increasingly recognised as a key enabling technology with wide-ranging applications across the European bioeconomy[741] [742] [743]. Metabolic engineering involves the

[735]Clomburg, J.M., and Gonzalez, R., Biofuel production in *Escherichia coli*: the role of metabolic engineering and synthetic biology. Applied Microbiology and Biotechnology 86 (2010) 419-434. **https://doi.org/10.1007/s00253-010-2446-1**

[736]Navale, G.R., et al., Metabolic engineering and synthetic biology for isoprenoid production in *Escherichia coli* and *Saccharomyces cerevisiae*. Applied Microbiology and Biotechnology 105 (2021) 457-475. **https://doi.org/10.1007/s00253-020-11040-w**

[737]Burgos-Morales, O., et al., Synthetic biology as driver for the biologization of materials sciences. Materials Today Bio 11 (2021) 100115. **https://doi.org/10.1016/j.mtbio.2021.100115**

[738]Escrich, A., et al., A novel step towards the heterologous biosynthesis of paclitaxel: characterization of *T1ßOH* taxane hydroxylase. Metabolic Engineering 85 (2024) 201-212. **https://doi.org/10.1016/j.ymben.2024.08.005**

[739]Combining SYnthetic Biology and chemistry to create novel CO_2-fixing enzymes, ORGanelles and ORGanisms | SYBORG | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[740]Solar to Butanol – Solar Butanol Production by Solid-state Photosynthetic Cell Factories | S2B | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[741]Pei, L., et al., Synthetic biology in the view of European public funding opportunities. Public Understanding of Science 21(2) (2011) 149-162. **https://doi.org/10.1177/0963662510393624**

[742]Flores Bueso, Y., and Tangney, M., Synthetic biology in the driving seat of the bioeconomy. Trends in Biotechnology 35(5) (2017) 373-378. **https://doi.org/10.1016/j.tibtech.2017.02.002**

[743]Donati, S., et al., Synthetic biology in Europe: current community landscape and future perspectives. Biotechnology Notes 3 (2022) 54-61. **https://doi.org/10.1016/j.biotno.2022.07.003**

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fine-tuning of native pathways, as demonstrated by the EU-funded BIOSURFING project, which engineered *Candida bombicola* to synthesise structurally tailored glycolipid biosurfactants with controlled fatty acid and sugar modifications, thereby overcoming previous market limitations[744]. In the field of lignocellulosic biomass conversion, European researchers have made significant progress by developing *Escherichia coli* and *Clostridium acetobutylicum* strains capable of co-fermenting mixed sugars from agricultural residues[745] [746] [747]. In a similar vein, *Saccharomyces cerevisiae* strains with surface-expressed cellulases have exhibited enhanced biomass degradation efficiency[748]. Its potential extends beyond biofuels to the creation of innovative materials, chemicals and even food, all of which are receiving significant support from various European funding programmes. Research in Europe is focused not only on the development of new bio-based materials, but also on ensuring the sustainability and circularity of the associated production processes, which are closely aligned with the overarching objectives of the European Green Deal.

4.1.3 Leveraging Genomics to develop new bio-based applications

Genomics is playing an increasingly important role in the European bio-based industry, providing the fundamental knowledge necessary to understand and sustainably use biological resources. The convergence of life sciences with digital technologies, in particular genomics, is empowering researchers to explore, understand and use biological resources in a sustainable way, leading to optimised and more efficient bio-based operations[749].

The applications of genomics are diverse, ranging from industrial biotechnology to the development of novel bio-based materials. For instance, next-generation sequencing (NGS) genome analyses are used to characterise microorganisms for industrial biotechnology, identifying genes that are active

[744] New-to-nature biosurfactants by metabolic engineering: production and application | BIOSURFING | Projekt | Fact Sheet | FP7 | CORDIS | European Commission

[745] Kim, J., et al., Systems metabolic engineering of Escherichia coli improves coconversion of lignocellulose-derived sugars. Biotechnology Journal 14(9) (2019) 1800441. **https://doi.org/10.1002/biot.201800441**

[746] Zetty-Arenas, A.M., et al., Co-fermentation of sugarcane bagasse hydrolysate and molasses by Clostridium saccharoperbutylacetonicum: effect on sugar consumption and butanol production. Industrial Crops and Products 167 (2021) 113512. **https://doi.org/10.1016/j.indcrop.2021.113512**

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[748] Mehmood, M.A., et al., Chapter Five – Development of synthetic microbial platforms to convert lignocellulosic biomass to biofuels. In: Y. Li, X. Ge (eds) Advances in Bioenergy (2017) 233-278, The Netherlands, Elsevier. **https://doi.org/10.1016/bs.aibe.2016.12.001**

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in the synthesis of desired products such as biosurfactants[750] [751] [752]. Furthermore, genomics is pivotal in comprehending and enhancing complex microbial communities involved in processes such as biogas production [753]. Wageningen Food & Bio-based Research is leveraging nature's functionalities, informed by genomic insights, to engineer innovative technologies and value chains for the sourcing and valorisation of all components of biomass as a feedstock for renewable materials[754]. The Microbial Physiology Section of the European Federation of Biotechnology actively promotes and disseminates the results of high-quality basic research in genomics and its applications in various fields of biotechnology[755].

Rational enzyme modification via computational modelling has led to significant improvements in stability and activity under industrial conditions, thereby reducing processing costs. Researchers are engaged in the active development of novel enzymes and microbial strains through techniques like adaptive laboratory evolution (ALE) and atmospheric room-temperature plasma (ARTP) mutagenesis[756]. These advanced strains are capable of efficiently degrading complex biomass into valuable intermediates and end products, such as biopolymers, antimicrobial agents, and even energy carriers derived from agricultural and forestry waste[757].

Furthermore, as was outlined before, genetic engineering techniques are being employed to enhance the photosynthetic efficiency of organisms such as algae, with the objective of augmenting biofuel production and carbon fixation. Notably, recent advancements in CRISRP-Cas9, as documented in the European Synthetic Biology Tools Market Report (with a projected CAGR of 17% to 2030), are enabling the precise engineering of metabolic pathways in cyanobacteria. This has resulted in the doubling of the rate of lipid accumulation, thus facilitating the production of free fatty

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[752]Gaur, V.K., et al., Opportunities and challenges in omics approaches for biosurfactant production and feasibility of site remediation: strategies and advancements. Environmental Technology & Innovation 25 (2022) 102132. **https://doi.org/10.1016/j.eti.2021.102132**

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[754]Biobased or renewable materials and plastics | Food & Biobased Research | Wageningen University & Research (WUR). Retrieved from [online]

[755]Microbial Physiology section of the European Federation of Biotechnology (EFB) Retrieved from [online].

[756]Li, D., et al., Recent progress of atmospheric and room-temperature plasma as a new and promising mutagenesis technology. Cell Biochemistry and Function 42(3) (2024) e3991. **https://doi.org/10.1002/cbf.3991**

[757]Garcia, J., and González-Flo, E., A new process with zero emissions for truly biodegradable plastics. ARPHA Preprints 6 (2025) e147255. **https://doi.org/10.3897/arphapreprints.e147255**

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acid and biodiesel with greater efficiency[758] [759]. Collectively, these advancements hold the promise of unlocking the potential of a broader spectrum of feedstocks, including lignocellulosic materials and industrial waste, for sustainable bio-based production[760].

A variety of European projects and consortia are specifically focused on advancing biodiversity genomics. Biodiversity Genomics Europe (BGE) is a pan-European consortium dedicated to the comprehensive application of genomic science to biodiversity research. The objective of this initiative is to propel fundamental advancements in the field of conservation science and policy[761]. The European Reference Genome Atlas (ERGA) pilot project has successfully brought together scientists from across Europe to produce high-quality reference genomes for a significant number of European species, marking a major step towards the creation of a comprehensive genomic database for the continent's biodiversity[762]. These initiatives highlight the growing recognition of genomics as a potent instrument for maximising the potential of biological resources in a sustainable manner.

The evolution of bioethanol production towards third and fourth generation biofuels, derived from sustainable feedstocks such as algae and enabled by genetic engineering, promises to reduce dependence on food competing resources and improve environmental performance. Genomics is becoming increasingly central to the progress of Europe's bio-based industries[763] [764] [765]. Genomics, as a field of science, provides the fundamental understanding of biological systems through the identification of crucial genes and regulatory networks. Genetic engineering, as a technological application, utilises this knowledge to modify organisms for the purpose of enhancing industrial performance. By facilitating a more profound comprehension of biological resources at the molecular level, genomics enables the identification of genes responsible for desirable traits and the

[758] Racharaks, R., et al., Development of CRISPR-Cas9 knock-in tools for free fatty acid production using the fast-growing cyanobacterial strain *Synechococcus elongatus* UTEX 2973. Journal of Microbiological Methods 189 (2021) 106315. **https://doi.org/10.1016/j.mimet.2021.106315**

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optimisation of micro-organisms for improved industrial performance. This commitment to sustainability and innovation is a key contributing factor to the success of these sectors. The establishment of large-scale, pan-European initiatives, such as Biodiversity Genomics Europe and ERGA, demonstrates a coordinated and strategic approach to using genomics for comprehensive biodiversity research and conservation efforts. This fundamental knowledge is invaluable for the long-term sustainable use of biological resources by the biobased industry.

4.1.4 Advanced bioreactor innovations: enhancing efficiency and scalability

In the biobased production landscape, bioreactors play a vital role. These vessels provide a controlled environment for the cultivation of microorganisms, stem cells or specialised cells, facilitating the synthesis of a wide range of functional materials. The range of bioreactors extends from traditional fermentation tanks, which are utilised in the food and beverage industry, to sophisticated digitally controlled systems. These bioreactors are integral to the production of a wide range of products, including vegan meat, bio-based textiles, advanced biofuels and biopolymers[766] [767] [768]. In line with this, the large-scale production of bio-based products to meet industrial demands increasingly relies on advanced bioreactor innovations and process intensification strategies (which will be explained later in this section).

Within the emerging field of cultured meat, there is a recognised need for bioreactor technologies specifically designed to meet the unique requirements of this sector. Current bioreactor designs have been adapted from those employed in the pharmaceutical and traditional food industries, resulting in inefficiencies and increased production costs due to a lack of customisation[769]. Innovation in this area is defined as the exploration of approaches to reactor technology design that enhance mass transfer and process control. Such innovations may take the form of developing scalable fit-for-

[766]Allan, S.J., et al., Bioprocess design considerations for cultured meat production with a focus on the expansion biorector. Frontiers in Sustainable Food Systems 3 (2019) 44. https://doi.org/10.3389/fsufs.2019.00044

[767] Pajcin, I., et al., Bioengineering outlook on cultivated meat production. Micromachines 13(3) (2022) 402. https://doi.org/10.3390/mi13030402

[768]Goral, V.N., et al., Innovative fixed bed bioreactor platform: enabling linearly scalable adherent cell biomanufacturing with real-time biomass prediction from nutrient consumption. Biotechnology Journal 19(8) (2024) 2300635. https://doi.org/10.1002/biot.202300635

[769]Vandenberghe, L.P.S., et al., Bioreactors for cultivated meat production. In: Soccol, C.R., Molento, C.F.M., Reis, G.G., Karp S.G. (eds) Cultivated Meat (2024) Springer, Cham. https://doi.org/10.1007/978-3-031-55968-6_6

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purpose bioreactors, extending the life of cell culture media through recycling and implementing process intensification strategies to improve efficiency and reduce costs[770] [771].

Several European research projects are currently engaged in the development of bioreactor technology. For instance, the CBE JU supports a portfolio of projects focused on the development of novel carbon and waste-based processes to produce cost-effective and sustainable bio-based products, many of which rely on innovative bioreactor designs. One example is the finished BIO-COMET project successfully developed a sensor-based bioreactor system for the controlled production of functional autologous engineered cartilage grafts, demonstrating sophisticated automation and real-time monitoring capabilities[772]. Similarly, the ongoing GoodByO project aims to set up a new generation biorefinery at ChainCraft BV using food waste, biogenic CO_2 and bioprocess effluent as sustainable feedstocks. The project will require the use of advanced bioreactor systems[773].

Research is increasingly focusing on the implementation of continuous flow bioreactors to achieve significant increases in productivity. Continuous flow bioreactors offer significant advantages over traditional batch systems, enabling enhanced productivity, improved control, and continuous product harvesting[774] [775] [776]. Studies have demonstrated the viability of continuous poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV) production in *Haloferax mediterranei* using continuous flow bioreactors, achieving significantly higher productivity compared to traditional batch fermentation methods. This approach enables sustainable polymer harvesting and presents a more industrially viable process for biopolymer production[777]. Moreover, the Bio Base Europe Pilot Plant (BBEPP)

[770] Verbruggen, S., et al., Bovine myoblast cell production in a microcarriers-based system. Cytotechnology 70 (2018) 503-512. **https://doi.org/10.1007/s10616-017-0101-8**

[771] Zhang, G., et al., Challenges and possibilities for bio-manufacturing cultured meat. Trends in Food Science & Technology 97 (2020) 443-450. **https://doi.org/10.1016/j.tifs.2020.01.026**

[772] Bioreactor-based, clinically oriented manufacturing of engineered tissues | BIO-COMET | Projekt | Fact Sheet | FP7 | CORDIS | European Commission

[773] Multi-commodities microbial-driven BiOrefinery based on food-processing industry wastes, biogenic CO_2 and bioprocess wastewaters | GoodByO | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[774] Xiao, Y., et al., Constructing a continuous flow bioreactor based on a hierarchically porous cellulose monolith for ultrafast and nonstop enzymatic esterification/transesterification. ACS Sustainable Chemistry & Engineering 7(2) (2019) 2056-2063. **https://doi.org/10.1021/acssuschemeng.8b04471**

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has demonstrated the feasibility of continuous bioprocessing by integrating advanced fermentation and separation methods, such as *in situ* product recovery, which significantly improves the efficiency of industrial platform molecule production[778]. Novel bioreactor designs are being developed to optimise cell culture conditions and improve the efficiency of various bio-based production processes. A notable example of this is the LUCRA project, which focuses on integrated electrochemical bioreactors for sustainable bio-succinic acid production from organic waste. This project demonstrates the potential of combining thermal, enzymatic, and fermentation technologies to achieve resource-efficient outcomes[779]. Furthermore, other significant advancements have been made in regions outside of the EU. One such development is the continuous Taylor Vortex Fermentor-Extractor-Separator, which was developed by the American company Bioindustrial Manufacturing and Development Ecosystem (BioMADE), which integrates product extraction and separation within the bioreactor, thereby improving flexibility, modularity, and energy efficiency. Another notable development is Capra Biosciences' modular biofilm reactors for converting waste feedstocks to Vitamin A, which feature next-generation sensing and automation, as well as a novel continuous-flow separation method[780].

These innovations in single-use, modular, and AI-integrated bioreactor systems are enabling scalability, sustainability, and high-throughput biomanufacturing, directly addressing bioeconomy bottlenecks like cost, contamination, and scale-up. For instance, some studies introduced a scalable single-used fixed bed bioreactor for adherent cell culture, showing high efficiency and viability (96 and 98%, respectively) and near-linear scalability that make it useful for advanced therapies such as gene and cell treatments[781]. Similarly, perfusion-based single-use bioreactors support continuous biomanufacturing, offering operational flexibility and reducing contamination risk[782]. Furthermore, the

[778] Home - Bio Base Europe Pilot Plant

[779] SustainabLe sUCcinic acid production using an integRAted electrochemical bioreactor and renewable feedstock | LUCRA | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[780] New Bioreactor Innovation Projects Announced | BioMADE

[781] Goral, V.N., et al., Innovative fixed bed bioreactor platform: enabling linearly scalable adherent cell biomanufacturing with real-time biomass prediction from nutrient consumption. Biotechnology Journal 19(8) (2024) 2300635. **https://doi.org/10.1002/biot.202300635**

[782] Lesch, H.P., et al., Evaluation of the single-use fixed-bed bioreactors in scalable virus production. Biotechnology Journal 16(1) (2020) 200020. **https://doi.org/10.1002/biot.202000020**

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implementation of 3D bioreactors, airlift bioreactors, microfluidic systems with plant-based scaffolds, and hollow fibre bioreactors are emerging as cost-effective, sustainable solutions[783] [784] [785] [786].

Thus, advanced bioreactor innovations are critical to improving the efficiency and scalability of bio-based production. There is a notable trend towards continuous processing and tailor-made designs for specialised applications. The trajectory of innovation in bioreactors is unmistakably marked by an inclination towards increased automation, the integration of continuous processing methodologies, and the customisation of bioreactor designs to align with the particular requirements of diverse bio-based products, notably within high-value sectors such as pharmaceuticals and the emerging area of cultured meat. This progression is driven by the need to enhance the efficiency, scalability and cost-effectiveness of bio-based production. Moreover, European research in this field is expanding beyond traditional industrial biotechnology to applications in innovative areas such as regenerative medicine and alternative food sources, thus broadening the scope of the bioeconomy.

4.1.5 Process intensification strategies for a more efficient EU bio-based industry

The process intensification strategies have emerged as a transformative pivotal tool for making bio-based production more economically competitive and environmentally sustainable[787]. It involves the development of innovative processing and engineering solutions to address energy inefficiencies, scalability challenges and resource limitations, resulting in more compact, energy-efficient, and cost-effective systems, with minimised waste generation[788]. For instance, it has been documented that the implementation of reactive distillation has led to a reduction in energy consumption by 20-80% in the petrochemical industry. Similar results, albeit less pronounced, have been reported in the adoption of Dividing-Wall-Column (DWC) distillation, which offers up to 30% in energy savings and has been widely adopted for its efficiency in separating multi-component mixtures. These reductions are strongly related to the parallel reduction in capital costs. Both technologies exemplify compact, integrated unit operations that significantly reduce energy consumption and operating costs but

[783]Paladino, O., and Neviani, M., Airlift photo-bioreactors for *Chlorella vulgaris* cultivation in closed-loop zero waste biorefineries. Biomass and Bioenergy 144 (2021) 105926. **https://doi.org/10.1016/j.biombioe.2020.105926**

[784]Lee, S.Y., et al., Current technology and industrialization status of cell-cultivated meat. Journal of Animal Science and Technology 66(1) (2024) 1-30. **https://doi.org/10.5187/jast.2023.e107**

[785]Gome, G., et al., Cultivation of bovine mesenchymal stem cells on plant-based scaffolds in a microfluidic single-use bioreactor for cultured meat. Foods 13(9) (2024) 1361. **https://doi.org/10.3390/foods13091361**

[786]Tuomisto, H.L., et al., Prospective life cycle assessment of a bioprocess design for cultured meat production in hollow fiber bioreactors. Science of the Total Environment 851(1) (2022) 158051. **https://doi.org/10.1016/j.scitotenv.2022.158051**

[787]Li, Q., et al., Challenges and opportunities for process intensification in Europe from a process systems engineering perspective. Frontiers in Energy Research 12 (2024) 1340635. **https://doi.org/10.3389/fenrg.2024.1340635**

[788]European Roadmap for Process Intensification | European Federation of Chemical Engineering

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increase production[789]. The employment of other process intensification methods, including integrated multifunctional reactors, microreactors, oscillatory flow reactors and hybrid separation processes (such as hybrid distillation-pervaporation) linked to the bioconversion techniques, has resulted in cost savings of 30-40% in specialty and fine chemicals due to their compact, multifunctional structure which provides enhanced heat/mass transfer, higher efficiency, and smaller footprints in comparison to traditional methods[790] [791] [792] [793].

In the bio-based sector, process intensification technologies have been also applied to biofuel production. For example, the use of high-frequency ultrasound in microalgal cell disruption and transesterification has significantly accelerated reaction rates and enhanced mixing of immiscible liquids, such as alcohols and oils[794], improving biofuel yields while reducing processing time[795]. Different initiatives demonstrate how process intensification can enhance resource efficiency by valorising side-streams such as water and fermentation media while ensuring high-purity outputs[796] [797] [798]. Furthermore, advancements in gas fermentation technologies enable the conversion of industrial CO_2 emissions into valuable products such as biofuels, bio-based platforms and bioplastics

[789]Harmsen, J., Process intensification in the petrochemicals industry: drivers and hurdles for commercial implementation. Chemical Engineering and Processing: Process Intensification 49 (2010) 70-73. https://doi.org/10.1016/j.cep.2009.11.009

[790]Luis, P., et al., Simulation and environmental evaluation of process design: distillation vs. hybrid distillation-pervaporation for methanol/tetrahydrofuran separation. Applied Energy 113 (2014) 565-575. https://doi.org/10.1016/j.apenergy.2013.06.040

[791]Wang, S., et al., Application of energy-saving hybrid distillation-pervaporation process for recycling organics from wastewater based on thermoeconomic and environmental analysis. Journal of Cleaner Production 294 (2021) 126297. https://doi.org/10.1016/j.jclepro.2021.126297

[792]Baharudin, L., et al., Process intensification in multifunctional reactors: a review of multi-functionality by catalytic structures, internals, operating modes and unit integrations. Chemical Engineering and Processing: Process Intensification 168 (2021) 108561. https://doi.org/10.1016/j.cep.2021.108561

[793]Ma, T., et al., Microreactors with multivariate external force field used for the chemical process intensification. Chemical Engineering Journal 493 (2024) 152508. https://doi.org/10.1016/j.cej.2024.152508

[794]Chit, V., et al., Advancing process intensification with high-frequency ultrasound: a mini-review of applications in biofuel production and beyond. Processes 11(4) (2023) 1236. https://doi.org/10.3390/pr11041236

[795]Vaidya, S., et al., Process intensification and its applications – a critical review. International Journal of ChemTech Research 13(4) (2020) 402-412. https://doi.org/10.20902/IJCTR.2019.130409

[796]Keil, F.J., Process intensification. Reviews in Chemical Engineering 34(2) (2018) 135-200. https://doi.org/10.1515/revce-2017-0085

[797]Ramírez-Márquez, C., et al., Processes intensification for sustainability: prospects and opportunities. Industrial & Engineering Chemistry Research 62(6) (2023) 2428-2443. https://doi.org/10.1021/acs.iecr.2c04305

[798]Schaub, J., et al., Processes intensification in biopharmaceutical process development and production – an industrial perspective. Physical Sciences Reviews 9(9) (2024) 2989-3041. https://doi.org/10.1515/psr-2022-0113

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amongst others, thus contributing to the establishment of a circular bioeconomy[799] [800] [801]. Moreover, process intensification improves reaction selectivity and yields at the molecular level, thereby reducing downstream purification costs and environmental impacts[802] [803]. Another example is the application of consolidated bioprocessing (CBP), an integration approach which combines the production of saccharolytic enzymes, pretreatment, saccharification and fermentation steps in a single reactor. The CBP process is facilitated by a single microorganism or microbial consortium[804]. The effective valorisation of lignocellulosic feedstock through consolidated bioprocessing (based on synthetic biology, two-step valorisation strategy, combined membrane and anti-solvent precipitation with fermentation, amongst others) facilitates the conversion of this material into bioethanol[805] and other valuable bio-based compounds, such as lactic acid, succinic acid or derivates[806] [807] [808] [809] [810].

Several European projects are centring on the development and implementation of compact reactor technology and continuous processing methods with a view to achieving process intensification in the bio-based sector. Although not directly bio-based, European initiatives concerning Small Modular

[799] Zeng, X., et al., Microalgae bioengineering: from CO_2 fixation to biofuel production. Renewable and Sustainable Energy Reviews 15(6) (2011) 3252-3260. https://doi.org/10.1016/j.rser.2011.04.014

[800] Mohan, S.V., et al., A circular bioeconomy with biobased products from CO_2 sequestration. Trends in Biotechnology 34(6) (2016) 506-519. https://doi.org/10.1016/j.tibtech.2016.02.012

[801] Chakrabortty, S., et al., Catalytic conversion of CO_2 to biofuel (methanol) and downstream separation in membrane-integrated photoreactor system under suitable conditions. International Journal of Hydrogen Energy 45(1) (2020) 675-690. https://doi.org/10.1016/j.ijhydene.2019.10.220

[802] Meyer, L.E., et al., Process intensification in continuous flow biocatalysis by up and downstream processing strategies. Current Opinion in Biotechnology 78 (2022) 102835. https://doi.org/10.1016/j.copbio.2022.102835

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[804] Phwan, C.K., et al., Overview: comparison of pretreatment technologies and fermentation processes of bioethanol from microalgae. Energy Conversion and Management 173 (2018) 81-94. https://doi.org/10.1016/j.enconman.2018.07.054

[805] Broda, M., et al., Bioethanol production from lignocellulosic biomass-challenges and solutions. Molecules 27(24) (2022) 8717. https://doi.org/10.3390/molecules27248717

[806] Shahab, R.L., et al., Consolidates bioprocessing of lignocellulosic biomass to lactic acid by a synthetic fungal-bacterial consortium. Biotechnology and Bioengineering 115(5) (2018) 1207-1215. https://doi.org/10.1002/bit.26541

[807] Han, X., et al., An approach of utilizing water-soluble carbohydrates in lignocellulose feedstock for promotion of cellulosic L-Lactic acid production. Journal of Agricultural and Food Chemistry 66(39) (2018) 10225-10232. https://doi.org/10.1021/acs.jafc.8b03592

[808] Sadare, O.O., et al., Membrane purification techniques for recovery of succinic acid obtained from fermentation broth during bioconversion of lignocellulosic biomass: current advances and future perspectives. Sustainability 13(12) (2021) 6794. https://doi.org/10.3390/su13126794

[809] Esquivel-Hernández, D.A., et al., Resource recovery of lignocellulosic biomass waste into lactic acid – trends to sustain cleaner production. Journal of Environmental Management 301 (2022) 113925. https://doi.org/10.1016/j.jenvman.2021.113925

[810] Ren, Y., et al., Lactic acid production by fermentation of biomass: recent achievements and perspectives. Sustainability 14(21) (2022) 14434. https://doi.org/10.3390/su142114434

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Reactors (SMRs) for low-carbon energy production illustrate a broader trend towards compact and efficient energy solutions that could potentially power future biorefineries. Germany, a leader in biorefinery development, is actively pursuing both bottom-up and top-down approaches to establish efficient bio-based production facilities[811]. The FRACTION project is pioneering a novel second-generation biorefinery approach that utilises a continuous organosolv fractionation process to maximise the purity and quality of valuable side streams from lignocellulosic feedstocks[812]. Studies indicate a substantial potential for the development of new biorefinery units in Europe by 2050, contingent upon supportive policies and a flexible feedstock supply chain[813] [814] [815] [816]. By contrast, the MIXMATTERS project aims to develop a highly integrated and diversified biorefinery concept that addresses the challenge of valorising heterogeneous agri-food waste, including streams contaminated with plastics and metals, through the use of a mobile, AI-driven separation unit and a centralised valorisation hub. This innovative system enables the extraction of diverse products, ranging from sugar concentrates and bioactive compounds to plastic monomers and green fibres, while diverting thousands of tonnes of biowaste from landfills and substantially reducing GHG emissions. Both projects are indicative of the EU's commitment to integrated, zero-waste biorefinery concepts that maximise resource efficiency and environmental sustainability through process intensification and advanced integration.

Continuous processing offers numerous benefits for biorefineries, including enhanced productivity, improved product quality and greater control over reaction conditions. The AFTERBIOCHEM project, which is supported by the CBE JU, serves as a prime example of this, employing a closed-loop, waste-free process for the continuous production of high-value bio-based organic acids from sugar industry by-products and organic waste. The field of biomanufacturing in Europe is witnessing an escalating adoption of continuous processing, with the aim of providing sustainable technologies for a variety of industries. Research has demonstrated the viability of continuous bioreactor operation to produce biopolymers such as PHBV, achieving higher productivity and simplifying downstream

[811] German Federal Government - Biorefineries Roadmap as part of the German Federal Government action plans for the material and energetic utilisation of renewable raw materials. Retrieved from [online].

[812] Novel lignocellulose fractionation process for high purity lignin, hemicellulose and cellulose valorisation into added value products | FRACTION | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[813] Mandley, S.J., et al., EU bioenergy development to 2050. Renewable and Sustainable Energy Reviews 127 (2020) 109858. **https://doi.org/10.1016/j.rser.2020.109858**

[814] Zhu, B.X., et al., Regional employment impacts of biorefineries in the EU. EuroChoices 22(3) (2023) 44-50. **https://doi.org/10.1111/1746-692X.12417**

[815] Cotana, F., et al., Bioenergy and biofuels for the environmental and energy transition through the net-Zero emissions 2050 scenario. Rendiconti Lincei. Scienze Fisiche e Naturali 35 (2024) 867-880. **https://doi.org/10.1007/s12210-024-01275-4**

[816] Többen, J., et al., Sustainability implications of the EU's bioeconomy transition along global supply chains. Journal of Cleaner Production 461 (2024) 142565. **https://doi.org/10.1016/j.jclepro.2024.142565**

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processing compared to batch modes[817]. While process intensification is able to reduce CAPEX by 20-30%, its implementation finds two significant barriers. Firstly, the high R&D costs associated with hybrid systems (e.g., microwave-assisted extraction) and, secondly, the regulatory challenges associated with continuous biomanufacturing (or continuous processing if the whole system is considered). Emerging innovations in this field, such as electrocatalytic CO_2 conversion (e.g., REUSE project[818]) and plasma-assisted lignin depolymerisation, hold great promise in further intensifying processes with pilot-scale demonstrations underway in Horizon Europe projects.

The increasing emphasis on process intensification, in particular through the adoption of continuous processing technologies and the development of compact reactor designs, represents a key strategy for improving efficiency, reducing the environmental footprint and lowering the overall cost of biobased production in Europe. European initiatives are actively supporting the development and implementation of integrated biorefineries that aim for zero waste and circular approaches. This reflects a comprehensive understanding of process intensification that prioritises resource efficiency and minimises environmental impact throughout the bio-based value chain.

4.1.6 Syngas Gas Fermentation for Carbon-Capture Utilisation (CCU)

Gasification-based syngas fermentation has emerged as a promising platform for biochemical production. It is a sophisticated hybrid conversion technology that integrates thermochemical, biological and biochemical pathways to convert carbon-rich feedstocks into bio-based fuels, chemicals or bioplastics, such as PHA. Fermentation technology can also convert industrial emissions into protein. With the new pilot level Steelanol site[819], Arcelor Mittal (largest Belgium steel manufacturer) converts emissions from the steel plant in Ghent into sustainable ethanol, which can then be valorised by fermentation technology from Ghent University (UGent) into high-quality protein (CEMPA project). Syngas fermentation provides a very high potential for carbon capture utilisation of very high syngas emitting industries, such as the steel industry, the chemical industry, the cement industry and also for biowaste plans.

The process can be initiated by the thermochemical gasification of biomass at temperatures between 750-900ºC, which involves the partial oxidation of biomass and produces a synthesis gas (syngas), a mixture consisting primarily of carbon monoxide (CO), carbon dioxide (CO_2), and hydrogen (H_2). Subsequently, this syngas is subjected to biological fermentation by anaerobic microbes, such as *Clostridium ljungdahlii*, *Clostridium carboxidivorans* or *Moorella thermoacetica*, which metabolise the

[817] Anaerobic FermenTation & EsteRification of BIOmass for producing fine CHEmicals | AFTERBIOCHEM | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[818] Enzymatic CO_2 Capture in a Rotating Packed Bed and Electrocatalytic CO_2 Reduction to Useful Products | REUSE | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[819] Steelanol – Fueling a sustainable future

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gaseous substrates via the Wood-Ljungdahl pathways into valuable chemicals, including ethanol, acetic acid and butanediol[820]. Critical operational parameters include fermentation temperature (30-37ºC for mesophilic bacteria, 55-60ºC for thermophiles), pH (5.5-6.5), and gas-liquid mass transfer coefficients[821].

Gasification systems have been demonstrated to possess a high degree of versatility, enabling the effective processing of a wide range of feedstocks, including the valorisation of organic waste streams. The feedstocks employed in this process consist of MSW, refuse-derived fuel (RDF), and agricultural residues such as wheat straw and forestry waste. Europe is currently disposed of over 50 million tonnes of MSW per year, which represents significant untapped potential[822].

Despite its promise, several critical barriers hinder the commercial viability of syngas fermentation. Firstly, the presence of high concentrations of tar, sulphur compounds and particulates in the gaseous stream inhibits microbial growth. In order to successfully reduce these concentrations, electrostatic precipitators and scrubbers must be used. Secondly, the mass transfer limitations associated with the poor solubility of CO and H_2 in aqueous media (83% and 71%, respectively, relative to O_2 at 37ºC) limit uptake[823]. Further innovations in high-mass transfer reactors are required in order to overcome this hurdle[824]. Additionally, high CO levels and contaminants can inhibit acetogen metabolism, requiring advanced control systems for maintaining non-inhibitory conditions.

Recent advancements in reactor engineering, incorporating rapid quenching systems and thermally regulated liners, along with innovations in bubble column reactors and hollow fibre membrane systems, are enhancing throughput and operational stability. There are promising developments within the fields of metabolic engineering and CRISPR-based strain modifications. Evidence suggests that these developments have the potential to enhance microbial productivity and improve

[820] Ciliberti, C., et al., Syngas derived from lignocellulosic biomass gasification as an alternative resource for innovative bioprocess. Processes 8(12) (2020) 1567. https://doi.org/10.3390/pr8121567

[821] Heijstra, B.D., et al., Gas fermentation: cellular engineering possibilities and scale up. Microbial Cell Factories 16 (2017) 60. https://doi.org/10.1186/s12934-017-0676-y

[822] Scarlat, N., et al., Status and opportunities for energy recovery from municipal solid waste in Europe. Waste and Biomass Valorization 10 (2019) 2425-2444. https://doi.org/10.1007/s12649-018-0297-7

[823] Phillips, J.R., et al., Syngas fermentation: a microbial conversion process of gaseous substrates to various products. Fermentation 3 (2017) 28. https://doi.org/10.3390/fermentation3020028

[824] Owoade, A., et al., Progress and development of syngas fermentation processes toward commercial bioethanol production. Biofuels, Bioproducts and Biorefining 17(5) (2023) 1328-1342. https://doi.org/10.1002/bbb.2481

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tolerance to microbial inhibitors[825] [826] [827]. For instance, these improvements have enabled the biosynthesis of polyhydroxybutyrate from syngas-derived by-products[828]. In addition, state-of-the-art gasification techniques, such as microwave-assisted pyrolysis, have been demonstrated to improve syngas purity during the processing of heterogeneous feedstocks[829].

The EU SYNPOL project established benchmarks of TRL 7-8 (achieving PHB titres of 12-27% cellular dry weight from syngas-derived acetate, thereby demonstrating its potential to produce biodegradable polymers)[830], while the Renewable Energy Directive III (RED III) stipulates a mandate for 3.5% advanced biofuels by 2030[831], with the potential to boost demand for syngas-derived ethanol by up to 1.5 million tonnes on an annual basis. Pilot and demonstration facilities are currently operational in the Netherlands and Germany, including the Amsterdam Port Hub initiative for circular economy[832] and the German R-GAS demonstration plant[833], which serve as notable examples of the growing readiness of syngas fermentation for scale-up. Capital expenditures remain high[834], but cost reductions are anticipated through improved carbon conversion efficiencies (target of 65%) and modular plant configurations under Horizon Europe and CBE-JU initiatives, amongst others.

4.1.7 Biohydrogen Production

Hydrogen is increasingly recognised as a key element in the transition towards a sustainable energy future within the European Union. Its potential to serve as a clean energy carrier places it at the

[825]Nagaraju, S., et al., Genome editing of *Clostridium autoethanogenum* using CRISPR/Cas9. Biotechnology for Biofuels 9 (2016) 219. **https://doi.org/10.1186/s13068-016-0638-3**

[826]Devi, N.B., et al., Synthetic biology approaches and bioseparations in syngas fermentation. Trends in Biotechnology 43(1) (2025) 111-130. **https://doi.org/10.1016/j.tibtech.2024.07.008**

[827]Sahoo, J., et al., Biochemical aspects of syngas fermentation. In: R. Prasad, V. Kumar, J. Singh, C.P. Upadhyaya (eds) Recent Developments in Microbial Technologies. Environmental and Microbial Biotechnology (2021) Springer, Singapore. **https://doi.org/10.1007/978-981-15-4439-2_19**

[828]Yoon, J., et al., Poly-3-hydroxybutyrate production in acetate minimal medium using engineered *Methylorubrum extorquens* AM1. Bioresource Technology 353 (2022) 127127. **https://doi.org/10.1016/j.biortech.2022.127127**

[829]Revelles, O., et al., Syngas obtained by microwave pyrolysis of household wastes as feedstock for plyhydroxyalkanoate production in *Rhodospirillum rubrum*. Microbial Biotechnology 10(6) (2016) 1412-1417. **https://doi.org/10.1111/1751-7915.12411**

[830]Biopolymers from syngas fermentation | SYNPOL | Projekt | Fact Sheet | FP7 | CORDIS | European Commission

[831]Directive (EU) 2023/2413 of the European Parliament and of the Council of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652

[832]Circular economy | Port of Amsterdam

[833]IEA Bioenergy Task-33 Gasification for Production of Chemicals (2025) | International Energy Agency

[834]Detz, R., et al., Towards the use of renewable syngas for the decarbonization of industry. ChemSusChem 17(15) (2024) e202400059. **https://doi.org/10.1002/cssc.202400059**

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forefront of solutions for decarbonising various sectors, including transportation, industry, and power generation. The European Union, through its commitment to fostering a sustainable and circular bioeconomy, identifies the development and deployment of bio-based technologies as a key priority. Amongst the abovementioned methods, biological techniques for hydrogen production, frequently termed biohydrogen, present a promising approach for the utilisation of renewable resources and the contribution to the EU's ambitious climate neutrality objectives.

Biohydrogen production is defined as a biologically driven, low-emission energy conversion process. It has gained strategic importance within the EU bioeconomy framework as a carbon-neutral energy carrier. Current research focuses on optimising biological conversion pathways for industrial deployment. The primary biological methods under investigation in Europe include dark fermentation, photo-fermentation and microbial electrolysis cells, as is shown in Figure 12.

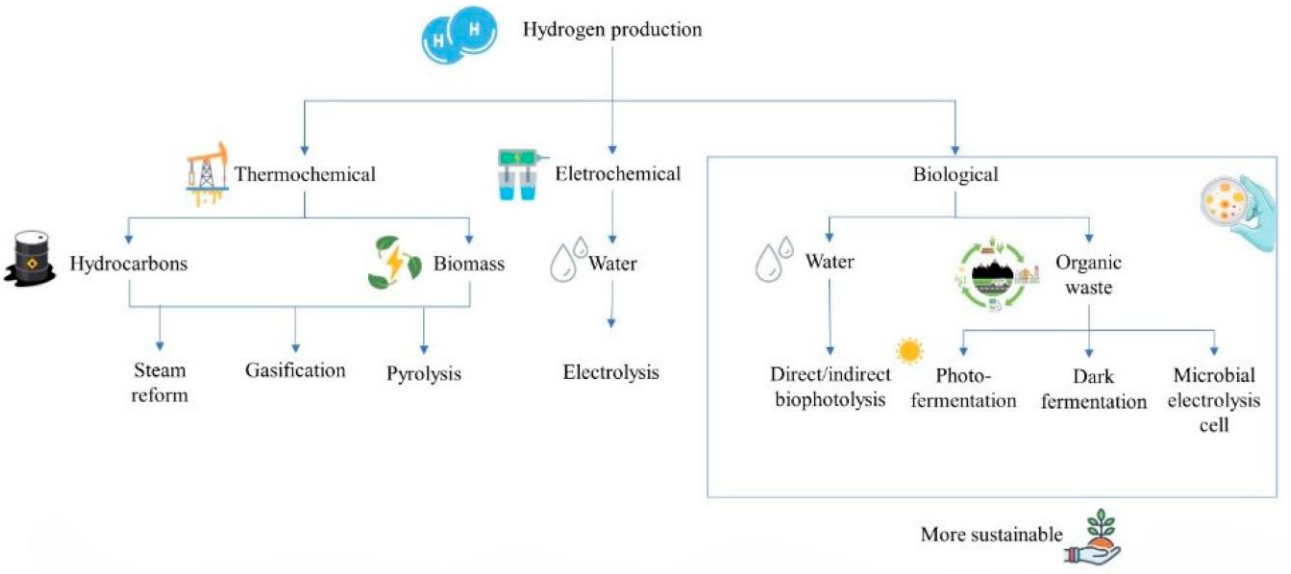


Figure 12 – Processes for producing biohydrogen.
Adapted from[835].

Biophotolysis has been excluded from this deliverable, as it is considered to be one of the less efficient methods for producing biological hydrogen. The key factor in this consideration is the inherently slow nature of the biochemical reactions involved. In addition, the process is highly sensitive to environmental conditions such as temperature and pH. These factors combine to make biophotolysis less viable than other biological hydrogen production methods in terms of efficiency, complexity and scalability. Other processes for hydrogen production tend to be more efficient and

[835] Alburquerque, M.M., et al., Biohydrogen produced via dark fermentation: a review. Methane 3(3) (2024) 500-532. https://doi.org/10.3390/methane3030029

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economically feasible than biophotolysis[836]. The main biochemical reactions involved in each biological method to produce hydrogen are shown below:

1. Dark fermentation (through mesophiles, thermophiles, hyperthermophiles):

$\mathbf{C_6H_{12}O_6}$ + $2H_2O$ → $2CH_3COOH$ + $2CO_2$ + $\mathbf{4H_2}$

2. Photo-fermentation (sulphur, non-sulphur bacteria):

$\mathbf{C_6H_{12}O_6}$ + $6H_2O$ → $6CO_2$ + $\mathbf{12H_2}$

3. Direct biophotolysis (algae, cyanobacteria):

$2H_2O$ + light energy → O_2 + $\mathbf{2H_2}$

4. Indirect biophotolysis (algae, cyanobacteria):

$\mathbf{C_6H_{12}O_6}$ + $12H_2O$ → $6CO_2$ + $\mathbf{12H_2}$

5. Microbial electrolysis cells (electrogens):

$\mathbf{CH_3COOH}$ + $2H_2O$ → $2CO_2$ + $\mathbf{4H_2}$

4.1.7.1 Dark Fermentation

Dark fermentation is a biological process wherein anaerobic bacteria, such as *Clostridium beijerinckii*, *Clostridium butyricum* and *Enterobacter aerogenes*, decompose organic matter in the absence of light, transforming it into hydrogen (H_2) and various by-products, notably VFAs such as acetic acid and butyric acid, along with carbon dioxide and potentially ethanol. Mixed microbial cultures are frequently employed due to their operational simplicity and ability to process a broader spectrum of feedstocks[837]. The specific metabolic route and the array of by-products formed are significantly influenced by the prevailing operational conditions[838].

Optimal operational parameters that influence the efficiency and yield of biohydrogen production include a pH of 5.5-6.0, temperatures of 35-40ºC for mesophilic strains (55-60ºC for thermophilic and 70-80ºC for hyperthermophilic strains), and a hydraulic retention time (HRT) of 24-72 hours for

[836]Osman, A.I., et al., Critical challenges in biohydrogen production processes from the organic feedstocks. Biomass Conversion and Biorefinery 13 (2023) 8383-8401. https://doi.org/10.1007/s13399-020-00965-x

[837]Lacroux, J., et al., Dark fermentation and microalgae cultivation coupled systems: outlook and challenges. Science of the Total Environment 865 (2023) 161136. https://doi.org/10.1016/j.scitotenv.2022.161136

[838] Alburquerque, M.M., et al., Biohydrogen produced via dark fermentation: a review. Methane 3(3) (2024) 500-532. https://doi.org/10.3390/methane3030029

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continuous-flow systems[839], depending on the nature of the substrate and the reactor design. The interaction between temperature, pH, and HRT is particularly important for process optimisation[840] [841]. Maintaining these optimal conditions are needed to prevent the accumulation of inhibitory by-products that can hinder the fermentation process[842]. However, thermophilic and hyperthermophilic conditions, in which homoacetogenic microorganisms can be eliminated and then a more stable hydrogen production is promoted even under moderately high hydrogen partial pressures[843], might necessitate different pH ranges and HRTs compared to mesophilic conditions to maximise hydrogen yield and process stability. For instance, the presence of an acidic environment (pH < 5.5) tends to favour the production of solvents (such as ethanol and butanol), whereas neutral to slightly acidic conditions have a positive effect on the production of acetate and butyrate, which are often associated with higher hydrogen yields[844]. Studies have indicated that reducing HRT can enhance hydrogen production rates, but the ideal duration must balance substrate consumption with sufficient biomass retention. Similarly, the reduction of hydrogen partial pressure in bioreactors can improve production yields[845].

The capacity of dark fermentation not to only generate biohydrogen but also to produce other valuable bio-based chemicals, including organic acids, alcohols, biofuels, and bioplastics, presents a significant opportunity for developing integrated biorefineries. This integrated approach could enhance the economic viability of the process by generating revenue streams from multiple products beyond just hydrogen. The effluent from dark fermentation, rich in VFAs, can serve as a valuable

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[843] Buitrón, G., et al., Biohydrogen production from winery effluents: control of the homoacetogenesis through the headspace gas recirculation. Journal of Chemical Technology & Biotechnology 95(3) (2020) 544-552. https://doi.org/10.1002/jctb.6263

[844] Mokhtarani, B., et al., A review on biohydrogen production through dark fermentation, process parameters and simulation. Energies 18(5) (2025) 1092. https://doi.org/10.3390/en18051092

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feedstock for other biotechnological processes, thereby maximising the overall value extracted from the initial biomass[846].

Europe has prioritised the use of waste-derived, non-food biomass streams for biohydrogen production, aligning with its bioeconomy strategy and contributing actively to the principles of waste valorisation and circular economy. The composition of the feedstock used in biohydrogen production is a critical factor that significantly influences the final hydrogen yield of the applied technologies.

In terms of dark fermentation, the utilisation of waste materials strongly reduces the cost of acquiring feedstock, emphasising the importance of using this technique to sustainably produce energy and to generate valuable products. Dark fermentation is particularly well-suited for processing carbohydrate-rich biomass, ranging from refined sugars such as glucose, sucrose, and xylose to more complex materials such as lignocellulosic biomass and starch. A significant advantage of this technology is its capacity to utilise various organic waste streams, offering a sustainable and cost-effective approach to both waste management and energy production. These waste streams include agricultural residues (e.g., sugarcane leaves, sugar beet tops, sugar molasses, wheat straw, and rice straw), agro-industrial wastes and by-products (e.g., fruit and vegetable peel wastes, cheese whey, glycerol from biodiesel production, industrial wastewater and liquid fraction of anaerobic digestate), municipal wastewater and even sludge from wastewater treatment plants[847 848 849 850 851].

Dark fermentation faces several challenges and limitations that prevent its industrial application. One of the most significant issues is the relatively low hydrogen yield achieved in comparison to the theoretical maximum. The formation of various by-products during the fermentation process causes a diversion of substrate away from hydrogen production, resulting in lower overall yields. The accumulation of these by-products, particularly VFAs, can also decrease the pH of the fermentation broth, thereby constraining the activity of hydrogen-producing bacteria. This metabolic shift has the

[846]Magdalena, J.A., et al., Sequential dark fermentation and microbial electrolysis cells for hydrogen production: volatile fatty acids influence and energy considerations. Bioresource Technology 374 (2023) 128803. https://doi.org/10.1016/j.biortech.2023.128803

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[848]Soares, J.F., et al., Dark fermentative biohydrogen production from lignocellulosic biomass: technological challenges and future prospects. Renewable and Sustainable Energy Reviews 117 (2020) 109484. https://doi.org/10.1016/j.rser.2019.109484

[849]Das, S.R., and N. Basak, Molecular biohydrogen production by dark and photo fermentation from wastes containing starch: recent advancement and future perspective. Bioprocess and Biosystems Engineering 44 (2021) 1-25. https://doi.org/10.1007/s00449-020-02422-5

[850]Ochoa, C., et al., Value-added by-products during dark fermentation of agro-industrial residual biomass: metabolic pathway analysis. Waste and Biomass Valorization 12 (2021) 5937-5948. https://doi.org/10.1007/s12649-021-01421-1

[851]Jain, R., et al., Bio-hydrogen production through dark fermentation: an overview. Biomass Conversion and Biorefinery 14 (2024) 12699-12724. https://doi.org/10.1007/s13399-022-03282-7

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potential to further reduce the efficiency of hydrogen production[852]. For this reason, a comprehensive approach to process optimisation is required to address the inherent trade-off between maximising hydrogen yield and the formation of other potentially valuable compounds such as VFAs, thus exploring their potential for valorisation (such as feedstock for other biotechnological processes or converted into higher-value products) and improving the economic viability and environmental sustainability of the entire dark fermentation process [853] [854]. Another challenge is microbial contamination, where undesirable microorganisms such as methanogens can consume the produced hydrogen or compete with the hydrogen-producing bacteria for available substrates. To address this issue, the implementation of pretreatment techniques is needed, with the aim of inactivating these undesirable microbes, creating a more conducive environment for the hydrogen producers[855]. The variability in the composition of waste feedstocks, such as food waste, is also a limitation, as it can lead to inconsistent hydrogen production and complicate the optimisation of the fermentation process. The presence of inhibitory compounds in these feedstocks has the potential to hinder the efficiency of biohydrogen production[856].

Many complex substrates, especially lignocellulosic biomass, require energy-intensive pre-treatment steps to break down their intricate structure and release fermentable sugars, increasing the overall cost and energy input of the process[857]. Furthermore, the biogas produced from dark fermentation is typically a mixture of hydrogen and carbon dioxide, requiring additional separation and purification steps to obtain high purity hydrogen, which adds to the complexity and cost of the overall process[858]

[852]Chen, Y., et al., Recent advance in inhibition of dark fermentative hydrogen production. International Journal of Hydrogen Energy 46(7) (2021) 5053-5073. https://doi.org/10.1016/j.ijhydene.2020.11.096

[853]Asunis, F., et al., Dark fermentative volatile fatty acids production from food waste: a review of the potential central role in waste biorefineries. Waste Management & Research 40(11) (2022) 1571-1593. https://doi.org/10.1177/0734242X221103940

[854]Lacroux, J., et al., Dark fermentation and microalgae cultivation coupled systems: outlook and challenges. Science of the Total Environment 865 (2023) 161136. https://doi.org/10.1016/j.scitotenv.2022.161136

[855]Sanghvi, A.H., et al., Advancements in biohydrogen production – a comprehensive review of technologies, lifecycle analysis, and future scope. RSC Advances 14 (2024) 36868-36885. https://doi.org/10.1039/D4RA06214K

[856]Gbiete, D., et al., Insights into biohydrogen production through dark fermentation of food waste: substrate properties, inocula, and pretreatment strategies. Energies 14(24) (2024) 6350. https://doi.org/10.3390/en17246350

[857]Soares, J.F., et al., Dark fermentative biohydrogen production from lignocellulosic biomass: technological challenges and future prospects. Renewable and Sustainable Energy Reviews 117 (2020) 109484. https://doi.org/10.1016/j.rser.2019.109484

[858]Tapia-Venegas, E., et al., Biohydrogen production by dark fermentation: scaling-up and technologies integration for a sustainable system. Reviews in Environmental Science and Bio/Technology 14 (2015) 761-785. https://doi.org/10.1007/s11157-015-9383-5

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[859] [860]. Finally, at higher hydrogen partial pressures, the dark fermentation process can become thermodynamically unfavourable, limiting the extent to which hydrogen can be produced[861].

Dark fermentation for biohydrogen production has advanced significantly and has undergone several pilot-scale demonstrations, with some applications entering the early stages of commercialisation. This finding suggests a comparatively higher level of technological maturity in comparison to other biohydrogen production methods, estimating the TRL for dark fermentation to fall within the range of 4 to 7. This range indicates that the technology has progressed beyond basic research and is currently being validated in relevant operational environments, with certain systems nearing commercial deployment. For this reason, biohydrogen production via dark fermentation in the EU is largely in the precommercial stage, where achieving complete commercial viability and competitiveness with conventional hydrogen production methods requires a more profound comprehension of pivotal physicochemical parameters and the surmounting of limitations associated with the scaling up process from laboratory models. The current focus is primarily on pilot and demonstration plants through several R&D projects in Europe. The University of Milano operated a farm-scale pilot plant using a two-stage anaerobic digestion process, in which a 0.7 m^3 reactor was devoted to dark fermentation (and 3.8 m^3 to methanogenic process) from livestock effluents and sugar/starch-rich residues, showing moderate-to-excellent hydrogen yields[862]. The HYCOFOL_BV project in France used wheat straw in a sequential process, which consists of hyperthermophilic dark fermentation followed by photo-fermentation, achieving 75% of the theoretical H_2 yield[863] [864]. Also in France, the ProBHyM project optimised parameters for intensified H_2 output in a 250 L pilot reactor[865]. The ongoing LIFE REPTES project in Span showcases a pioneering circular biohydrogen

[859] Nemestóthy, N., et al., Enhancement of dark fermentative H_2 production by gas separation membranes: a review. Bioresource Technology 302 (2020) 122828. **https://doi.org/10.1016/j.biortech.2020.122828**

[860] Han, W., et al., Techno-economic analysis of a novel bioprocess combining solid state fermentation and dark fermentation for H_2 production from food waste. International Journal of Hydrogen Energy 41(48) (2016) 22619-22625. **https://doi.org/10.1016/j.ijhydene.2016.09.047**

[861] Buitrón, G., et al., Biohydrogen production from winery effluents: control of the homoacetogenesis through the headspace gas recirculation. Journal of Chemical Technology & Biotechnology 95(3) (2020) 544-552. **https://doi.org/10.1002/jctb.6263**

[862] Oberti, R., et al., A farm-scale pilot plant for biohydrogen and biomethane production by two-stage fermentation. Journal of Agricultural Engineering 44(2s) (2013) 544-552. **https://doi.org/10.4081/jae.2013.357**

[863] Production d'HYdrogène par COuplage de procédés de Fermentation à l'Obscurité et à la Lumière appliqué à la Biomasse Végétale | HYCOFOL_BV | ANR

[864] Bioleau, C., et al., Hydrogen production by the hyperthermophilic bacterium *Thermotoga maritima* part I: effects of sulfured nutriments, with thiosulfate as model, on hydrogen production and growth. Biotechnology for Biofuels 9 (2016) 269. **https://doi.org/10.1186/s13068-016-0678-8**

[865] Production de Bio-HYdrogène : vers une voie additionnelle de valorisation biologique des déchets pour la filière de Méthanisation | ProBHyM | ANR

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production process, utilising lignocellulosic by-products and WWTP sludge[866]. The EU-side WASTE2BIOHY project has developed a system that integrates dark fermentation with microbial electrochemical cells for H_2 generation from organic waste[867]. ENEA/CREA (Italy) developed a 50 L two-stage system using cheese whey and manure[868]. Finally, the BIOPHOTO project in Spain is pursuing the production and storage of green hydrogen from organic waste via biological processes[869].

Techno-economic assessments suggest that the cost of biohydrogen production through dark fermentation can range from €1.15 to €9.65 per kg of hydrogen[870], influenced by feedstock costs, plant capacity, and potential revenue from the produced by-products, amongst others. The implementation of carbon credits could also reduce the production cost, making it more competitive with conventional hydrogen production methods[871] [872]. While substantial pilot-scale activities are in progress, the actual biohydrogen production scale is still limited, emphasising on developing and optimising dark fermentation for future commercial deployment. The potential for integrating this technology with the existing anaerobic digestion infrastructure (bottom-up approach) offers a promising pathway for near-term adoption.

4.1.7.2 Photo-Fermentation

Photo-fermentation is a light-dependent biological process that employs photosynthetic bacteria to convert organic substrates (primarily VFAs) into biohydrogen. The process involves a series of biochemical reactions and is predominantly mediated by a diverse group of purple non-sulphur (PNS) bacteria, including genera such as *Rhodobacter*, *Rhodopseudomonas*, and *Rhodospirillum*. These bacteria possess the enzyme nitrogenase, which, under anaerobic conditions and using light energy, catalyses the production of hydrogen from organic acids that act as electron donors. In contrast to dark fermentation, which occurs in the absence of light, photo-fermentation requires a

[866]Renewable bio-hydrogen production technologies from lignocellulosic waste and sewage sludge co-fermentation | LIFE REPTES | LIFE 3.0 - LIFE21-CCM-ES-LIFE-REPTES/101074329

[867]Sustainable hydrogen production from waste via two-stage bioconversion process: an eco-biotechnological approach | Waste2bioHy | Projekt | Fact Sheet | FP7 | CORDIS | European Commission

[868]Marone, A., et al., Biological processes in the Green Hydrogen value chain. Energia, ambiente e innovazione 1/2021 (2021) 95-100. **https://doi.org/10.12910/EAI2021-019**

[869]BIOPHOTO – CETIM, Centro Tecnológico de Investigación Multisectorial

[870]Pasteris, M., Biohydrogen: affordable, green and yet overlooked. Fuels Cells Bulletin 12 (2023). **https://doi.org/10.12968/S1464-2859(23)70088-6**

[871]Dong, Z.Y., et al., A green hydrogen credit framework for international green hydrogen trading towards a carbon neutral future. International Journal of Hydrogen Energy 47(2) (2022) 728-734. **https://doi.org/10.1016/j.ijhydene.2021.10.084**

[872]Sharmila, V.G., et al., Trends in dark biohydrogen production strategy and linkages with transition towards low carbon economy: an outlook, cost-effectiveness, bottlenecks and future scope. International Journal of Hydrogen Energy 47(34) (2022) 15309-15332. **https://doi.org/10.1016/j.ijhydene.2021.12.139**

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light source to drive metabolic reactions. This process has the potential to achieve higher hydrogen yields and avoid the formation of inhibitory acidic end products[873] [874]. However, the need for substantial light availability imposes a distinct operational requirement. The integration of photo-fermentation with dark fermentation establishes a synergistic two-stage system that can enhance the overall efficiency of biomass conversion to hydrogen. In this process, the VFAs produced in the latter act as the feedstock for the former[875] [876].

The primary feedstocks for photo-fermentation are organic acids, particularly VFAs such as acetic acid, butyric acid, lactic acid, and propionic acid. Consequently, apart from the effluent from dark fermentation, which is characterised by its high concentrations of VFAs, photo-fermentation has the capacity to utilise various wastewater streams and organic acid-rich wastes as substrates, including dairy wastewater and olive wastewater[877]. Moreover, the versatility of photo-fermentation in utilising a wide array of organic waste streams, including those from agriculture, food processing, wastewater treatment and other industries, highlights its potential as a sustainable biohydrogen production technology. For instance, research has also explored the use of pretreated lignocellulosic biomass as a feedstock, often in conjunction with dark fermentation, where the resulting products are then used in the photo-fermentation stage[878] [879]. This broad feedstock flexibility enhances its applicability across diverse contexts and regions where various types of organic waste are available.

However, there are significant challenges that limit the widespread application of the photo-fermentation technology. Its operational limitations are dictated by its reliance on light, which confines its functionality to the use of sunlight or energy-intensive artificial illumination, thereby

[873]Putatunda, C., et al., Current challenges and future technology in photofermentation-driven biohydrogen production by utilizing algae and bacteria. International Journal of Hydrogen Energy 48 (2023) 21088-21109. **https://doi.org/10.1016/j.ijhydene.2022.10.042**

[874]Hanipa, M.A.F., et al., Illumination optimization strategies to enhance hydrogen productivity and light conversion efficiency for photo-fermentation by *Rhodobacter sphaeroides* KKU-PS1 using a concentrated multi-substrate feedstock. International Journal of Hydrogen Energy 88 (2024) 418-431. **https://doi.org/10.1016/j.ijhydene.2024.09.132**

[875]Uyar, B., et al., Photofermentative hydrogen production from volatile fatty acids present in dark fermentation effluents. International Journal of Hydrogen Energy 34(10) (2009) 4517-4523. **https://doi.org/10.1016/j.ijhydene.2008.07.057**

[876]Cai, J., et al., Photosynthetic bacteria improved hydrogen yield of combined dark- and photo-fermentation. Journal of Biotechnology 302 (2019) 18-25. **https://doi.org/10.1016/j.jbiotec.2019.06.298**

[877]Islam, A.K.M.K., et al., Bio-hydrogen production from wastewater: a comparative study of low energy intensive production processes. Clean Technologies 3(1) (2021) 156-182. **https://doi.org/10.3390/cleantechnol3010010**

[878]Saha, R., et al., Enhanced production of biohydrogen from lignocellulosic feedstocks using microorganisms: a comprehensive review. Energy Conversion and Management: X 13 (2021) 100153. **https://doi.org/10.1016/j.ecmx.2021.100153**

[879]Hitam, C.N.C., and Jalil, A.A., A review on biohydrogen production through photo-fermentation of lignocellulosic biomass. Biomass Conversion and Biorefinery 13 (2023) 8465-8483. **https://doi.org/10.1007/s13399-020-01140-y**

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increasing operational costs[880]. Achieving uniform light distribution in large-scale bioreactors is a significant engineering challenge, further complicated by the inherently low efficiency of converting light into biohydrogen, which limits productivity and economic viability[881] [882]. The nitrogenase enzyme, which is essential for hydrogen production in PNS bacteria, is highly oxygen-sensitive, thus necessitating strict anaerobic conditions that are difficult to maintain at scale, particularly in open systems. The issue of temperature control for optimal bacterial activity in outdoor settings is also problematic due to environmental fluctuations[883]. The efficient design of photobioreactors remains a critical hurdle, requiring solutions for optimal light penetration, uniform distribution, and effective gas collection. All of these are affected by light attenuation in dense cultures. The process of upscaling from laboratory to industrial scale introduces further technical and economic complexities. These are especially relevant when it comes to maintaining ideal light and anaerobic conditions across large volumes and complex piping and reactor designs. Furthermore, in addition to the abovementioned light intensity, parameters such as wavelength, nutrient and substrate availability, and temperature have been demonstrated to exert a significant influence on bacterial performance and hydrogen yield[884] [885]. Consequently, the practical deployment of photo-fermentation remains constrained, necessitating innovative strategies to overcome these limitations.

The current production scale of biohydrogen via photo-fermentation in the EU is very limited. Most efforts are still focused on research and development, and the technology is estimated to be between TRL 4 and 5. Photo-fermentation is generally at an earlier stage of development compared to dark fermentation, with preliminary studies being conducted on a small scale (in a laboratory or pilot project). However, at present, there are no significant industrial-scale facilities in operation within the European Union. In order to gather operational data and assess the commercial viability of photo-fermentation, further development and construction of pilot plants are necessary. Several European initiatives have investigated photo-fermentation for biohydrogen production. In France, the

[880]Melitos, G., et al., Waste to sustainable biohydrogen production via photo-fermentation and biophotolysis – a systematic review. Renewable Energy and Environmental Sustainability 6 (2021) 45. **https://doi.org/10.1051/rees/2021047**

[881]Uyar, B., Bioreactor design for photofermentative hydrogen production. Bioprocess and Biosystems Engineering 39 (2016) 1331-1340. **https://doi.org/10.1007/s00449-016-1614-9**

[882]Zhang, Z., et al., Photo-bioreactor structure and light-heat-mass transfer properties in photo-fermentative bio-hydrogen production system: a mini review. International Journal of Hydrogen Energy 42(17) (2017) 12143-12152. **https://doi.org/10.1016/j.ijhydene.2017.03.111**

[883]Gabrielyan, L., et al., Novel properties of photofermentative biohydrogen production by purple bacteria *Rhodobacter sphaeroides*: effects of protonophores and inhibitors of responsible enzymes. Microbial Cell Factories 14 (2015) 131. **https://doi.org/10.1186/s12934-015-0324-3**

[884]Hay, J.X.W., et al., Biohydrogen production through photo fermentation or dark fermentation using waste as a substrate: overview, economics, and future prospects of hydrogen usage. Biofuels, Bioproducts and Biorefining 7(3) (2013) 334-352. **https://doi.org/10.1002/bbb.1403**

[885]Emetere, M.E., Progress, limitations, and advances of biohydrogen technologies: bringing the technology close to energy participants in developing countries. Biofuels (2025) 1-17. **https://doi.org/10.1080/17597269.2025.2467493**

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abovementioned HYCOFOL_BV project incorporated a photo-fermentation stage following dark fermentation of wheat straw in a 5 L bioreactor[886]. The EU-wide HyTime project focused on optimising a biotechnological process using photosynthetic bacteria and second-generation biomass, with a target hydrogen productivity of 1-10 kg/day[887]. Germany's SmartBioH2-BW project integrated a biorefinery approach, employing PNS bacteria and microalgae to produce hydrogen and other bio-based products from industrial wastewater, achieving extrapolated yields of up to 3400 L/month in a 75 L bioreactor via microaerobic dark fermentation and photo-fermentation[888]. As previously stated, Spain's BIOPHOTO project is also exploring biological routes for producing green hydrogen from organic waste, including photo fermentation[889]. Collectively, albeit the present limitations, photo-fermentation demonstrates these efforts reflect sustained interest in developing photo-fermentation as a practical pathway for sustainable hydrogen generation. Further research is required to overcome the fundamental challenges concerning light efficiency and scalability, with the objective of raising its TRL to a level suitable for commercial application. The viability of this approach is contingent on advancements in light efficiency, bioreactor design, and cost-effectiveness[890]. Its capacity to utilise the by-products of other processes renders it a key component in integrated biorefinery concepts.

4.1.7.3 Microbial Electrolysis Cells

Microbial electrolysis cells (MECs) are a bioelectrochemical technology that harnesses the metabolic activity of electroactive microorganisms to produce hydrogen gas from organic matter typically found in wastewater, with the assistance of a small externally applied voltage. This approach offers a sustainable solution for both energy production and wastewater treatment. In an MEC, electroactive bacteria (EAB), such as *Geobacter sulfurreducens*, colonise the surface of the anode, forming a biofilm. These bacteria oxidise the organic substrates present in the wastewater, releasing electrons and protons. The electrons thus generated are subsequently transferred to the anode, and flow through an external electrical circuit to the cathode. A small external voltage, typically ranging from 0.2 to 0.8 V, is applied to the system to provide the necessary thermodynamic driving force for hydrogen production at the cathode, rendering the process more energy-efficient in comparison to

[886] Production d'HYdrogène par COuplage de procédés de Fermentation à l'Obscurité et à la Lumière appliqué à la Biomasse Végétale | HYCOFOL_BV | ANR

[887] Low temperature hydrogen production from second generation biomass | HyTime | Projekt | Fact Sheet | FP7 | CORDIS | European Commission

[888] SmartBioH$_2$-BW – Biohydrogen from industrial wastewater and residual streams as a platform for versatile biosynthetic routes - Fraunhofer IGB

[889] BIOPHOTO – CETIM, Centro Tecnológico de Investigación Multisectorial

[890] Ahmed, S.F., et al., Biohydrogen production from biomass sources: metabolic pathways and economic analysis. Frontiers in Energy Research 9 (2021) 753878. **https://doi.org/10.3389/fenrg.2021.753878**

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conventional water electrolysis[891] [892]. The protons (H+) produced at the anode migrate through the electrolyte, which can be the wastewater itself or a separate solution in a two-chamber system, towards the cathode. At the cathode, these protons are reduced to hydrogen gas (H_2) by the electrons that arrive from the anode via the external circuit. The electrochemical reduction reaction is frequently facilitated by a catalyst material deposited on the cathode surface. While noble metals such as platinum have historically been utilised, there has been an increasing focus on the development of more cost-effective and sustainable non-noble metal catalysts[893] and even carbon-based electrodes[894]. MECs can be designed in a variety of configurations, primarily in single and dual chamber systems. In single-chamber MECs, the anode and cathode are positioned within the same compartment, potentially separated by an ion-exchange membrane to impede oxygen crossover from the anode. Membraneless single-chamber MECs are also being investigated for their potential to reduce costs and provide high hydrogen production rates. Double chamber MECs are characterised by the presence of distinct anode and cathode compartments, which are generally separated by an ion exchange membrane[895]. This membrane facilitates proton transport while impeding the mixing of the anolyte and catholyte[896]. The dual functionality of MECs, producing biohydrogen from diverse organic-rich feedstocks while treating wastewater, makes them a highly versatile and promising technology for integrated energy and environmental solutions[897]. [898]. The organic matter present in these effluents serves as the primary fuel source for the electroactive bacteria at the anode (or bioanode, in this case). The process of microbial degradation of complex organic compounds in these feedstocks is achieved through bioelectrochemical reactions, which lead to hydrogen production.

[891]Cui, W., et al., Hydrogen production in single-chamber microbial electrolysis cell under high applied voltages. Science of the Total Environment 780 (2021) 146597. https://doi.org/10.1016/j.scitotenv.2021.146597

[892]Gautam, R., et al., Bio-hydrogen production through microbial electrolysis cell: structural components and influencing factors. Chemical Engineering Journal 455 (2023) 140535. https://doi.org/10.1016/j.cej.2022.140535

[893]Wu, H., et al., Non-noble metal electrocatalysts for the hydrogen evolution reaction in water electrolysis. Electrochemical Energy Reviews 4 (2021) 473-507. https://doi.org/10.1007/s41918-020-00086-z

[894]Xu, L., et al., Carbon-based materials as highly efficient catalysts for the hydrogen evolution reaction in microbial electrolysis cells: mechanisms, methods, and perspectives. Chemical Engineering Journal 471 (2023) 144670. https://doi.org/10.1016/j.cej.2023.144670

[895]Bora, A., et al., Microbial electrolysis cell (MEC): reactor configurations, recent advances and strategies in biohydrogen production. Fuel 328 (2022) 125269. https://doi.org/10.1016/j.fuel.2022.125269

[896]El-Qelish, M., et al., Membrane-based technologies for biohydrogen production: a review. Journal of Environmental Management 316 (2022) 115239. https://doi.org/10.1016/j.jenvman.2022.115239

[897]Dange, P., et al., Recent developments in microbial electrolysis cell-based biohydrogen production utilizing wastewater as a feedstock. Sustainability 13(16) (2021) 8796. https://doi.org/10.3390/su13168796

[898]Marone, A., et al., Coupling dark fermentation and microbial electrolysis to enhance bio-hydrogen production from agro-industrial wastewaters and by-products in a bio-refinery framework. International Journal of Hydrogen Energy 42(3) (2017) 1609-1621. https://doi.org/10.1016/j.ijhydene.2016.09.166

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Beyond wastewater treatment, MECs have also demonstrated their adaptability to diverse organic-rich wastewaters types, treating a variety of substrates and organic waste, including synthetic wastewater, domestic wastewater, industrial wastewater derived from sectors such as food and beverage processing and olive mill wastewater, glycerol from biodiesel production, sludge and liquid fraction of industrial and municipal anaerobic digestion, and agricultural wastewater[899] [900] [901] [902] [903] [904] Furthermore, dark fermentation effluent, which is abundant in VFAs, is an ideal raw material for MECs. The combination of dark fermentation and MECs in a sequential process is a highly effective strategy for increasing the conversion of complex organic substances to hydrogen. This two-stage approach facilitates the complete utilisation of the initial organic matter, thereby enhancing overall energy recovery[905].

The current production scale of biohydrogen via MECs in the EU is very limited as well as dark fermentation and photo-fermentation. In comparison with them, this technology is regarded as being at a more preliminary stage of development. Its implementation in industry is yet to be widespread. Estimates suggest that the TRL for MECs ranges from 4 to 6, indicating that MECs have advanced beyond fundamental research and are currently undergoing testing and validation in laboratory-scale and pilot-scale settings. While specific examples of large-scale MEC plants dedicated to biohydrogen production in the EU are not prominent, the implementation of MECs in several National and European research projects indicates a growing interest in demonstrating the potential of the technology in relevant applications, particularly in wastewater treatment. For instance, the WASTE2BIOHY project, as previously referenced, integrated dark fermentation and MECs for

[899] Cristiani, L., et al., Renewable gases production coupled to synthetic wastewater treatment through a microbial electrolysis cell. Biochemical Engineering Journal 205 (2024) 109249. https://doi.org/10.1016/j.bej.2024.109249

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[901] Muddasar, M., et al., Performance efficiency comparison of microbial electrolysis cells for sustainable production of biohydrogen – a comprehensive review. International Journal of Energy Research 46(5) (2022) 5625-5645. https://doi.org/10.1002/er.7606

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[903] Badia-Fabregat, M., et al., Hydrogen production from crude glycerol in an alkaline microbial electrolysis cell. International Journal of Hydrogen Energy 44(32) (2019) 17204-17213. https://doi.org/10.1016/j.ijhydene.2019.03.193

[904] Onwuemezie, L., and Darabkhani, H.G., Solar and wind assisted biohydrogen production from integrated anaerobic digestion and microbial electrolysis cell coupled with catalytic reforming. Energy Conversion and Management 305 (2024) 118224. https://doi.org/10.1016/j.enconman.2024.118224

[905] Ndayisenga, F., et al., Thermophilic-operating environment promotes hydrogen-producing microbial growth in a lignocellulose-fed DF-MEC system for enhanced biohydrogen evolution. Process Safety and Environmental Protection 167 (2022) 213-224. https://doi.org/10.1016/j.psep.2022.09.026

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sustainable hydrogen production from diverse organic waste streams[906]. These efforts are centred on improving the efficiency, scalability, and cost-effectiveness of MEC technology. However, the current research trend related to MECs is on desulphurisation and biofuels and biomethane production, leaving aside their potential application in biohydrogen production[907] [908] [909] [910]. The further development and deployment of pilot plants and demonstrators is required, particularly those integrated with wastewater treatment facilities, in order to assess the commercial viability of MEC technology in real-world settings. MECs have the potential to facilitate decentralised treatment of wastewater at the source, while simultaneously producing renewable hydrogen, a development that could prove advantageous for smaller communities or industries. While the potential of MEC technology for future biohydrogen production is promising, further validation through pilot-scale studies and optimisation is required to demonstrate its economic and technical feasibility for industrial applications, especially in the context of wastewater treatment and resource recovery. Consequently, the current scale reflects a technology that is undergoing a transition from research to commercial application.

4.1.7.4 Potential breakthroughs in biohydrogen production

Several potential breakthroughs could enhance the efficiency and economic viability of biohydrogen production. Metabolic engineering of microorganisms to optimise hydrogen production pathways, improve the utilisation of diverse substrates, enhance tolerance to inhibitory by-products, and improve the performance of photosynthetic bacteria and microbial electrolysis cell (MEC) communities shows considerable promise[911] [912]. Such approaches could involve enhancing the activity of key enzymes, redirecting metabolic fluxes towards hydrogen production, improving light-harvesting efficiency and oxygen tolerance in photosynthetic microorganisms, or combining genetic

[906] Sustainable hydrogen production from waste via two-stage bioconversion process: an eco-biotechnological approach | Waste2bioHy | Projekt | Fact Sheet | FP7 | CORDIS | European Commission

[907] Development of A Novel Submerged Anaerobic Electrochemical Membrane Bioreactor (e-SAnMBR) for bilge water treatment | ElectroSAnMBR | Projekt | Results | H2020 | CORDIS | European Commission

[908] Capture and Reuse Of biogenic gases for Negative-emission - sustainable biofUelS | CRONUS | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[909] Sistema bioelectroquímico para la valorización integral de las aguas residuales y los fangos de EDAR | VIOe- | DAM

[910] Arranca ECLOSION: el proyecto MISIONES de hidrógeno renovable y biometano para impulsar una economía descarbonizada, sostenible y circular. - IDECAL

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[912] Awate, B., et al., Stimulation of electro-fermentation in single-chamber microbial electrolysis cells driven by genetically engineered anode biofilms. Journal of Power Sources 356 (2017) 510-518. **https://doi.org/10.1016/j.jpowsour.2017.02.053**

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engineering and bioaugmentation strategies to increase hydrogen production rates in MEC systems[913] [914] [915].

Process integration, particularly the coupling of dark fermentation with photo-fermentation or MEC technologies in hybrid or two-stage systems, offers a pathway towards higher overall hydrogen yields and more efficient substrate utilisation[916] [917] [918]. In these systems, the VFAs produced during the dark fermentation process can be used as a source of fuel for hydrogen-producing processes. This increases the efficiency of substrate conversion and recovery of hydrogen[919] [920]. Similarly, the utilisation of microalgae in photo-fermentation or integrated systems could offer advantages in terms of CO_2 fixation and biomass production. Moreover, the incorporation of these technologies devoted to biohydrogen production into existing infrastructures (e.g., wastewater treatment plants) can establish synergistic effects and favour their technological leap and implementation at larger scales, thus improving their overall energy efficiency and resource recovery.

The development of novel bioreactor designs, such as membrane bioreactors or continuous stirred tank reactors (CSTRs) with improved systems for hydrogen removal, could enhance productivity and overcome limitations related to mass transfer and internal resistance[921] [922]. Similarly, the development of novel and more efficient photobioreactor design, such as those utilising internal light sources, light guide plate, thermosiphon photobioreactor, continuous-flow moving bed biofilm

[913]Oh, Y.K., et al., Current status of the metabolic engineering of microorganisms for biohydrogen production. Bioresource Technology 102 (2011) 8357-8367. https://doi.org/10.1016/j.biortech.2011.04.054

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[922]Brindhadevi, K., et al., Biohydrogen production using horizontal and vertical continuous stirred tank reactor – a numerical optimization. International Journal of Hydrogen Energy 46(20) (2021) 11305-11312. https://doi.org/10.1016/j.ijhydene.2020.06.155

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reactor, thin-layer reactors or two-phase systems, could optimise light irradiation and hydrogen recovery in photo-fermentation[923]. Following the same idea, exploring and optimising various configurations in MEC technology, such as single-chamber systems, two-chamber systems (with and without ion-exchange membranes), and three-electrode setups should be considered to enhance its overall performance[924] [925]. Research into more cost-effective and efficient pretreatment methods for complex feedstocks, including physical, chemical, and biological approaches, is also crucial for improving the accessibility of fermentable sugars and reducing the overall cost of the process.

The incorporation of specific additives or nanomaterials into the fermentation process has shown potential for enhancing microbial activity, improving enzyme efficiency, enhancing light absorption, and increasing hydrogen production rates, depending on the biohydrogen production technique[926]. Regarding MEC technology, continued research into the development of cost-effective and highly efficient electrodes, including advanced catalysts (such as noble metals, transition metals, carbon-based nanomaterials, and metal-organic frameworks), bio-inspired materials and chemically modified electrodes, is crucial for improving MEC performance and then reducing overall costs[927] [928].

Finally, continuous optimisation and precise control of key operational parameters such as pH, temperature, HRT, and OLR, using advanced monitoring and control systems[929] [930], can lead to more stable and efficient hydrogen production.

[923]Shresh, G., et al., Light-dependent biohydrogen production: progress and perspectives. Bioresource Technology 380 (2023) 129007. https://doi.org/10.1016/j.biortech.2023.129007

[924]Su, M., et al., Hydrogen production in single chamber microbial electrolysis cells with stainless steel fiber felt cathodes. Journal of Power Sources 301 (2016) 29-34. https://doi.org/10.1016/j.jpowsour.2015.09.108

[925]Cristiani, L., et al., Enhancing energy efficiency and H_2 production in lab-scale dual chamber microbial electrolysis cells: a focus on catholyte composition and voltage losses. Journal of Environmental Chemical Engineering 12(1) (2024) 111782. https://doi.org/10.1016/j.jece.2023.111782

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4.2 THERMOCHEMICAL CONVERSION TECHNOLOGIES

Thermochemical Conversion Technologies offer versatile pathways for transforming biomass into advanced biofuels and biochemicals. Gasification, pyrolysis and hydrothermal liquefaction enable the capacity to convert a variety of biomass feedstocks, including woody biomass, crop residues, sewage sludge and organic waste, into energy carriers (e.g., syngas, bio-oil) and chemical building blocks such as platform molecules (acetoin, 2,3-butanediol)[931] [932]. For instance, the BRISK project integrated European research infrastructures to optimise gasification and pyrolysis parameters, achieving reduced tar formation and improved resistance to ash sintering through advanced reactor designs and catalytic processes[933]. Similarly, the BIOCTANE project is working on demonstrating a novel one-pot catalytic method to convert organic waste-derived platform molecules into jet-fuel-range hydrocarbons, highlighting the potential for nutrient recovery and carbon-neutral aviation fuels[934].

The integration of thermochemical pathways with biochemical methods, such as coupling thermochemical pretreatment (e.g., pyrolysis) with subsequent fermentation, presents opportunities for creating highly efficient hybrid biorefineries. Such integrated systems have been shown to enhance yields of bio-based plastics and platform chemicals while using lignocellulosic residues[935] [936]. This approach has been shown to maximise biomass utilisation, as evidenced by project investigating co-processing of biomass with waste polymers or glycerol. Furthermore, techno-economic analyses have identified pyrolysis and hybrid systems as the most cost-effective routes, improving economic viability. LCA-driven process optimisation is also emphasised in recent advancements, particularly for reducing GHG emissions in hard-to-descarbonise sectors like

[931] Lee, D., et al., Recent progress in the catalytic thermochemical conversion process of biomass for biofuels. Chemical Engineering Journal 447 (2022) 137501. **https://doi.org/10.1016/j.cej.2022.137501**

[932] Wu, Y., et al., Applications of catalysts in thermochemical conversion of biomass (pyrolysis, hydrothermal liquefaction and gasification): a critical review. Renewable Energy 196 (2022) 462-481. **https://doi.org/10.1016/j.renene.2022.07.031**

[933] The European Research Infrastructure for Thermochemical Biomass Conversion | BRISK | FP7 | CORDIS | European Commission

[934] Synergetic integration of BIOteChnology and thermochemical CaTalysis for the cAscade coNvErsion of organic waste to jet-fuel | BIOCTANE | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[935] Ong, H.C., et al., Catalytic thermochemical conversion of biomass for biofuel production: a comprehensive review. Renewable and Sustainable Energy Reviews 113 (2019) 109266. **https://doi.org/10.1016/j.rser.2019.109266**

[936] Begum, Y.A., et al., A review on the waste biomass-to-energy: integrated thermochemical and biochemical conversion for resource recovery. Environmental Science: Advances 3(9) (2024) 1197-1216. **https://doi.org/10.1039/D4VA00109E**

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aviation[937] [938]. However, the successful scaling of these technologies will require targeted responses to challenges such as feedstock variability, which could be mitigated through the deployment of AI-driven pretreatment systems.

4.3 NANOTECHNOLOGY APPLICATIONS

Nanotechnology and Advanced Materials are rapidly evolving into a transformative force within the European bio-based sector, offering innovative solutions and enhancing the properties of a broad range of products. Nanomaterials, defined by their miniscule size, demonstrate distinctive physical, mechanical, chemical and electrical properties, significantly broadening the scope of bio-based polymers and related materials.

The potential for nanotechnology in the bio-based sector is significant, particularly in biorefineries and the development of advanced bio-based materials. Regarding bio-based packaging, nanotechnology facilitates the creation of materials with enhanced barrier properties (e.g., nanocellulose-based films with oxygen resistance), antimicrobial activity via lignin nanoparticles, and enhanced mechanical strength through nanocomposites such as biochar-reinforced polymers[939] [940]. A case in point is the EU-funded NanoPack project, which is developing and demonstrating state-of-the-art antimicrobial packaging solutions for perishable foods. These solutions use natural nanomaterials to prevent food-borne illness and reduce food waste[941]. Another Horizon 2020 initiative, the BIOMAC project, aims to reduce barriers to the use of bio-based polymers and nanomaterials by providing services for the upscaling of nano-enabled bio-based materials (NBMs) from laboratory validation to industrial prototypes. Their Open Innovation Test Bed facilitates the progression of NBMs up to industrial prototypes, ensuring compliance with EU regulations while reducing commercialisation risks[942]. The growing impact of nanotechnology and advanced materials in the European bio-based sector is driving a surge in research and innovation, leading to the development of sustainable solutions that underpin the EU's greener development and circular

[937] Marciello, V., et al., Design exploration for sustainable regional hybrid-electric aircraft: a study based on technology forecasts. Aerospace 10 (2023) 165. **https://doi.org/10.3390/aerospace10020165**

[938] Sadhukhan, J., and Sen, S., A novel mathematical modelling platform for evaluation of a novel biorefinery design with green hydrogen recovery to produce renewable aviation fuel. Chemical Engineering Research and Design 175 (2021) 358-379. **https://doi.org/10.1016/j.cherd.2021.09.014**

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[941] Pilot line production of functional polymer nanocomposites from natural halloysite nanotubes: demonstrating controlled release of active antimicrobials in food packaging applications. | NanoPack | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[942] European Sustainable BIObased nanoMAterials Community | BIOMAC | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

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economy ambitions. Beyond the field of packaging, research studies focus on advancing nanotechnology for a sustainable circular bioeconomy, in particular exploring applications in renewable energy, agriculture and bioplastics[943] [944] [945] [946]. In addition, nanotechnology is being investigated for its potential to optimise biofuel production through the use of nanomaterial-based catalysts for transesterification and enzyme immobilisation[947] [948] [949]. In the field of algal biorefineries, the potential of nanoparticles to enhance cell growth, harvesting efficiency, product extraction and conversion processes is being investigated[950] [951]. Furthermore, the impact of nanotechnology in biorefineries extends to improving catalytic conversion and durability in the production of biofuels from different biomass sources. A notable example would be the development of lignin-derived catalysts for the efficient production of biofuels and the minimisation of downstream processing to purify bio-based chemicals such as succinic acid[952].

In biomedical applications, bio-based drug delivery systems are emerging, leveraging nanocarriers such as glycol-functionalized cellulose nanocrystals for targeted therapies[953] [954]. Collaborative

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[950] Thanigaivel, S., et al., Nanotechnology for improved production of algal biofuels: a review. Environmental Chemistry Letters 21 (2023) 821-837. https://doi.org/10.1007/s10311-022-01529-3

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ecosystems exemplify strategic efforts to unify R&D and industrial scaling, addressing challenges like cost competitiveness and global market leadership. Recent policy initiatives underscore the pivotal role advanced materials play in safeguarding Europe's economic sovereignty, with innovations in NBMs projected to capture 15–20% of the global bioeconomy market by 2030[955] [956].

Several European research initiatives and projects are dedicated to the advancement of nanobiotechnology and bio-based nanomaterials. The JRC Nanobiotechnology Laboratory is equipped with cutting-edge facilities for interdisciplinary studies, with a particular emphasis on the characterisation of nanomaterials and their interactions with biological systems. This supports the safe and sustainable development of nanotechnology [957]. ERA4Health has issued calls for transnational collaboration in the field of nanomedicine research, inviting the participation of academic institutions, clinical researchers and SMEs [958]. The BIOMAC project, as previously referenced, plays an important role in promoting the European bioeconomy by supporting the development and upscaling of bio-based nanomaterials across diverse sectors[959]. Moreover, the European Commission, in collaboration with the JRC, is actively promoting the concept of 'safe and sustainable by design' in nanotechnology to ensure that innovations in this field contribute to a greener and more circular EU economy[960] [961].

The integration of nanotechnology into the European bio-based sector is vital for achieving the EU's energy transition and expanding rapidly, with the potential to go beyond the simple enhancement of the properties of existing materials to enable the creation of entirely new functionalities. This is particularly evident in areas such as food packaging with advanced antimicrobial properties and the development of high-performance materials for various industrial applications. European research in bio-based nanotechnology places a strong emphasis on ensuring the safety and sustainability of these innovations, considering the environmental and health impacts of nanomaterials throughout their life cycle, from design to disposal.

4.4 Advances In Downstream Processing

[955] A. Wolf, Advanced materials for the green and digital age: harnessing material innovation for Europe's economic sovereignty. CepInput 8 (2024) Centrum für Europäische Politik, Deutschland

[956] Horizon Europe: opportunities for the Nanotech and Material sector | Wheesbee

[957] JRC Nanobiotechnology Laboratory – European Commission's Joint Research Centre (JRC) - Ceric

[958] ERA4Health Partnership

[959] European Sustainable BIObased nanoMAterials Community | BIOMAC | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[960] Safe and sustainable by design – Research and Innovation - European Commission

[961] Safe and sustainable by design chemicals and materials for Europe's green transition | Results Pack | CORDIS | European Commission

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Downstream processing represents a critical stage in bio-based processes, particularly within the context of biorefineries. The term refers to the sequence of unit operations employed to separate, recover and purify desired bio-based products from complex mixtures, such as biological raw materials or upstream bioprocessing stages. The efficiency and cost-effectiveness of these processes are pivotal to the overall feasibility and sustainability of the European bio-based industry, given their significant impact on product yields and the quality of the bioproducts obtained[962]. In the context of the EU bioeconomy, the transformation of sustainably sourced biomass into a wide array of value-added products is a key priority. This priority is driven by the need to improve both bioconversion technologies and downstream processing [963] . These products include food ingredients, animal feed, bio-based chemicals and biomaterials.

Significant research efforts in Europe are focused on the development of novel separation techniques to improve the recovery of bioproducts in biorefineries. For instance, several researchers are focusing on the development of aquatic biotechnology solutions, including the optimisation of selective downstream processing techniques for the recovery of valuable metabolites from marine and other aquatic organisms. Other investigations emphasise the demonstration of sustainable and efficient production processes for bio-based solvents, with a focus on improving both upstream and downstream aspects to reduce costs and improve environmental performance. Research also explores the application of membrane-based techniques such as ultrafiltration and nanofiltration for the recovery of valuable bioproducts, including acetic acid and phenolic compounds, from biorefinery streams. These techniques offer distinct advantages in terms of energy efficiency and selectivity when compared to conventional methods, such as distillation. Furthermore, novel separation techniques such as solvent extraction in two-phase systems and reactive adsorption using zeolite and carbon sorbents are being investigated for the selective recovery of bioproducts from complex reaction media. The NoviCo project, which is funded by the EEA, is investigating the use of ionic liquid-based extraction for the sustainable separation of lignin from lignocellulosic biomass. This will be followed by electrochemical oxidation and fungal conversion to valuable products. In addition, the company is exploring the potential of extraction methodologies, including microwave-assisted extraction, ultrasound-assisted extraction, enzyme-assisted extraction and supercritical fluid

[962]Cuellar, M.C., and Straathof, A.J.J., Downstream of the bioreactor: advancements in recovering fuels and commodity chemicals. Current Opinion in Biotechnology 62 (2020) 189-195. https://doi.org/10.1016/j.copbio.2019.11.012

[963]Dupont-Inglis, J., and Borg, A., Destination bioeconomy – the path towards a smarter, more sustainable future. New Biotechnology 40(A) (2018) 140-143. https://doi.org/10.1016/j.nbt.2017.05.010

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extraction, for the valorisation of marine, agricultural and food by-products[964] [965] [966] [967] [968]. These methods offer enhanced yields and reduced treatment times in comparison to conventional solvent extraction techniques.

A key goal of these research efforts is to boost the economic viability and sustainability of downstream processing within the bio-based industry. This encompasses endeavours to enhance process efficiency, curtail capital and operational expenditure (CAPEX/OPEX), minimise process waste, and optimise process safety throughout the value chain. The development and implementation of efficient downstream processing technologies is crucial to enable the wider market uptake of industrial biotechnology products and to ensure the competitiveness of the European bio-based sector.

Amongst the different technologies applicable in downstream processing, membrane technologies and novel separation techniques are critical to the efficient and cost-effective operation of biorefineries. European initiatives, including the IETS Task Annex XVII, are encouraging innovation through multinational collaboration between Austria, Denmark, France and Sweden[969]. The primary focus of the task is the integration of membrane processes into biorefineries, with a view to addressing the significant challenge of membrane fouling. This is a key issue, as it contributes to 50-80% of operating costs in separation steps[970] [971] [972]. Recent advances in the field include the development of novel osmotic pressure-driven processes such as forward osmosis (FO) and organic

[964] Vilas-Franquesa, A., et al., Recent advances in bio-based extraction processes for the recovery of bound phenolics from agro-industrial by-products and their biological activity. Critical Reviews in Food Science and Nutrition 64(29) (2024) 10643-10667. **https://doi.org/10.1080/10408398.2023.2227261**

[965] Zhang, Q., et al., Microwave-assisted biorefineries. Nature Reviews Clean Technology 1 (2025) 269-287. **https://doi.org/10.1038/s44359-025-00033-5**

[966] Pizani, R.S., et al., New selective and sustainable ultrasound-assisted extraction procedure to recover carnosic and rosmarinic acids from *Rosmarinus officinalis* by sequential use of bio-based solvents. Food Chemistry 435 (2024) 137540. **https://doi.org/10.1016/j.foodchem.2023.137540**

[967] Streimikyte, P., et al., Enzyme-assisted extraction of plants for sustainable and functional applications. International Journal of Molecules Sciences 23(4) (2022) 2359. **https://doi.org/10.3390/ijms23042359**

[968] Zhou, J., et al., The application of supercritical fluids technology to recover healthy valuable compounds from marine and agricultural food processing by-products: a review. Processes 9(2) (2021) 357. **https://doi.org/10.3390/pr9020357**

[969] Membrane Processes in Biorefineries | Industrial Energy-Related Technologies and Systems | IETS

[970] Abels, C., et al., Membrane processes in biorefinery applications. Journal of Membrane Science 444 (2013) 285-317. **https://doi.org/10.1016/j.memsci.2013.05.030**

[971] Garcia-Ivars, J., et al., Treatment of table olive processing wastewaters using novel photomodified ultrafiltration membranes as first step for recovering phenolic compounds. Journal of Hazardous Materials 290 (2015) 51-59. **https://doi.org/10.1016/j.jhazmat.2015.02.062**

[972] Ennaceri, H., et al., Membrane fouling control for sustainable microalgal biodiesel production: a review. Renewable and Sustainable Energy Reviews 161 (2022) 112335. **https://doi.org/10.1016/j.rser.2022.112335**

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solvent reverse osmosis (OSRO) and thermal-driven processes such as pervaporation (PV) and membrane distillation (MD). These innovations enhance the selectivity for the recovery of high-value compounds from lignocellulosic streams, including lignin and hemicellulosic derivatives and organic acids. For instance, FO has demonstrated its potential in terms of biofuels concentration, achieving moderate energy consumption savings compared to thermal methods[973] [974] [975] [976] [977].

Inorganic nanofillers, including graphene oxide and metal-organic frameworks (MOFs), are being integrated into polymeric membranes. This development is aimed at enhancing permeability and antifouling properties, thereby extending the operational lifespan in harsh conditions[978] [979] [980]. At the same time, supercritical fluid extraction (SFE) is being optimised for specific applications. These include the recovery of lipids, carotenoids and phenolic compounds from sugarcane and rice husk using ethanol-modified supercritical CO_2, achieving 95% purity in pilot studies[981] [982]. Furthermore, hybrid systems combining membranes with other separation techniques such as isoelectric precipitation, adsorption, ion-exchange, or spray-drying techniques have been demonstrated to reduce concentrations of impurities and inhibitors in bio-based products and bioethanol while

[973] Wibisono, Y., et al., Microalgae in food-energy-water nexus: a review on progress of forward osmosis applications. Membranes 9(12) (2019) 166. https://doi.org/10.3390/membranes9120166

[974] Rodríguez-Galán, M., et al., Forward osmosis for sustainable industrial growth. In: Zhang, Z., Zhang, W., Chehimi, M.M. (eds) Membrane Technology Enhancement for Environmental Protection and Sustainable Industrial Growth. Advances in Science, Technology & Innovation (2021) Springer, Cham. https://doi.org/10.1007/978-3-030-41295-1_1

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[976] Galiano, F., et al., Chapter 10 – Pervaporation and membrane distillation technology in biorefinery. Membrane Engineering in the Circular Economy: Renewable Sources Valorization in Energy and Downstream Processing in Agro-Food Industry (2022) 251-280. https://doi.org/10.1016/B978-0-323-85253-1.00015-0

[977] Barrios, N., et al., Innovation in lignocellulosics dewatering and drying for energy sustainability and enhanced utilization of forestry, agriculture, and marine resources. Advances in Colloid and Interface Science 318 (2023) 102936. https://doi.org/10.1016/j.cis.2023.102936

[978] García-Ivars, J., et al., Chapter 6 – Development of mixed matrix membranes: incorporation of metal nanoparticles in polymeric membranes. In: Thomas, S., Pasquini, D., Leu,, S.Y., Gopakumar, D.A. (eds) Nanoscale Materials in Water Purification: Micro and Nano Technologies (2019) 153-178 The Netherlands, Elsevier. https://doi.org/10.1016/B978-0-12-813926-4.00011-2

[979] Wang, Z., et al., Kraft black liquor concentration with graphene oxide membranes: process simulations and technoeconomic analysis. Journal of Advanced Manufacturing and Processing 3(4) (2021) e10104. https://doi.org/10.1002/amp2.10104

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[981] Albarelli, J.Q., et al., Product diversification in the sugarcane biorefinery through algae growth and supercritical CO_2 extraction: thermal and economic analysis. Renewable Energy 129(B) (2018) 776-785. https://doi.org/10.1016/j.renene.2017.05.022

[982] Kaur, S., and Ubeyitogullari, A., Extraction of phenolic compounds from rice husk via ethanol-water-modified supercritical carbon dioxide. Heliyon 9(3) (2023) e14196. https://doi.org/10.1016/j.heliyon.2023.e14196

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doubling flux rates[983] [984] [985] [986]. These innovations align with the objectives of the European Green Deal, as evidenced by the IETS Task's expanded focus on water and resource recovery loops to achieve near-zero waste biorefineries by 2030. Nevertheless, concerns regarding scalability persist as a significant impediment, underscoring the necessity for additional validation through pilot-scale experimentation with modular membrane integrated processes (including membrane reactors) for the purpose of continuous processing, such as biodiesel and/or bio-based chemicals production.

The progress achieved in the field of downstream processing within the European bio-based industry highlights the critical focus on enhancing the economic and environmental sustainability of bioproduct recovery. A wide range of advanced separation techniques, including membrane technologies, solvent extraction and adsorption, are being investigated in ongoing research. These techniques are being adapted to suit specific biomass types and target bioproducts. This trend indicates a shift towards the creation of more specialised and optimised recovery processes. These processes are considered essential for the ongoing growth and success of the European bioeconomy.

4.5 Digital Technologies And Artificial Intelligence

Following the implementation of digital technologies and AI in biotechnology, there is considerable potential for these to transform the bio-based industry across its entire value chain[987]. AI is already playing a significant role in accelerating drug discovery and development within the broader biotech sector, offering valuable insights and reducing timelines. In biomanufacturing, AI and machine learning algorithms are being utilised to optimise production processes, predict outcomes and enhance efficiency[988]. Moreover, the establishment of digital information systems is imperative for tracking and reporting the sustainability and circularity of bio-based products, thus enabling enhanced decision-making and transparency across the value chain. The European Union is uniquely positioned to spearhead bio-based innovation, from the production of drop-in chemicals to

[983] Upscaling and Market Introduction of Simultaneous Biogas Upgrading and Bio-Succinic Acid Production | NEOSUCCESS | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[984] Pan, L., et al., Simultaneous concentration and detoxification of lignocellulosic hydrolysates by novel membrane filtration system for bioethanol production. Journal of Cleaner Production 227 (2019) 1185-1194. **https://doi.org/10.1016/j.jclepro.2019.04.239**

[985] Arnese-Feffin, E., et al., Hybrid modeling of a biorefinery separation process to monitor short-term and long-term membrane fouling. Chemical Engineering Science 283 (2024) 119413. **https://doi.org/10.1016/j.ces.2023.119413**

[986] Siddique, M.B.M., et al., Chapter 19 – Recent progress in the application of hybrid processes for industrial effluents treatment in biorefineries. In: Naushad, M., Kutty, S.R.M., Hossain, M.S., Birniwa, A.H., Jagaba, A.H. (eds) Biorefinery of Industrial Effluents for a Sustainable Circular Economy (2025) 287-296. The Netherlands, Elsevier. **https://doi.org/10.1016/B978-0-443-21801-9.00019-7**

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[988] Udugama, I.A., et al., Digital twin in biomanufacturing: challenges and opportunities towards its implementaiton. Systems Microbiology and Biomanufacturing 1 (2021) 257-274. **https://doi.org/10.1007/s43393-021-00024-0**

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the development of advanced biofuels, in accordance with the principles of a circular economy. This is facilitated by the integration of these digital tools, such as computational modelling, high-throughput screening, and modular genetic building blocks, which is pivotal for realising the full potential of the bio-based industry in Europe[989].

4.5.1 The integration of Digital Technologies for improved efficiency and sustainability

Digital technologies are playing an increasingly important role in driving efficiency and improving sustainability across the European bio-based manufacturing landscape. The convergence of life sciences with digital innovations is enabling a deeper understanding and more sustainable use of biological resources, leading to optimised and more efficient bio-based industrial operations. Digital tools, sensors and advanced methodologies are being integrated into industrial processes in the bio-based sectors to improve overall efficiency, facilitate adaptation to climate change and enhance sustainability, while considering the diverse needs of stakeholders[990] [991] [992].

European initiatives and funding programmes are playing an active role in supporting the digital transformation of the bio-based industry. For instance, Horizon Europe has initiated calls for proposals with a specific focus on promoting the digitalisation of bio-based sectors, with the overarching objective being the achievement of efficient, sustainable, and climate-neutral production processes, whilst ensuring transparent information flows. Another Horizon Europe call focuses on the development of digital information systems for bio-based products, with the aim of improving sustainability, promoting circularity and improving the information available to both industry and consumers. These digital systems are designed to track the entire journey of bio-based products, components and materials, ensure secure access to the resulting data and facilitate a more effective circular economy through improved material flow information. In addition, research will focus on the development of integrated biological designs and data models incorporating bioinformatics, biosensors, bioindicators and machine learning techniques. The aim of this research is to optimise bio-based operations and improve their economic and environmental sustainability. Furthermore, there are some examples of EU-funded projects that align closely with the objectives of promoting the digital transformation of bio-based industries. The SUSTCERT4BIOBASED project has been

[989] Lange, L., et al., Developing a sustainable and circular bio-based economy in EU: by partnering across sectors, upscaling and using new knowledge faster, and for the benefit of climate, environment & biodiversity, and people & business. Frontiers in Bioengineering and Biotechnology 8 (2021) 619066. **https://doi.org/10.3389/fbioe.2020.619066**

[990] Krüger, A., et al., Digitalization in microbiology – paving the path to sustainable circular bioeconomy. 59 (2020) 88-96. **https://doi.org/10.1016/j.nbt.2020.06.004**

[991] Barteková, E., and Börkey, P., Digitalisation for the transition to a resource efficient and circular economy. 192 (2022) OECD Publishing, Paris. **https://doi.org/10.1787/6f6d18e7-en**

[992] Tsui, T.H., et al., Machine learning and circular bioeconomy: building new resource efficiency from diverse waste streams. Bioresource Technology 369 (2023) 128445. **https://doi.org/10.1016/j.biortech.2022.128445**

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developed to deliver a comprehensive monitoring system for bio-based products across their entire value chains. The project will focus on environmental, social, economic, and governance aspects. Furthermore, the objective is to enhance transparency and sustainability in bio-based industries by providing comprehensive information flows, aligning with the goal of improving sustainability and promoting circularity through digital information systems[993]. Another relevant example is the BIOTRANSFORM project, which places significant emphasis on the utilisation of digital tools and data-driven approaches to support the development of an assessment and policy development framework. The objective of this framework is to facilitate the transition to circular bio-based systems in various European regions, in line with the goal of achieving efficient, sustainable, and climate-neutral production processes[994].

A fundamental element of this digital transformation is the emphasis on data sharing, interoperability and the establishment of the European Data Space for Smart Circular Applications. The objective is to ensure that data related to bio-based products is shared in an accessible and easily processable way, following the FAIR (Findable, Accessible, Interoperable and Reusable) principles[995]. This initiative is expected to enhance the sustainability of production and empower consumers to make more responsible and informed choices. The EU is actively committed to promoting collaboration and innovation in the sector by facilitating the participation of bio-based industries in the European Dataspace, with the aim of driving the transition to a more circular and sustainable bioeconomy. In addition, TRUST (Transparency, Responsibility, User focus, Sustainability and Technology) principles are now often used in conjunction with FAIR principles, particularly in the context of ensuring the reliability of repositories or platforms[996]. However, it should be noted that TRUST principles do not replace FAIR principles.

The strategic integration of digital technologies is recognised as a critical enabler for the European bio-based industry to achieve greater efficiency, improved sustainability and greater circularity. The emphasis on developing comprehensive digital information systems is therefore pivotal in ensuring better data management, analysis and informed decision-making throughout the bio-based value chain.

[993] Sustainability Certification for Biobased Systems | SUSTCERT4BIOBASED | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[994] Circular BIOeconomy TRANSFORMation for regions by enabling resource and governance networks | BIOTRANSFORM | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[995] Wilkinson, M.D., et al., The FAIR guiding principles for scientific data management and stewardship. Scientific Data 3 (2016) 160018. **https://doi.org/10.1038/sdata.2016.18**

[996] Lin, D., et al., The TRUST principles for digital repositories. Scientific Data 7 (2020) 144. **https://doi.org/10.1038/s41597-020-0486-7**

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4.5.2 Harnessing the potential of AI-driven biomanufacturing in Europe

The potential of AI to transform various aspects of the European bio-based industry is significant, revolutionising bioprocess design and control. The technology has the capacity to drive significant change, from accelerating drug discovery in biotechnology to optimising process control and automation in biomanufacturing and biorefineries. The ability of AI to analyse extensive data sets, predict outcomes and optimise complex processes is proving invaluable in advancing the bioeconomy.

European biotech start-ups are increasingly using AI for breakthroughs in drug discovery, diagnostics and personalised medicine, demonstrating AI's potential to significantly reduce drug discovery timelines and costs by predicting the efficacy of potential drug candidates with remarkable accuracy[997]. Furthermore, AI is being used to optimise enzyme design for converting vegetable oils into biofuels and improve the precision of gene-editing tools such as CRISPR, accelerating the identification of novel CRISPR-associated proteins and improving the accuracy of genetic modifications[998].

In the domain of biomanufacturing and biorefineries, AI is being explored for its potential to optimise process control, increase efficiency and automate complex operations. AI techniques such as machine learning and predictive modelling are being investigated for their ability to analyse large amounts of data from biorefinery processes, identify key parameters, detect production anomalies and ultimately provide autonomous control, leading to improved yields and reduced operating costs[999] [1000]. For instance, Bayesian optimisation, a machine learning framework, has been successfully used to optimise a lignin biorefinery, identifying processing conditions that maximise lignin yield and tailor its structural properties for specific applications[1001]. A further illustration of this phenomenon is constituted by the development and validation of workflows for the prediction of the performance of oil-producing fermentations at demo-scale, derived from lab experiments[1002]. The

[997]EIT Health, 6 biotech start-ups developing life-changing innovations (February 2025). Visited 03-05-25. Retrieved from: [online].

[998]Galanakis, C.M., The future of food. Foods 13(4) (2024) 506. **https://doi.org/10.3390/foods13040506**

[999]Clauser, N.M., et al., Integrating the new age of bioeconomy and industry 4.0 into biorefinery process design. BioResources 17(3) (2022) 5510-5531. **https://doi.org/10.15376/biores.17.3.Clauser**

[1000]Abdullah, M., et al., AI-driven algae biorefineries: a new era for sustainable bioeconomy. Current Pollution Reports 11 (2025) 21. **https://doi.org/10.1007/s40726-025-00352-y**

[1001]Löfgren, J., et al., Machine learning optimization of lignin properties in green biorefineries. ACS Sustainable Chemistry & Engineering 10(29) (2022) 9469-9479. **https://doi.org/10.1021/acssuschemeng.2c01895**

[1002]Muddle, R., et al., Chapter 3 – Bioreactor modeling. In: Wittmann, C., and Liao, J.C. (Eds), Industry Biotechnology: Products and Processes (2017) 81-128. **https://doi.org/10.1002/9783527807833.ch3**

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integration of AI into biorefinery process design and evaluation is regarded as a pivotal step in achieving sustainable economic growth through the efficient valorisation of biomass.

European research initiatives are working to facilitate greater accessibility to AI tools and resources for researchers in the life sciences and the broader biobased industry. The AI4LIFE project, for instance, aims to make AI technologies, including models and AI-ready datasets, freely available to researchers, including those without extensive expertise in computational sciences. The provision of user-friendly platforms and the fostering of collaboration between life scientists and AI experts are two key objectives of this initiative[1003]. The overarching ambition is to bridge the existing expertise gap and accelerate the adoption of AI-driven solutions across the European bioeconomy.

The potential of AI as a transformative tool is poised to significantly impact the European bio-based industry. Its wide-ranging applications, from accelerating innovation in biotechnology and drug discovery to optimising the efficiency and sustainability of biomanufacturing processes, highlight its potential to drive the sector towards greater competitiveness and a more sustainable future. The strategic importance of this technology in realising the full potential of the European bioeconomy is further emphasised by proactive efforts to make AI more accessible to researchers and industry stakeholders.

4.6 Technology Readiness Levels (TRLs) and Development Stages

This section provides a concise overview of the maturity and evolution of the identified emerging technologies within the European bio-based industry. This objective is accomplished by means of a synthesis of the prevailing TRLs and developmental stages, as established by extant research. Table 7 provides the corresponding development stage in of each of the emerging technologies mentioned above in Europe, together with the two approaches to biorefining (bottom-up and top-down), which will be defined in Section 5.2.

This summary indicates that a significant proportion of emerging technologies are currently at the mid-range of the TRL scale, suggesting a transition from fundamental research and concept development to validation and demonstration in relevant environments. Technologies such as bottom-up and top-down biorefineries are generally more mature, with some initiatives reaching the prototype demonstration and even qualification stage. Digital technologies and AI-driven biomanufacturing, while demonstrating considerable promise and activity, are also largely in the validation and demonstration phase within the European bio-based industry.

[1003] Artificial Intelligence for Image Data Analysis in the Life Sciences | AI4LIFE | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

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Table 7 – Maturity assessment of the analysed emerging bio-based processes.

Technology	Current TRL range in Europe	Development stage in Europe
Advanced Bioreactor innovations	3-6	Research to prototype/demo plant
Third-generation bioethanol	3-5	Research to validation in lab/relevant environment
Fourth-generation bioethanol	3-5	Research to validation in lab/relevant environment
Algae-based biofuels	5-7	Demonstrations ongoing for advanced biofuel production
Synthetic biology	3-6	Research to demonstration in relevant environment
Genomics	4-7	Validation in lab to prototype demonstration
Biohydrogen production	4-7	Validation in lab to prototype demonstration
Dark Fermentation	4-7	Validation in lab to prototype demonstration
Photo-fermentation	4-5	Pilot and demonstration stage
Bioelectrochemical systems	4-6	Pilot and demonstration stage
Process intensification	4-7	Validation in lab to prototype demonstration
Gasification*	6-8	Demonstrations ongoing for advanced biofuel production from various feedstocks.
Pyrolysis*	5-7	Pilot and demonstration plants exist for bio-oil and biochar production.
Hydrothermal liquefaction*	4-6	Research and pilot projects focused on biocrude production from wet biomass.
Nanotechnology	3-6	Research to demonstration in relevant environment
Downstream processing	4-7	Validation in lab to prototype demonstration
Membrane separation*	6-8	Increasingly used for various separation and purification steps, with ongoing advancements in membrane materials and technologies.
Digital technologies	5-7	Validation in relevant environment to operational
AI-driven biomanufacturing	4-6	Validation in lab to demonstration
Bottom-up biorefineries	6-8	Demonstration to system complete and qualified
Top-down biorefineries	5-8	Validation in relevant environment to qualification

Note: The TRL ranges presented in this table are derived from the citations used and may not fully reflect the entire range of development across all European research institutions and companies.

While these emerging technologies present significant opportunities for Europe to consolidate its position as a global leader in the bioeconomy, it will be necessary to continue to invest in research and development, establish supportive regulatory frameworks and effective mechanisms to facilitate the scale-up and commercialisation of these innovations if the full potential of these technologies is to be realised. Addressing challenges related to cost-competitiveness, scaling up, feedstock availability, and public acceptance will be crucial in harnessing the transformative power of these emerging technologies to build a truly sustainable and circular bio-based economy in Europe.

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5 TECHNOLOGY INTEGRATION FOR SUSTAINABLE BIO-BASED PROCESSES

The European Union is committed to the transition from a linear, fossil-based economy to a circular and low-carbon economic model, driven by ambitious environmental targets outlined in initiatives such as the European Green Deal. This significant economic transformation necessitates a fundamental shift towards the use of sustainable, bio-based resources across various industrial sectors[1004]. In this context, the strategic integration of diverse technological approaches is essential for maximising the efficiency, enhancing the sustainability and improving the overall economic viability of bio-based processes. This chapter conducts a comprehensive analysis of the crucial role of technology integration in fostering a sustainable European bio-based industry. It explores the synergistic relationship that can be forged between different technological pathways. It also examines the implementation of diverse biorefinery concepts designed for optimal resource utilisation. Finally, it highlights the pivotal role of technology in facilitating the widespread adoption of zero-waste approaches. In addition, the report presents several successful European case studies, with a particular focus on flagship projects. These projects serve as exemplary models of effective technology integration, which is essential for the development of a truly sustainable bio-based industrial landscape.

5.1 SYNERGIES BETWEEN DIFFERENT TECHNOLOGIAL APPROACHES

5.1.1 Circular bioeconomy approach.

The integration of technology within the bio-based sector can be defined as the deliberate and synergistic combination of distinct technological processes, often coupled with the strategic incorporation of renewable energy sources, with the aim of achieving a more sustainable and resource-efficient production of bio-based products. This integration of bioeconomy, circular economy principles and fossil-to-bio-based transitions creates resilient, closed-loop systems that maximise resource efficiency while minimising environmental impact[1005]. In this context, synergies refer to mutually reinforcing interactions between systems, technologies, and stakeholders that amplify the efficiency, sustainability, and economic viability of bio-based products. The key drivers of this process include the exchange of knowledge between different sectors. For example, the collaboration between agriculture, biorefineries and energy sectors (i.e. industrial symbiosis) results in enhanced efficiency. Another driver is the use of shared infrastructure for biomass valorisation, such as the cascading use of resources across multiple industries, which increases valorisation potential. Finally, policy alignment incentivises circular practices, such as waste-to-resource

[1004] Bio-based products and processes | Bioeconomy | European Commission

[1005] IEA Bioenergy Synergies for bioenergy supply chains in bioeconomy networks (2025) | International Energy Agency

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conversion and carbon-neutral production[1006] [1007] [1008]. The process of operationalising these synergies is achieved through the identification of seven functional drivers within innovation ecosystems. These drivers include entrepreneurial experimentation, knowledge development, network collaboration, policy-guided market formation, resource mobilisation and advocacy coalitions.

The circular economy is process-dependent, focusing on system circularity rather than the type of raw materials used. By aligning bioeconomy and circular economy principles, the "linear" and "fossil" elements of economic growth can be eliminated. A circular bioeconomy is a model of sustainable development that integrates bioeconomy expertise, biotechnological innovation, and resource circularity. The aim is to create a self-sustaining bioprocess model that enhances both environmental sustainability and economic resilience[1009]. This integrated approach is exemplified by the combination of advanced biorefining processes with green hydrogen. Green hydrogen is produced via electrolysis powered by renewable sources, such as solar and wind energy. It serves as a clean and sustainable energy carrier[1010] [1011]. When used in conjunction with biorefineries, it facilitates innovative, low-emission processes for the production of a broad spectrum of bio-based chemicals, biofuels and sustainable aviation fuel (SAF)[1012] [1013] [1014]. This approach provides a sustainable alternative to fossil-derived production, thereby reducing carbon footprints and promoting the growth of a resilient bio-based industry.

[1006] Philp, J., and Winickoff, D., Innovation ecosystems in the bioeconomy, OECD Science, Technology and Industry Policy Papers 76 (2019), OECD Publishing, Paris, **https://doi.org/10.1787/e2e3d8a1-en**

[1007] Tan, E.C.D., and Lamers, P., Circular bioeconomy concepts – a perspective, Frontiers in Sustainability 2 (2021) 701509, **https://doi.org/10.3389/frsus.2021.701509**

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[1009] Konstantinis, A., et al., A definition of bioeconomy through the bibliometric networks of the scientific literature, AgBioForum 21(2) (2018) 64-85. https://agbioforum.org/wp-content/uploads/2021/02/AgBioForum-21-2-64.pdf

[1010] Di Menno Di Bucchianico, D., et al., Sustainable design of biomass valorization processes for the production of gamma valerolactone integrating wind energy and green hydrogen, Journal of Cleaner Production 491 (2025) 144829. **https://doi.org/10.1016/j.jclepro.2025.144829**

[1011] Grira, S., et al., Sustainable green hydrogen from algae: assessing biological, thermochemical, and bioelectrochemical pathways, Biomass and Bioenergy 193 (2025) 107512. **https://doi.org/10.1016/j.biombioe.2024.107512**

[1012] De Vrieze, J., et al., The hydrogen gas bio-based economy and the production of renewable building block chemicals, food and energy, New Biotechnology 55 (2020) 12-18. **https://doi.org/10.1016/j.nbt.2019.09.004**

[1013] Harnisch, F., and Chavez Morejon, M., Hydrogen from water is more than a fuel: hydrogenations and hydrodeoxygenations for a biobased economy, The Chemical Record 21 (2021) 2277-2289. **https://doi.org/10.1002/tcr.202100034**

[1014] Brodzik, L., et al., Minimizing the environmental impact of aircraft engines with the use of sustainable aviation fuel (SAF) and hydrogen, Energies 18(3) (2025) 472. **https://doi.org/10.3390/en18030472**

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This transition to a circular bioeconomy is more than just a simple substitution of raw materials. In order to achieve sustainable production, it is necessary to strategically combine infrastructure and policy. This will involve retrofitting existing industrial processes and implementing regulatory changes. These changes will facilitate the intelligent integration of diverse technologies. A successful transition demands a meticulous, holistic lifecycle approach of bio-based products, beginning with biomass sourcing, continuing through conversion and processing, and concluding with final product development and responsible waste management. Similarly, digital tools such as blockchain support the tracking of biogenic carbon, while AI enhances the efficiency of biomass allocation across value chains. Furthermore, cross-sector integration has been shown to promote cascading resource use, industrial symbiosis and fossil-bio hybridisation. This, in turn, strengthens the economic viability of bio-based ecosystems in Europe.

Consequently, the circular bioeconomy, by embedding circularity within bioeconomic processes, emerges as a pragmatic and scalable framework that delivers enhanced resource productivity compared to traditional linear models, while supporting Europe's net-zero objectives. The European bio-based industry stands to benefit substantially from the integration of diverse technological approaches, which will drive greater efficiency, sustainability, and product diversification across value chains.

5.1.2 Biotechnological synergies in traditional biochemical conversion processes.

Biochemical conversion processes, including established technologies such as anaerobic digestion for biogas production and fermentation for bioethanol and other biochemicals, can be significantly enhanced through strategic biotechnological advancements. The employment of metabolic engineering, which involves the genetic modification of organisms to optimise specific biochemical pathways, and synthetic biology, which focuses on the design of new biological components and systems, offers a powerful means to increase yields and diversify the range of bio-based outputs from various biomass feedstocks[1015] [1016] [1017] [1018]. An excellent illustration of this collaborative effort is the metabolic engineering of microorganisms such as yeast or bacteria. Precisely modifying their genetic composition allows researchers to enhance their capacity to efficiently convert sugars derived from biomass into specific biofuels (e.g. advanced bioethanol or biobutanol) and high-value

[1015] Chen, X., et al., Metabolic engineering of Escherichia Coli: a sustainable industrial platform for bio-based chemical production, Biotechnology Advances 31 (2013) 1200-1223. https://doi.org/10.1016/j.biotechadv.2013.02.009

[1016] Kang, M.K., et al., Microbial cell factories for bio-based isoprenoid production to replace fossil resources, Current Opinion in Systems Biology 37 (2024) 100502. https://doi.org/10.1016/j.coisb.2023.100502

[1017] Iram, A., et al., Synthetic biology advances towards a bio-based society in the era of artificial intelligence, Current Opinion in Biotechnology 87 (2024) 103143. https://doi.org/10.1016/j.copbio.2024.103143

[1018] Barboza-Pérez, U.E., et al., Synthetic biology in Mexico: brief history, current landscape, and perspectives towards a bio-based economy, Engineering Biology 9(1) (2025) e12037. https://doi.org/10.1049/enb2.12037

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biochemicals that substitute for fossil-based counterparts[1019]. In this context, biotechnology is of critical importance as it provides the molecular tools to fine-tune biological processes at a fundamental level. This has resulted in significant improvements in the efficiency of conversion and the range of valuable, renewable products derived from biomass.

5.1.3 Integration between biotechnology and thermochemical conversion.

The strategic convergence of biotechnology (the use of living organisms and enzymatic systems) and thermochemical conversion technologies (the transformation of biomass through heat and chemical reactions) offers substantial potential for maximising the valorisation of complex biomass components[1020]. Lignocellulosic biomass is an abundant and readily available resource derived from agricultural and forestry residues, and it exemplifies this opportunity. Through the implementation of advanced biotechnological pretreatment methods, including biological and enzymatic processes, the inherently recalcitrant structure of lignocellulose can be effectively broken down, thereby enhancing its accessibility and rendering it more amenable to subsequent thermochemical conversion. This integrated approach facilitates the efficient production of advanced biofuels, such as bioethanol and biodiesel, as well as a wide spectrum of bio-based chemicals. These chemicals can be produced in a cost-effective manner, thus serving as essential building blocks for industrial applications[1021].

The strategic synergy between these two distinct technological domains enables a more complete and resource-efficient utilisation of biomass. Biotechnology is highly effective at selectively deconstructing complex biological structures under mild conditions, while thermochemical methods, operating at elevated temperatures and pressures, are particularly effective in processing residual fractions of biomass, such as lignin, which are less tractable through biological means. This dual-mode strategy leads to a holistic, less wasteful conversion process, enhancing both energy and carbon efficiency. The following illustrative examples may be considered: the integration of microwave thermochemical pretreatment prior to anaerobic digestion; the combination of enzymatic

[1019]Zhu, X., et al., Is biorefinery establishment enhancing the EU labour market on a regional level?, Regional Studies 58(8) (2024) 1603-1617. **https://doi.org/10.1080/00343404.2023.2292251**

[1020]Marzban, N., et al., Smart integrated biorefineries in bioeconomy: a concept toward zero-waste, emission reduction, and self-sufficient energy production. Biofuel Research Journal 12(1) (2025) 2319-2349. **https://doi.org/10.18331/BRJ2025.12.1.4**

[1021]German Federal Government - Biorefineries Roadmap as part of the German Federal Government action plans for the material and energetic utilisation of renewable raw materials. Retrieved from [online].

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hydrolysis with pyrolysis or gasification; and the coupling of sugar fermentation with lignin valorisation[1022] [1023] [1024].

The integration of these processes is of pivotal importance in enhancing the overall conversion efficiency of lignocellulosic biomass into high-value products, thereby propelling the development of sustainable biorefineries. This, in turn, contributes to the realisation of a circular bioeconomy, reinforcing environmental sustainability while maintaining economic viability.

5.1.4 Integration between biotechnology and nanotechnology.

The integration of biotechnology with nanotechnology, which involves the manipulation of matter at the atomic and molecular level, presents a plethora of possibilities for enhancing various stages of bio-based processes. Nanotechnology provides a versatile toolkit of materials and techniques that can be strategically incorporated into crucial steps such as enzyme immobilisation, catalysis, and product separation[1025]. The use of nanomaterials in these areas has the potential to markedly improve the overall efficiency of bio-based production whilst also reducing associated costs. An example of this synergy is the use of nanoparticles to carry immobilised enzymes for the production of biodiesel or bioethanol. The attachment of enzymes to the surface of nanoparticles can significantly enhance stability and reusability[1026] [1027]. This enhancement in enzyme performance can be translated into a reduction in the amount of enzyme required for the conversion process, as well as facilitating easier separation and recycling of the biocatalyst. Furthermore, the use of functionalised nanoparticles in the immobilisation of enzymes has been shown to enhance the efficiency of the saccharification and fermentation stages in the production of biofuels[1028]. This, in

[1022]Yu, I.K.M., et al., Chemicals from lignocellulosic biomass: a critical comparison between biochemical, microwave and thermochemical conversion methods, Critical Reviews in Environmental Science and Technology 51(14) (2021) 1479-1532. https://doi.org/10.1080/10643389.2020.1753632

[1023]Awasthi, M.K., et al., A comprehensive review on thermochemical, and biochemical conversion methods of lignocellulosic biomass into valuable end product, Fuel 342 (2023) 127790. https://doi.org/10.1016/j.fuel.2023.127790

[1024]Zhao, C., et al., Editorial: From biomass to bio-energy and bio-chemicals: pretreatment, thermochemical conversion, biochemical conversion and its bio-based applications, Frontiers in Bioengineering and Biotechnology 10 (2022) 975171. https://doi.org/10.3389/fbioe.2022.975171

[1025]Chintada, V., et al., The development in nanotechnology and tailor-made enzymes as the future of biobased economy. In: Agrawal, K., Verma, P. (eds) Biotechnological Advances in Biorefinery. Interdisciplinary Biotechnological Advances. Springer, Singapore. https://doi.org/10.1007/978-981-97-5544-8_13

[1026]Khan, N.R., and Bin Rashid, A., Carbon-based nanomaterials: a paradigm shift in biofuel synthesis and processing for a sustainable energy future, Energy Conversion and Management: X 22 (2024) 100590. https://doi.org/10.1016/j.ecmx.2024.100590

[1027]Atiroglu, V., et al., Green immobilization: enhancing enzyme stability and reusability on eco-friendly support, Food Chemistry 448 (2024) 138978. https://doi.org/10.1016/j.foodchem.2024.138978

[1028]Ingle, A.P., et al., Production of biomaterials and biochemicals from lignocellulosic biomass through sustainable approaches: current scenario and future perspectives, Biotechnology for Sustainable Materials 2 (2025) 3. https://doi.org/10.1186/s44316-025-00025-2

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turn, can lead to a significant decrease in the operational costs associated with large-scale biofuel production plants. The approach's effectiveness is further demonstrated by using magnetic nanoparticles as carriers. These offer the advantages of easy separation and reusability of biocatalysts and improve the viability of continuous bio-based production processes [1029]. Nanotechnology provides innovative solutions that overcome the inherent limitations often encountered in traditional bio-based processes. The distinctive physical and chemical characteristics of nanoscale materials, including their high surface area to volume ratio and enhanced reactivity, can lead to significant enhancements in the efficiency, selectivity and overall sustainability of various bioconversion steps.

The strategic integration of nanotechnology can also significantly enhance the efficiency of thermochemical conversion processes. Nanomaterials have been shown to function as highly effective catalysts in thermochemical conversion pathways, such as pyrolysis and gasification. The tailored properties of these nanomaterials can result in improved reaction rates, enhanced selectivity towards desired products, and potentially lower operating temperatures. This, in turn, can contribute to an overall increase in process efficiency and a reduction in energy consumption. Specifically engineered nanocatalysts can be used to enhance the production of targeted hydrocarbons during the pyrolysis process of biomass. These hydrocarbons are key components of advanced biofuels[1030]. These catalysts have been shown to promote specific reaction pathways, thereby enabling greater control over the final product composition. This, in turn, has the potential to improve the quality and yield of the desired biofuel components[1031] [1032]. In summary, nanotechnology is an effective means of optimising thermochemical conversion pathways. By providing catalysts with precisely tailored properties and significantly increased surface area compared to conventional catalysts, nanomaterials can facilitate a more efficient and selective conversion of diverse biomass feedstocks into valuable energy carriers and chemical intermediates.

5.1.5 Integration between biotechnology and digital technologies.

Beyond these specific combinations, the broader integration of digital technologies is emerging as a transformative force across the entire spectrum of bio-based processes. Digital tools, including AI and sophisticated machine learning algorithms, offer powerful capabilities for process optimisation,

[1029]Gama Cavalcante, A.L., et al., Advancements in enzyme immobilization on magnetic nanomaterials: toward sustainable industrial applications, RSC Advances 14 (2024) 17946. https://doi.org/10.1039/d4ra02939a

[1030]Shafizadeh, A., et al., A critical review of the use of nanomaterials in the biomass pyrolysis process, Journal of Cleaner Production 400 (2023) 136705. https://doi.org/10.1016/j.jclepro.2023.136705

[1031]Shahbeik, H., et al., Using nanocatalysts to upgrade pyrolysis bio-oil: a critical review, Journal of Cleaner Production 413 (2023) 137473. https://doi.org/10.1016/j.jclepro.2023.137473

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advanced process control, and in-depth data analysis. As outlined in the preceding section, the strategic implementation of these technologies has the potential to significantly enhance the efficiency, sustainability and economic viability of the bio-based industry[1033] [1034]. To illustrate this point, consider the employment of AI algorithms to analyse vast and complex genomic datasets. Such algorithms can be used to identify enzymes that are more efficient and robust for bioconversion processes[1035]. In a similar manner, machine learning models can be used to optimise the intricate operating parameters of biorefineries. This includes temperature, pressure and residence time. The aim is to achieve maximum product yield while minimising energy consumption and waste generation[1036]. The strategic integration of digital technologies is a key enabler for the entire bio-based industry. By providing sophisticated tools for modelling, simulation, optimisation, and real-time control, these technologies can unlock significant improvements in the efficiency, sustainability, and economic performance of all technological approaches within the sector. Nevertheless, this provides the foundation for a more competitive and environmentally responsible bio-based economy in Europe.

5.2 Biorefinery Concepts And Zero-Waste Approaches

Biorefineries are becoming an integral part of sustainable industrial systems, with the objective of achieving zero-waste production and supporting circular economy models. These facilities transform biomass and residual waste into high-value products[1037] [1038]. Biorefineries mirror the structure of traditional petroleum refineries, using a fractionation approach that prioritises renewable feedstocks and closed-loop systems. As illustrated in Figure 13, there is a wide variety of bioproducts with multiple properties and diverse nature that can be obtained from well-designed, operative biorefineries.

[1033]Pomeroy, B., et al., Artificial neural networks for bio-based chemical production or biorefining: a review, Renewable and Sustainable Energy Reviews 153 (2022) 111748. https://doi.org/10.1016/j.rser.2021.111748

[1034]Gebremariam, E.C., et al., Development of bio-based adhesive using tannery shaving dust: process optimization using statistical and artificial intelligence techniques, Bioresource Technology Reports 22 (2023) 101413. https://doi.org/10.1016/j.biteb.2023.101413

[1035]Singh, S., et al., Revolutionizing enzyme engineering through artificial intelligence and machine learning, Emerging Topics in Life Sciences 5(1) (2021) 113-125. https://doi.org/10.1042/ETLS20200257

[1036]Velidandi, A., et al., State-of-the-art and future directions of machine learning for biomass characterization and for sustainable biorefinery, Journal of Energy Chemistry 81 (2023) 42-63. https://doi.org/10.1016/j.jechem.2023.02.020

[1037]Maity, S.K., Opportunities, recent trends and challenges of integrated biorefinery: part I, Renewable and Sustainable Energy Reviews 43 (2015) 1427-1445. https://doi.org/10.1016/j.rser.2014.11.092

[1038]Wagh, M.S., et al., Valorisation of agro-industrial wastes: circular bioeconomy and biorefinery process – a sustainable symphony, Process Safety and Environmental Protection 183 (2024) 708-725. https://doi.org/10.1016/j.psep.2024.01.055

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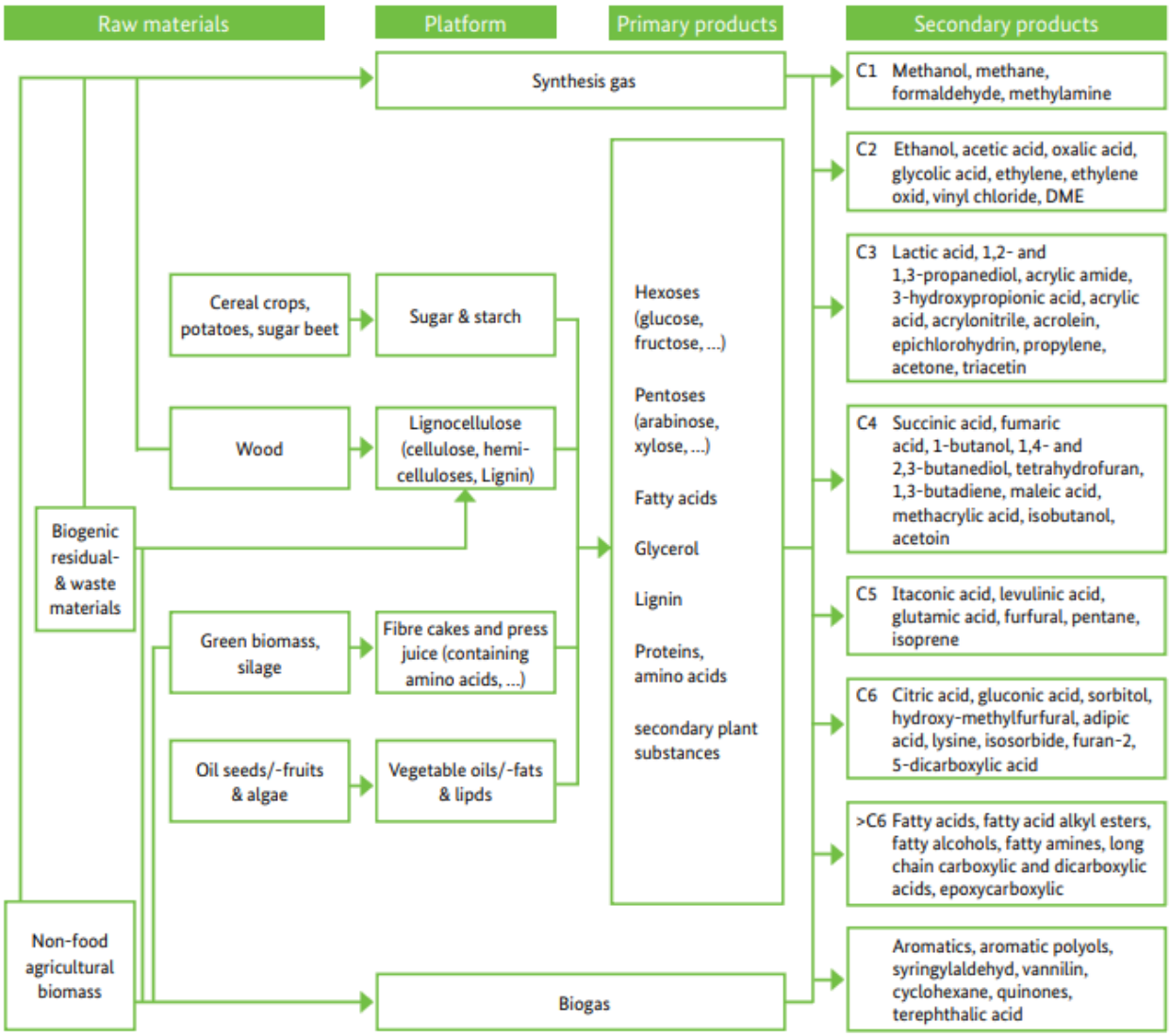


Figure 13 – Example of products obtained in biorefineries. Adapted from: Biorefineries Roadmap as part of the German Federal Government action plans for the material and energetic utilisation of renewable raw materials[1039].

Integrated biorefineries adopt a holistic strategy for biomass utilisation, seeking to extract the maximum possible value from bio-based feedstocks through a diversified output portfolio of bio-based products, including biofuels, biochemicals, biomaterials, and bioenergy. This is achieved

[1039]German Federal Government - Biorefineries Roadmap as part of the German Federal Government action plans for the material and energetic utilisation of renewable raw materials. Retrieved from [online].

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through a carefully designed series of linked conversion processes[1040]. A key principle is the cascading use of biomass, where residues or by-products from one process serve as valuable inputs for another, thereby maximising resource efficiency and minimising waste.

Current biorefining approaches can be characterised by two main strategies: the bottom-up approach and the top-down approach. The first approach involves the extension or upgrade of the existing biomass processing factories, which have reached commercial scale. Meanwhile, the second approach is centred on the establishment of new, highly integrated industrial value chains[1041]. Further details on each of these approaches can be found below.

The "bottom-up" approach to biorefinery integration in Europe focuses on the strategic expansion and diversification of existing biomass-processing facilities by incorporating advanced biorefining capabilities. These mature, fully commercialised systems (TRL 9) rely on proven technologies such as fermentation and transesterification to expand their product portfolios while minimising investment risk through "brownfield" implementation (such as retrofitting existing operations). This method allows well-established industries, such as sugar mills, pulp and paper mills, and conventional oil refineries, to leverage their existing infrastructure, expertise and supply chains to produce a wider range of bio-based outputs, while enhancing their sustainability profiles[1042]. A notable example is the sugar and starch biorefineries operating in Germany (such as the integrated sites in Zeitz of the Südzucker Group). These facilities use locally sourced cereal crops or sugar beets not only for traditional sugar production, but also for the generation of bioethanol and a variety of other valuable co-products, such as animal feed and specialty chemicals[1043] [1044]. This integrated use of feedstocks significantly improves resource efficiency and boosts profitability by maximising value extraction from a single biomass source. As with other areas of the bioeconomy, there are a variety of examples of biorefineries in Europe. These include, but are not limited to, vegetable oil and algal lipid

[1040]Klein, B.C., et al., A systematic multicriteria-based approach to support product portfolio selection in microalgae, Chemical Engineering Journal 481 (2024) 148462. https://doi.org/10.1016/j.cej.2023.148462

[1041]Scholten, P.B.V., and Figueiredo, M.B., Back to the future with biorefineries: bottom-up and top-down approaches toward polymers and monomers, Macromolecular Chemistry and Physics 223(13) (2022) 2200017. https://doi.org/10.1002/macp.202200017

[1042]Kamm, B., Integrated biorefineries-a bottom-up approach to biomass fractionation. In: Mascia, P., Scheffran, J., Widholm, J. (eds) Plant Biotechnology for Sustainable Production of Energy and Co-products. Biotechnology in Agriculture and Forestry 66 (2010) Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-13440-1_12

[1043]Kunz, S., et al., Biorefinery Zeitz of the Südzucker Group – status quo and future perspectives, Chemie Ingenieur Technik 92(11) (2020) 1752-1763. https://doi.org/10.1002/cite.202000061

[1044]Alexandri, M., et al., Chapter 22: Biorefineries in Germany, In: Bhaskar, T., Pandey, A., Rene, E.R., Tsang, D.C.W. (eds) Waste Refinery (2020) 601-629. https://doi.org/10.1016/B978-0-12-818228-4.00022-8

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biorefineries, lignocellulosic (including co-production of lignin derivatives) biorefineries, green biorefineries, synthetic gas biorefineries and biogas refineries[1045].

Implementing biorefinery concepts through this bottom-up strategy is seen as a pragmatic and cost-effective pathway for scaling the European bioeconomy. This approach is a cost-effective strategy that accelerates the transition towards a more sustainable and diversified bio-based economy. It achieves this by repurposing and upgrading existing industrial assets, thereby reducing capital expenditure.

The "top-down" approach to biorefinery integration in Europe represents a departure from the more common "bottom-up" strategy. The top-down approach involves the conceptualisation, design, and construction of entirely new, highly integrated biorefinery systems. These advanced systems are specifically engineered from the outset for the comprehensive and efficient utilisation of various biomass fractions. The focus on industrial symbiosis and cross-sector collaboration is key to achieving the objective of broader systemic impact. The ultimate goal is to achieve near-zero-waste operation and to produce a diverse range of high-value products[1046] [1047]. However, the main challenges are the high capital costs for novel, integrated systems and the complexity of process optimisation required for zero-waste workflows. The EUROBIOREF project is a notable European case study that exemplifies this top-down approach. This ambitious research and development initiative aimed to develop a novel multilevel integrated biorefinery concept capable of processing multiple non-edible biomass feedstocks, such as lignocellulosic crops and oilseed plants, through a strategic combination of chemical, biochemical, and thermochemical processes. The project's primary objective was to produce a diverse range of high-value products, including advanced bio-aviation fuels that meet stringent performance requirements and various bio-based chemicals that can serve as sustainable alternatives in numerous industrial applications[1048]. The CHEERS and MIXMATTERS projects are also prime examples of top-down biorefinery approaches that emphasise scalability and integration, and the valorisation of existing waste streams, rather than designing systems around specific feedstocks. The objective of the CHEERS project aims to develop a modular biorefinery system that has the capacity to convert underused existing by-products and waste side-streams (bagasse, wastewater, CO_2, and CH_4) from beer production into high-value bioproducts. The objective is to be achieved by using microbial and insect platforms in processing demonstration

[1045] Parisi, C., Biorefineries distribution in the EU, Publications Office, 2018, **https://data.europa.eu/doi/10.2760/126478**

[1046] Kumar, S. et al., Valorizing cellulosic biomass waste into valuable nano-biosorbents. In: Gupta, A., Kumar, R., Kumar, V. (eds) Integrated Waste Management (2024) Springer, Singapore. **https://doi.org/10.1007/978-981-97-0823-9_12**

[1047] Reshmy, R., et al., Lignocellulose in future biorefineries: strategies for cost-effective production of biomaterials and bioenergy. Bioresource Technology 344(B) (2022) 126241. **https://doi.org/10.1016/j.biortech.2021.126241**

[1048] EUROpean multilevel integrated BIOREFinery design for sustainable biomass processing | EUROBIOREF | Project | News & Multimedia | FP7 | CORDIS | European Commission

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units. The aim is to transform these streams into disinfectants, insect and single cell proteins, ectoine and caproic acid[1049]. Concurrently, the MIXMATTERS project aims to separate and valorise pre-existing mixed agri-food biowaste (with impurities such as plastics) from wholesale markets, greenhouses, and food industries into six high-value outputs (such as sugar concentrates, bioactive compounds or plastic monomers) through the application of mobile separation units and AI-driven decision tools[1050]. The top-down approach to biorefinery integration offers the potential for greater flexibility in the types of feedstocks that can be processed and a wider scope for product diversification. By designing systems from the ground up with sustainability, resource efficiency and circularity as core principles, this strategy will lead to the development of highly optimised and resilient biorefineries. These will be well-equipped to adapt to evolving market demands and increasingly stringent environmental considerations in Europe.

Consequently, despite the fact that the top-down approach is a traditional approach at the microbial level, it is regarded as emerging technology at the biorefinery infrastructure level due to its lower TRLs, reliance on novel integrations (e.g., AI and pyrolysis combination[1051] or lignocellulose-to-aviation fuels[1052] [1053]), and alignment with circular economy goals through zero-waste designs and carbon-negative processes. Most top-down biorefineries (e.g., lignocellulosic biomass conversion producing C5/C6 sugars and lignin, CO_2 to chemical platforms, and algae-based systems) remain in pilot/demonstration scales (TRL 6-7) and are still scaling up, while the bottom-up approach represents established, mature dominant technologies. In a similar manner, despite the higher initial costs, EU initiatives and investment trends give precedence to top-down approaches to decarbonisation. This is evidenced by the fact that 75% of recent R&D funding targets top-down biorefineries, with a particular emphasis on lignocellulosic and algae-based platforms[1054].

[1049] Producing novel non-plant biomass feedstocks and bio-based products through upcycling and the cascading use of brewery side-streams | CHEERS | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

[1050] Smart and flexible Separation and Valorisation of mixed bio-waste from along the agri-food value chain. | MixMatters | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

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5.3 CASE STUDIES OF SUCCESSFUL INTEGRATION

The European bio-based industry is characterised by a multitude of innovative projects and initiatives that exemplify the potential of sustainable biomass utilisation and its applications in both technological and end-product domains. The examination of these case studies provides valuable insights into successful strategies and technological advances. The subsequent section will focus on the presentation of case studies of successful integration of technology initiatives within the European bio-based industry. Firstly, two examples of active biorefineries in 2024 are presented, accompanied by a table that summarises other notable mentions, which have a substantial presence in the European bioeconomy. Further examples are then presented to inspire readers and researchers to access this result. These include flagship projects.

The Fabiola™ technology, developed by The Netherland's Organisation of Applied Scientific Research (TNO) and displayed in Figure 14, is a next-generation biorefinery process that converts biomass waste (e.g., agricultural residues) into green building blocks such as lignin, cellulose, and sugars. The technology has been demonstrated to extract over 75% of the lignin present in the biomass and to process up to 1 million kilos of biomass on an annual basis. These materials are replacing fossil-based inputs in construction, textiles, material composites, consumer electronics, and bioplastics. This transition is driven by the development of proprietary technology in projects such as HEREWEAR, BIONTIER, and HYPELIGNUM[1055] [1056] [1057].

[1055] TNO's next generation biorefinery accelerates material transition | TNO innovation for life

[1056] Bio-based local sustainable circular wear | HEREWEAR | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[1057] Exploring wooden materials in hybrid printed electronics: a holistic approach towards functional electronics with net zero carbon emissions | HyPELignum | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

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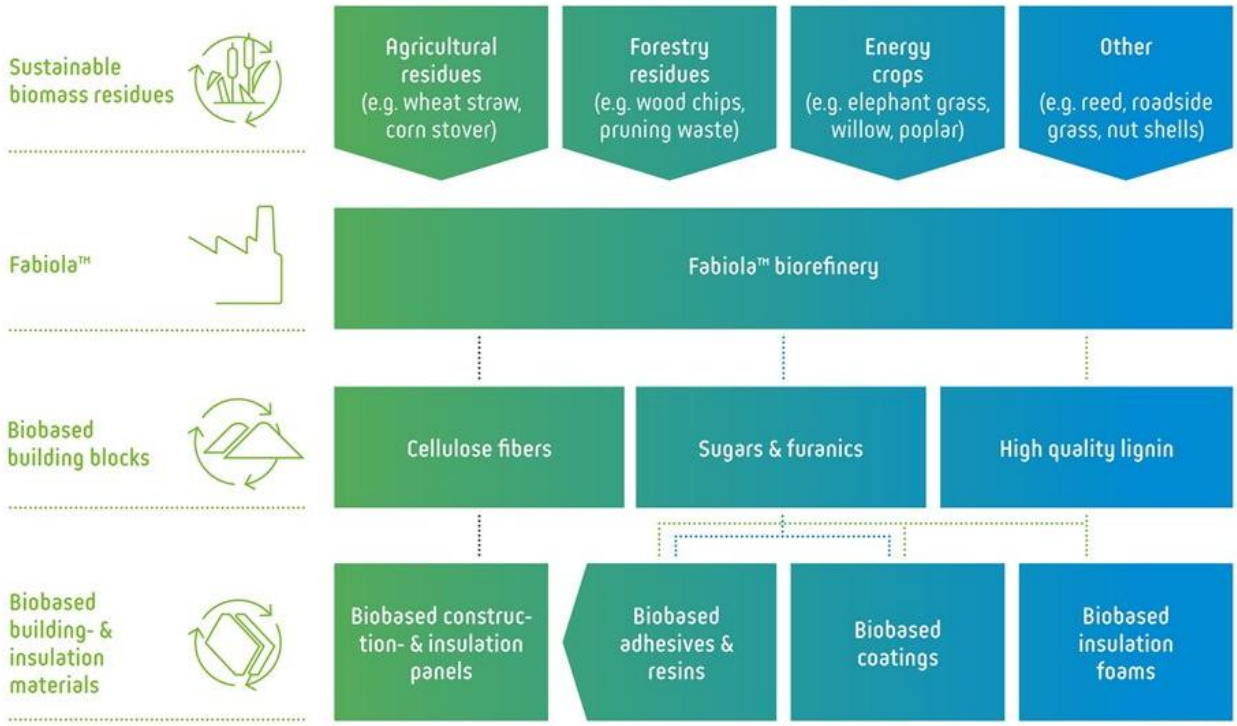


Figure 14 – Schematic diagram of Fabiola™ biorefinery from TNO website[1058].

The Perseo Biotechnology platform, developed in Spain, is a full-scale biorefinery solution designed to convert agricultural and forestry residues into high-value bio-based products. Perseo's process utilises proprietary, integrated technology to produce advanced biofuels, biochemicals and biomaterials through a zero-waste strategy that maximises the valorisation of lignocellulosic biomass. The technology has been deployed at an industrial scale and is supported by both public and private funding sources. The outputs of this process are replacing fossil-derived alternatives in various sectors, including energy, chemicals, packaging, and materials innovation, through collaborations and pilot projects across Europe. The EU projects that are currently underway include URBIOFIN, WaysTUP! and PERCAL[1059] [1060] [1061].

[1058] Fabiola - TNO Tech Transfer | TNO Ventures

[1059] Demonstration of an integrated innovative biorefinery for the transformation of Municipal Solid Wate (MSW) into new biobased products | URBIOFIN | Circular Bio-based Europe Joint Undertaking (CBE JU)

[1060] Value chains for disruptive transformation of urban biowaste into biobased products in the city context | WaysTUP! | Project | Fact sheet | H2020 | CORDIS | European Commission

[1061] Chemical building blocks from versatile MSW biorefinery | PERCAL | Project | Fact sheet | H2020 | CORDIS | European Commission

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More examples of active biorefineries can be found in Table 8.

Table 8 – Active advanced biorefinery facilities, indicating feedstocks used, zero-waste strategies and key products.

Name	Country	Feedstock(s)	Integrated Technologies	Zero-Waste Strategies	Key Products
Fabiola Technology	Netherlands	Agricultural and Forestry residues, Energy crops, others	Proprietary disruptive technology for biorefining	Unspecified	Cellulose fibres, sugars, furanics, high-quality lignin
Perseo Biotechnology	Spain	Agricultural and Forestry residues; Municipal Solid Waste	Proprietary disruptive technology for biorefining	High valorisation of lignocellulosic biomass	Advanced biofuels, biochemicals, biomaterials
Neste Porvoo	FInland	Vegetables oils, animal fats, used cooking oils	Hydrotreatment	Uses waste and residues to produce renewable products	Renewable diesel, jet fuel, and propane
La Mède	France	Vegetable oils, animal fats, used cooking oils	Hydrotreatment	Dedicated to the production of renewable diesel	Renewable diesel
Kajaani Biorefinery	Finland	Wood biomass (sawdust)	Integration of biochemical and thermochemical processes	High utilization of wood components	Lignin products, biogas, ethanol, bio-oil, wood-based sugars, animal feed
Äänekoski Biorefinery	Finland	Wood biomass	Integration of biochemical and thermochemical processes	High utilization of wood components	Cellulose, turpentine, biogas, sulphuric acid, lignin products, tall oil, wood fuel
Borregaard Biorefinery	Norway	Wood biomass	Sulphite pulping and advanced bioprocessing	High utilization of wood components	Specialty cellulose, lignin, vanillin, bioethanol
BioMCN	Netherlands	Glycerine	Transesterification	Production of biodiesel with glycerine as a co-product	Biodiesel
Enerkem	Netherlands	Non-recyclable waste materials	Thermochemical gasification	Conversion of waste into advanced biofuel	Biomethanol via syngas production
Fibenol	Estonia	Wood chips	Steam explosion pretreatment, enzymatic hydrolysis, fermentation	High utilization of wood components	Wood sugars (C5 and C6), lignin
Örnsköldsvik Biorefinery	Sweden	Wood biomass	Black liquor gasification	Production of renewable transportation fuels	Cellulose, lignin, bioethanol, biogas
Sarpsborg Biorefinery	Norway	Forest residues, Wood waste	Gasification	Advanced biofuel and biochar production	Cellulose, lignin, biochar, biopolymers, bioethanol, biomethanol, vanillin, biogas

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Integrated biorefinery concepts are being developed and implemented across Europe, demonstrating different approaches to maximise biomass valorisation. In this regard, key initiatives supported by programmes such as CBE JU demonstrate the transformative potential of bio-based solutions. For instance, the AFTERBIOCHEM project in France is establishing an integrated biorefinery to convert sugar industry by-products into valuable bio-based molecules[1062].

Concurrently, in Spain and Italy, the CIRCULAR BIOCARBON project is engineering biorefineries to transform municipal solid waste and sewage sludge into high-value products. The project is scheduled to run from 2021 to 2026 and employs a top-down integration strategy. Specifically designed to valorise urban biowaste streams, the project includes the organic fraction of municipal solid waste and sewage sludge. The project employs a range of integrated technologies, including anaerobic digestion and a series of separation and purification technologies, to convert waste streams into valuable end products. These include biopolymers, biofertilisers, green graphene and specialty chemicals. The project's objective is to achieve complete valorisation of the input waste[1063].

Moreover, the SWEETWOODS project in Estonia has established an industrial plant to produce high-purity lignin and wood-derived sugars from hardwood biomass. This flagship initiative, which was developed from 2018 to 2024, showcased a bottom-up integration by focusing on the efficient fractionation of hardwood biomass. The project utilised a pioneering pre-treatment technology (Sunburst^{TM}) in conjunction with enzymatic hydrolysis, a process that enabled the sustainable separation of the wood biomass into high-purity lignin and cellulosic sugars. These components were then used to produce a variety of high-value biomaterials for applications in construction, packaging, and other industrial sectors. The objective of the project was to achieve close to 100% utilisation of wood biomass, thereby minimising waste and incorporating a highly efficient water treatment system for recycling[1064].

Additionally, the PROTEUS project in Norway (2024-2028) is an exemplar of a top-down approach focused on the comprehensive utilisation of brown seaweed biomass. By a combination of integrating harvesting and advanced biorefining and sequential extraction processes, the project extracts alginates, subsequently processing the residual seaweed components into other high-value ingredients for various markets, including food, feed, personal care products, and industrial applications. The objective of the project is to attain complete biomass utilisation without the employment of harmful chemicals, thereby underscoring the principles of sustainable harvesting and

[1062] Anaerobic FermenTation & EsteRification of BIOmass for producing fine CHEmicals | AFTERBIOCHEM | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[1063] Turning carbon of complex organic urban waste streams into value-added products | CIRCULAR BIOCARBON | Project | Fact sheet | H2020 | CORDIS | European Commission

[1064] Production and deploying of high purity lignin and affordable platform chemicals through wood-based sugars | SWEETWOODS | Project | Fact sheet | H2020 | CORDIS | European Commission

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effective resource management[1065]. These examples illustrate the variety of feedstocks and technologies being used in integrated biorefineries across the EU[1066].

The integration of technology within the existing pulp and paper industry represents a significant opportunity for diversification and value creation. The pulp and paper industry is facing challenges from digitalisation and global competition. It can integrate biorefining technologies to produce a wider range of bio-based products, including biofuels and biochemicals, from its existing biomass resources. Projects exploring gasification and other advanced conversion technologies illustrate the potential for pulp and paper mills to become key players in the bioeconomy.

The PEFerence project (2017–2025) is a prime example of this, through its pioneering biorefinery in the Netherlands, which scales production of FDCA, a bio-derived chemical critical for synthesising polyethylene furanoate (PEF). This polymer has been shown to exceed conventional polyethylene terephthalate (PET) in terms of barrier performance and recyclability, thus positioning it as a sustainable alternative for packaging applications. The project integrates biotechnological processes (enzyme-driven sugar conversion) with chemical methods (dehydration, oxidation, polymerisation) to transform agri-food feedstocks into FDCA. A fundamental objective of the project is to operate in a manner that generates negligible waste, a goal that is pursued by leveraging regional agricultural inputs and repurposing by-products such as humins, water-insoluble carbon macromolecules that possess soil-enhancement properties[1067]. By integrating technological innovation with the principles of a circular economy, PEFerence is enabling the advancement of scalable bio-based material production while concurrently minimising the environmental footprint.

Other examples are the FARMŸNG project, which is located in France and focuses on the production of sustainable plant-based proteins for animal feed using vertical worm farms[1068], and the FIRST2RUN project in Italy, which is an example of a successful collaboration between local farmers and researchers, with the aim of growing cardoons to produce bioplastics and biolubricants[1069]. These projects exemplify the commercial viability and environmental benefits of diverse bio-based technologies.

[1065] kelP side stReam valOrisaTion to dEvelop new biobased valUe chainS | PROTEUS | Project | Fact sheet | HORIZON | CORDIS | European Commission

[1066] Biorefinery map | Circular Bio-based Europe Joint Undertaking (CBE JU)

[1067] From bio-based feedstocks via di-acids to multiple advanced bio-based materials with a preference for polyethylene furanoate | PEFerence | Project | Fact sheet | H2020 | CORDIS | European Commission

[1068] FlAgship demonstration of industrial scale production of nutrient Resources from Mealworms to develop a bioeconomY New Generation | FARMYNG | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

[1069] Flagship demonstration of an integrated biorefinery for dry crops sustainable exploitation towards biobased materials production | FIRST2RUN | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

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The European bio-based industry is continuously exploring emerging technologies and their applications. Research into fourth-generation biofuels, using genetic engineering to improve biofuel production from organisms such as algae, shows great promise for sustainable fuel production. The field of synthetic biology is expanding to encompass applications beyond chemical production, including biosensors, modified agricultural organisms and bioremediation. Research and development is ongoing into the potential of algae-based bioethanol and other advanced biofuels derived from non-food feedstocks. Finally, a summary table is presented, which includes a list of the flagship projects and their main characteristics.

Table 9 – Summary of the main features of the flagship projects listed.

Project Name (Funding source(s))	Country	Feedstock(s)	Biorefinery Concept	Zero-Waste Strategies	Key Products
AFTERBIOCHEM (CBE JU)	France	Non-food biomass (sugar beet byproducts: pulp, molasses)	Bottom-up	Mineral fertiliser side-stream, acetic acid esterification to ethyl acetate	Organic acids (caproic, propionic, lactic, succinic), vinyl acetate monomer (VAM), cellulose acetate
CIRCULAR BIOCARBON (Horizon 2020, BBI JU)	Spain & Italy	Organic fraction of municipal solid waste, Sewage sludge	Top-Down	100% valorisation of waste streams	Biopolymers (PHA), Minerals (struvite), Biofertilisers, Green graphene
SWEETWOODS (CBE JU)	Estonia	Hardwood biomass	Bottom-Up	Near 100% biomass utilisation, lignin and sugars to high-value materials, water recycling	Lignin (LIGNOVA™), Cellulosic sugars (glucose, fructose, xylose, glucosone)
PROTEUS (CBE JU)	Norway	Brown seaweed (*Laminaria hyperborea*)	Top-Down	100% biomass utilisation, no harmful chemicals	Alginates, Fucoidan, Cellulose, Seaweed extracts, Kelp fibres, Kelp powders
PEFerence (CBE JU)	Netherlands	Sugar-based feedstocks	Bottom-Up	100% bio-based, recyclable PEF, lightweighting, humins valorisation	FDCA, PEF, PBF, Polyurethanes
FARMŸNG (Horizon 2020, BBI JU)	France	Mealworms (insect biomass) fed with vegetal byproducts	Top-down	Full insect utilisation	Protein meal, insect oil, organic fertiliser
FIRST2RUN (Horizon 2020, BBI JU)	Italy	Cardoon (arid/marginal land crop)	Bottom-up	Cascading use of cardoon	Biolubricants, bioplastics, cosmetics, additives

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6 TECHNOLOGICAL BARRIERS AND CHALLENGES

The bio-based industry in Europe is a vital sector in the continent's efforts to achieve a sustainable, circular, and low-carbon economy. The industry is committed to the principles of the Circular Economy Action Plan and the Bioeconomy Strategy. It employs renewable biological resources to produce a diverse range of products and services, from chemicals and materials to fuels and energy[1070] [1071]. These initiatives highlight the strategic importance of the bioeconomy in modernising and strengthening Europe's industrial base, fostering new value chains, and offering environmentally sound alternatives to traditional, fossil-intensive processes. The overarching goals are to reduce reliance on finite resources, mitigate climate change, and enhance resource efficiency across various sectors[1072].

The technological landscape of the European bio-based industry presents a series of interconnected challenges that span the entire value chain, from the initial sourcing and pre-treatment of feedstock to the final stages of product development and waste management. The consequences of these challenges are twofold: they hinder the sector's capacity to achieve its full potential in terms of sustainability and economic growth. A key challenge relates to the ongoing cost difference between bio-based products and their fossil-based equivalents. The cost-competitiveness issue is influenced by a number of factors, including feedstock costs (especially lignocellulosic biomass due to logistics, seasonality and pretreatment needs), the maturity of the technologies employed (lower TRLs result in less efficient scale-up and higher CAPEX/OPEX) and the level of market support for bio-based products (uneven across the European Union, limiting economies of scale)[1073]. High production costs (including the use of expensive enzymes or catalysts, high energy and water inputs, a lack of fully integrated biorefinery infrastructures, and limited availability of platform technologies and skilled labour for scale-up) further exacerbate this challenge, hindering the widespread adoption of bio-based materials and chemicals[1074].

[1070] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: a new Circular Economy Action Plan for a cleaner and more competitive Europe (COM/2020/98).

[1071] European Commission: Directorate-General for Research and Innovation, *A sustainable bioeconomy for Europe – Strengthening the connection between economy, society and the environment – Updated bioeconomy strategy*, Publications Office, 2018, **https://data.europa.eu/doi/10.2777/792130**

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A further significant obstacle to the translation of promising technologies from the laboratory to the commercial sphere is described by the so-called 'valley of death'. This term refers to the critical gap between promising lab-scale research and successful commercial implementation[1075] [1076]. It has not to be confused with other definitions of the “valley of death” related to technology and innovation, which can be also described as the inability of a new company to have a breakthrough, a lack of governmental support to foster a new company or start-up or the failure of many new ideas to progress in an industry and even those that do can spend years trying to escape from it[1077]. A multitude of innovative technologies are unsuccessful in transitioning from lab to industrial scale due to a combination of technical and economic hurdles. This transition necessitates substantial investment and the ability to overcome unforeseen technical challenges that often emerge at larger scales. The fragmentation of funding for pilot and demonstration facilities further complicates this process, requiring companies, particularly SMEs, to navigate multiple funding streams to progress their innovations.

European policies, supported by funding mechanisms such as Horizon Europe and the CBE JU, actively promote the development and deployment of bio-based solutions[1078] [1079]. The bioeconomy’s potential extends beyond environmental benefits, encompassing energy security, the revitalisation of rural areas, and the creation of numerous job opportunities[1080] [1081]. However, despite this promising landscape and strong policy backing, the growth and optimisation of the European bio-based industry are currently impeded by a complex web of technological barriers and challenges. The following sections delve into the specific technological barriers and challenges within each key area of the European bio-based industry, providing a detailed analysis of key areas, including process efficiency, scalability issues, product development and differentiation, process innovation, digital transformation, circularity and waste management, and environmental performance. By identifying and elaborating on these limitations, this analysis seeks to inform policy advisors and

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[1077]Gbadegeshin, S.A., et al., Overcoming the valley of death: a new model of high technology startups. Sustainable Futures 4 (2022) 100077. **https://doi.org/10.1016/j.sftr.2022.100077**

[1078]Horizon Europe | Cluster 6: Food, Bioeconomy, Natural Resources, Agriculture and Environment - European Commission

[1079]Home | Circular Bio-based Europe Joint Undertaking (CBE JU)

[1080]Fritsche, U., Brunori, G., Chiaramonti, D., Galanakis, C., Hellweg, S. et al., *Future transitions for the bioeconomy towards sustainable development and a climate-neutral economy – Knowledge synthesis – Final report*, Publications Office, 2020, **https://data.europa.eu/doi/10.2760/667966**

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research funding bodies, guiding future strategies to unlock the full potential of the European bio-based industry.

6.1 PROCESS EFFICIENCY

6.1.1 Optimisation of bioconversion processes: current limitations

The optimisation of bioconversion processes in Europe is hindered by several technological limitations that affect the overall efficiency and economic viability of the bio-based industry[1082]. The achievement of adequate yield, productivity and robustness in these processes remains a considerable challenge[1083]. In comparison to well-established petrochemical processes, numerous bioconversions demonstrate reduced efficiency, impeding their capacity to compete on cost and scale. This is partly attributed to the limitations of current microbes and biocatalysts, which often do not perform optimally, especially when using the complex non-hexose sugars derived from lignocellulosic biomass, a key feedstock for second-generation biofuels and biochemicals[1084] [1085]. The development of tailored enzymes and microorganisms with enhanced activity, selectivity, and tolerance to harsh industrial conditions is crucial for improving bioconversion efficiency[1086].

Furthermore, a significant proportion of bioconversion processes are still primarily conducted using batch fermentation, which can be less efficient than continuous fermentation systems in terms of productivity and resource utilisation[1087] [1088]. The implementation of continuous fermentation at an industrial scale faces technological complexities, including the maintenance of sterility over extended periods and the ensuring of consistent operating conditions within large bioreactors. The presence of impurities generated during bioconversion steps also poses a challenge, as these can significantly complicate and increase the cost of subsequent downstream processing, impacting the overall

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economic viability of bio-based production[1089] [1090]. Therefore, advancements in enzyme engineering, metabolic pathway optimisation and the design of more efficient and robust bioreactor systems are essential for overcoming these limitations and enhancing the efficiency of bioconversion processes in Europe.

6.1.2 Enhancing energy efficiency in bio-based production

Energy efficiency is a critical aspect of the European bio-based industry. High energy consumption has the potential to compromise both the economic competitiveness and the environmental sustainability of bio-based products. The pretreatment of biomass, especially recalcitrant lignocellulosic feedstocks, to disrupt their complex structures and release sugars for bioconversion, is an inherently energy-intensive stage[1091] [1092]. The pretreatment of different types of biomasses, such as agricultural residues, forestry waste, and algae, requires the development of tailored pretreatment methods that optimise energy efficiency while maximising the yield of desired intermediates. This represents a complex challenge that requires further investigation.

Downstream processing, which involves the separation and purification of target bio-based products from the complex mixture resulting from bioconversion, is another stage with significant energy demands[1093] [1094]. A significant proportion of bioconversion processes take place in aqueous solutions, necessitating the undertaking of energy-intensive steps for product recovery and purification, particularly the removal of substantial volumes of water. Addressing these challenges needs the development and implementation of integrated biorefinery concepts. The integration of diverse conversion technologies, in conjunction with a holistic consideration of the entire production chain, facilitates the optimisation of energy flows, the recovery of heat, and the utilisation of by-products for energy generation. Consequently, this approach contributes to a reduction in the overall energy footprint of bio-based production. Innovations in both upstream and downstream processes,

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with a focus on reducing energy consumption at each stage, are vital for enhancing the sustainability and economic viability of the European bio-based industry.

6.1.3 Strategies for reducing processing time and costs

In the context of the European bio-based industry, there is a clear imperative to reduce processing time and costs if the industry is to achieve competitiveness with established fossil-based industries. As outlined in the report, feedstock variability, particularly in the case of heterogeneous biomass and waste streams, has been demonstrated to lead to inconsistent processing times and higher costs due to the need for flexible and adaptable technologies. Current bioconversion and downstream processing methods are not efficient enough to enable the desired level of productivity. This is due to the fact that they result in prolonged processing times and elevated costs. For instance, slow reaction rates in enzymatic hydrolysis and fermentation, as well as complex and multi-step downstream purification processes, can extend the overall production cycle and increase operational expenses[1095] [1096] [1097].

The absence of robust predictive models for process design and optimisation further hinders efforts to streamline production and reduce costs. The lack of accurate simulation tools can result in longer development times and potentially higher capital investments[1098] [1099]. As mentioned before, process intensification technologies have been identified as a potentially effective solution to these challenges[1100]. By reducing the size of equipment, energy consumption, and waste generation through innovative process schemes and equipment, process intensification can lead to a reduction in processing time and overall costs. Examples of this, which have been observed along the entire deliverable, include the combination of reaction and separation steps, the utilisation of novel reactor designs, and the enhancement of mass and heat transfer. The adoption and further development of such strategies, in conjunction with advancements in process modelling and optimisation, are

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[1096]Dheskali, E., et al., Optimal design of upstream processes in biotransformation technologies. Bioresource Technology 224 (2017) 509-514. **https://doi.org/10.1016/j.biortech.2016.10.084**

[1097]Pothakos, V., et al., Fermentation titer optimization and impact on energy and water consumption during downstream processing. Chemical Engineering & Technology 41(12) (2018) 2358-2365. **https://doi.org/10.1002/ceat.201800279**

[1098]Angenendt, E., et al., Chapter 9 – Modelling and tools supporting the transition to a bioeconomy. In: Lewandowski, I. (ed.) Bioeconomy: Shaping the Transition to a Sustainable, Biobased Economy (2018) 289-316. **https://doi.org/10.1007/978-3-319-68152-8_9**

[1099]Pyka, A., et al., Modelling the bioeconomy: emerging approaches to address policy needs. Journal of Cleaner Production 330 (2022) 129801. **https://doi.org/10.1016/j.jclepro.2021.129801**

[1100]Igbokwe, V.C., et al., Biochemical biorefinery: a low-cost and non-waste concept for promoting sustainable circular bioeconomy. Journal of Environmental Management 305 (2022) 114333. **https://doi.org/10.1016/j.jenvman.2021.114333**

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considered to be pivotal for achieving a reduction in processing time and costs within the European bio-based industry.

6.1.4 Challenges in the integration of multiple processes for improved efficiency

Significant improvements in efficiency within the European bio-based industry can only be achieved through a holistic approach to biorefinery design, where different processes are seamlessly integrated. The integration of bioconversion with pretreatment and downstream processing represents a substantial challenge in the present context. The lack of seamless integration between discrete unit operations can result in bottlenecks and diminished overall efficiency within biorefineries[1101]. Conventionally, bioprocesses have been developed through a series of discrete steps, frequently without adequate consideration for subsequent purification stages, impeding comprehensive system optimisation.

To overcome this issue, it is essential to develop bioprocesses as a whole system, considering all stages from feedstock to product. The transition to continuous integrated biorefineries has been shown to enhance efficiency in comparison with traditional batch processes. Furthermore, integrated biorefineries should aim to valorise all components of biomass, including co-products, to ensure enhanced economic and environmental sustainability[1102] [1103]. Employing a systems-level perspective is vital in identifying synergies between diverse processes and optimising the entire biorefinery to ensure maximum resource utilisation and minimised waste generation[1104].

6.2 SCALABILITY ISSUES

6.2.1 Difficulties in Scaling Up processes from laboratory to industrial level

The process of transitioning bio-based processes from laboratory to industrial scale in Europe is encountering significant challenges, which are hindering the commercialisation of innovative technologies. A commonly cited barrier pertains to the limited access to, and high cost of, specialised

[1101] Kokossis, A.C., et al., Design of integrated biorefineries. Computers & Chemical Engineering 81 (2015) 40-56. https://doi.org/10.1016/j.compchemeng.2015.05.021

[1102] Budzianowski, W.M., and Postawa, K., Total chain integration of sustainable biorefinery systems. Applied Energy 184 (2016) 1432-1446. https://doi.org/10.1016/j.apenergy.2016.06.050

[1103] Slegers, P.M., et al., Design of value chains for microalgal biorefinery at industrial scale: process integration and techno-economic analysis. Frontiers in Bioengineering and Biotechnology 8 (2020) 550758. https://doi.org/10.3389/fbioe.2020.550758

[1104] Parada, M.P., et al., Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design. Industrial Crops and Products 106 (2017) 105-123. https://doi.org/10.1016/j.indcrop.2016.08.052

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scale-up equipment, including pilot and demonstration facilities[1105] [1106]. SMEs, which frequently drive early-stage innovation, encounter considerable difficulties in financing the necessary trials to generate compelling data for investment decisions, whilst also needing to protect their intellectual property. This situation leads to the abovementioned "Valley of Death", where many promising lab-scale innovations fail to reach commercial viability due to technical and economic hurdles. Investors frequently require substantial data from pilot and demonstration projects to assess the economic feasibility of scaling up, and the absence of such data increases the perceived risk and hinders investment[1107] [1108]. Consequently, significant investment in infrastructure and the implementation of de-risking strategies are essential to attract the necessary funding and facilitate the successful scale-up of bio-based processes in Europe.

6.2.2 Challenges in technology integration and continuous processing

The European bio-based industry is encountering difficulties in assimilating novel technologies into extant industrial infrastructure and in implementing continuous processing at an industrial scale. The integration of novel bio-based processes into well-established industries such as pulp and paper can be a gradual process due to the presence of entrenched business structures and a relatively low rate of internal R&D investment within the sector. Continuous processing offers significant advantages in terms of efficiency and productivity, but its implementation requires overcoming technical and regulatory hurdles, as well as adapting existing infrastructure geared towards batch operations. A significant proportion of contemporary biorefining technologies are still in a developmental phase and may focus on a limited number of biomass streams, which further hinders the widespread implementation of continuous processes across diverse feedstocks. The transition from batch to continuous production necessitates a fundamental change in process design and control, which can be complex and costly, requiring specialised equipment and expertise for continuous biomanufacturing. Furthermore, regulatory considerations for continuous processes may differ from those for traditional batch processes, adding another layer of complexity to scale-up efforts.

[1105]Usmani, Z., et al., Lignocellulosic biorefineries: the current state of challenges and strategies for efficient commercialization. Renewable and Sustainable Energy Reviews 148 (2021) 111258. https://doi.org/10.1016/j.rser.2021.111258

[1106]Makepa, D.C., and Chihobo, C.H., Barriers to commercial deployment of biorefineries: a multi-faceted review of obstacles across the innovation chain. Heliyon 10(12) (2024) e32649. https://doi.org/10.1016/j.heliyon.2024.e32649

[1107]Gatto, F., and Re, I., Circular bioeconomy business models to overcome the valley of death. A systematic statistical analysis of studies and projects in emerging bio-based technologies and trends linked to the SME instrument support. Sustainability 13(4) (2021) 1899. https://doi.org/10.3390/su13041899

[1108]Romme, A.G.L., et al., Designing a deep-tech venture builder to address grand challenges and overcome the valley of death. Journal of Organization Design 12 (2023) 217-237. https://doi.org/10.1007/s41469-023-00144-y

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6.2.3 The impact of infrastructure limitations on large-scale production

Inadequate infrastructure, particularly with regard to bioreactor capacity and biomass feedstock supply chains, represents a significant barrier to the scaling up of bio-based production in Europe. The dearth of bioreactors designed specifically for biomanufacturing is impeding the growth of biotech start-ups across Europe. The bio-based industry requires dedicated infrastructure that can effectively handle the specific requirements of biological processes, and the large volumes of diverse biomass feedstocks needed for continuous operation. Securing a stable and consistent supply of biomass feedstock is itself a critical challenge for large-scale bio-based production. The establishment of robust and resilient supply chains, including efficient logistics for the collection, storage and transport of different types of biomass, is often lacking. Furthermore, the substantial capital expenditures associated with the development of new, large-scale infrastructure for bio-based production can act as a significant deterrent for potential investors. It is therefore essential that the European bio-based industry addresses these infrastructure constraints through strategic investment and the development of fit-for-purpose facilities if it is to reach its full potential in terms of scale and market impact.

6.3 Product Development And Differentiation

6.3.1 Barriers in the development of novel bio-based materials and chemicals.

The development of novel bio-based materials and chemicals in Europe is hindered by several technological barriers that prevent their widespread adoption and market success. The achievement of the desired material properties and functionalities often poses a significant technical challenge. The inherent complexity of biomass, while offering a diverse range of potential building blocks, also poses difficulties in selectively extracting and utilizing its various components for specific applications. With the purpose of overcoming these challenges, there is a need to develop innovative conversion technologies and highly efficient catalysts to transform biomass into valuable materials and chemicals with tailored properties. Nevertheless, a key challenge remains in ensuring the cost-competitiveness of these novel bio-based products when compared to their established fossil-based counterparts. High production costs are a recurring factor that hampers the successful market penetration of many promising bio-based innovations. Addressing these challenges necessitates sustained research and development initiatives, with a focus on enhancing material performance, improving conversion efficiencies, and reducing production costs. These efforts are crucial in ensuring that novel bio-based materials and chemicals become a viable and competitive alternative to traditional options.

6.3.2 Technological challenges in creating products with improved functionalities and sustainability

The creation of bio-based products with improved functionalities and enhanced sustainability in Europe necessitates the navigation of a complex set of technological challenges. Achieving a balance between the performance requirements of diverse applications and the overarching objective of sustainability frequently necessitates judicious trade-off decisions. While bio-based

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materials offer the promise of renewability, ensuring their biodegradability and recyclability throughout their lifecycle is a significant technological challenge. It is important to note that not all bio-based plastics are biodegradable, and the conditions required for biodegradation can vary significantly, creating challenges for effective waste management and achieving the principles of circularity. Furthermore, the development of bio-based alternatives to hazardous chemicals and materials, while highly desirable, requires significant innovation in chemistry and materials science. Addressing concerns about land use and potential environmental trade-offs associated with large-scale biomass production is also crucial. The creation of truly sustainable bio-based products demands a holistic approach that considers the entire lifecycle, minimises environmental impact across various indicators, and ensures that the products perform as well as or better than existing fossil-based alternatives without compromising functionality. Achieving these objectives necessitates continuous innovation in material design, processing technologies, and end-of-life management strategies.

6.4 PROCESS INNOVATION

6.4.1 The technological imperative for competitive and sustainable industrial processes

It is imperative that the European bio-based industry develops competitive and sustainable industrial processes if it is to realise its full potential. Disruptive technologies are required to achieve cost parity with established fossil-based processes, thereby rendering bio-based alternatives economically viable on a large scale. It is imperative that resource efficiency and waste minimisation be accorded a high priority in the design of processes, ensuring both economic and environmental sustainability. Process intensification technologies, which aim to dramatically improve manufacturing processes by combining operations and improving mass and heat transfer, can play a crucial role in developing competitive and sustainable industrial practices. The employment of biotechnology and analogous innovative technologies is also imperative in establishing efficient and sustainable pathways to bio-based products. Continued innovation in process technologies is vital for the European bio-based industry. This necessity is driven by two key imperatives: firstly, to ensure competitiveness with existing industries, and secondly, to spearhead the transition to a future that is more sustainable and efficient in its use of resources.

6.4.2 The role and challenges of technical due diligence in biorefining

In the bio-based industry, technical due diligence is of crucial importance, particularly in the context of biorefining. It provides a thorough assessment of the technical feasibility and risks associated with new technologies. The evaluation of the performance and reliability of novel biorefining processes at scale is imperative to de-risk investments and ensure the long-term viability of these projects. However, conducting technical due diligence in the bio-based industry can be challenging due to the novelty and complexity of many of the technologies involved. The absence of standardised methodologies specifically tailored to the bio-based sector can also hinder the capacity to compare different technologies and assess their true potential. Furthermore, there is an increasing necessity

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to incorporate sustainability considerations into technical due diligence, necessitating a comprehensive assessment of the environmental, social and economic impacts of biorefining processes. Consequently, there is an imperative for the development of robust and standardised approaches to technical due diligence that take into account the unique characteristics and sustainability goals of the bio-based industry. Such an approach is likely to stimulate innovation and attract investment in this pivotal sector.

6.4.3 Technological hurdles in developing new biorefining technologies

The development of novel biorefining technologies within the European context is encumbered by several technological challenges. Securing sufficient funding for high-risk, capital-intensive biorefinery projects is a key challenge. Furthermore, the complex regulatory frameworks and protracted permitting processes associated with the construction and operation of biorefineries can impede the development and deployment of new technologies. Furthermore, the necessity for adequate infrastructure to support the deployment of new biorefineries, including facilities for feedstock pre-treatment, conversion, and product purification, can be a major hurdle. Ensuring a sustainable and consistent supply of diverse biomass feedstocks at a competitive price is another critical technological challenge that needs to be addressed for the successful development of new biorefining technologies within the European context. The successful overcoming of these challenges, which relate to financial, regulatory, infrastructural, and feedstock-related issues, necessitates a coordinated effort involving government support, industry collaboration, and continued innovation in biorefining technologies.

6.5 DIGITAL TRANSFORMATION

6.5.1 Challenges in process automation within biorefineries

Process automation in biorefineries in Europe is confronted with numerous technological challenges that impede its extensive implementation. In comparison to the highly automated chemical industry, the bio-based industry, particularly in sectors such as food and pharmaceuticals, often has lower levels of automation due to the prevalence of small-scale and batch production. The automation of these batch processes poses distinct challenges compared to the continuous processes prevalent in bulk chemical production. The paucity of reliable and timely data and measurements from complex biological systems further complicates the implementation of effective process control and automation strategies. The inherent variability and complexity of these biological processes further compound the challenges associated with modelling. The modelling of these complex biological processes for automation purposes can also be challenging due to inherent variability and a lack of comprehensive understanding of all underlying phenomena. To advance process automation in European biorefineries, there is a need to develop robust sensors, sophisticated control systems and accurate predictive models tailored to the specific nuances of biological processes.

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6.5.2 Barriers to the integration of digital technologies in existing biorefining processes

The integration of digital technologies into existing biorefining processes in Europe is impeded by several barriers that hinder the digital transformation of the sector. A fundamental challenge pertains to the dearth of knowledge, expertise and understanding regarding the potential benefits and implementation strategies for digital technologies within the bio-based industry. Many existing biorefineries rely on legacy systems and infrastructure that are not easily compatible with modern digital technologies, making integration a significant challenge. Concerns regarding data security and privacy, as well as the growing interconnectedness of systems, further impede the adoption of these technologies. Furthermore, negative perceptions towards the adoption of new technologies within the industry, often stemming from concerns about job losses, act as a significant barrier. Furthermore, negative perceptions about the adoption of new technologies within the industry, often stemming from concerns about job displacement or the complexity of implementation, can create resistance to digital transformation. To overcome these barriers, targeted efforts must be made to build digital skills within the workforce, develop interoperable digital platforms, address security concerns and clearly communicate the value proposition of digital technologies for the European bio-based industry.

6.5.3 Technological needs for accelerating digital innovation in the blue bioeconomy

In order to accelerate digital innovation in the blue bioeconomy in Europe, it is essential to address specific technological needs that are unique to the marine environment. Distinct digital and technological challenges have been identified in key areas of the blue bioeconomy, including the sustainable harvesting of marine resources, the optimisation of biomass production from algae and other aquatic organisms, and the discovery of novel biomolecules through bioprospecting. The sector requires digital tools and platforms for efficient data management, enhanced collaboration amongst researchers and industry stakeholders, and the acceleration of innovation in marine biotechnology. Digital solutions for process optimisation and product differentiation, tailored to the specific characteristics of marine biological resources, are also crucial. Digital technologies also play an increasingly important role in supporting the green transition and promoting sustainable resource management within the blue bioeconomy. Addressing these technological needs through targeted research and innovation initiatives will be essential for unlocking the full potential of the blue bioeconomy in Europe.

6.6 CIRCULARITY AND WASTE MANAGEMENT

6.6.1 Difficulties in implementing circular economy principles and closed-looping

The implementation of circular economy principles and the establishment of closed-loop systems within the European bio-based industry is challenging due to a paucity of standardised definitions and widely accepted metrics for assessing circularity in the context of bio-based products and processes. A significant challenge is the absence of standardised definitions and widely accepted metrics for evaluating circularity in the context of bio-based products and processes. Absent clear

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and consistent ways to measure circularity, it becomes difficult to track progress and compare different approaches. The effective recycling of bio-based products is hindered by the diverse nature of these materials and the potential for degradation during recycling processes. The management of diverse and often complex biowaste streams generated by industry represents another technical challenge, requiring innovative technologies for efficient waste valorisation and up-cycling into valuable products. Addressing these challenges necessitates targeted research and development in key areas such as advanced recycling technologies, waste pre-treatment and fractionation methods, and the establishment of clear standards and metrics for circularity within the bio-based sector.

6.6.2 Challenges in maximising value generation from biological resources

The maximisation of the value of biological resources in Europe is hindered by several technological challenges. A significant challenge pertains to the inefficient utilisation of all biomass components, particularly lignin and hemicellulose, which are frequently under-utilised despite their substantial potential as sources of valuable chemicals and materials. Addressing these challenges necessitates the development of advanced biorefining technologies. These technologies will enable the complete valorisation of biomass, allowing the efficient extraction and conversion of all major components into a wide range of high-value products. Optimising extraction and separation techniques to isolate specific compounds with desired functionalities and purity is also a technological challenge. Furthermore, the development of cost-effective and scalable methods for converting diverse biological resources, including agricultural and forestry residues and novel feedstocks such as algae, into a wide range of products remains a critical area for technological innovation. Addressing these challenges through continued research and development of biorefining technologies is essential to maximise the economic and environmental value of Europe's biological resources.

6.7 ENVIRONMENTAL PERFORMANCE

6.7.1 The need for better metrics/indicators to assess sustainability in the EU bio-based industry

The European bio-based industry is in need of enhanced metrics and indicators in order to accurately assess its sustainability and guide its development towards environmentally sound practices. While the current LCA methodologies have proven to be valuable tools, they are often limited in their application to bio-based products, particularly in accounting for the unique aspects of biological resources, such as carbon sequestration and land-use change impacts. There is an evident necessity for the development of more comprehensive indicators that encompass the environmental, social, and economic dimensions of sustainability, thereby providing a holistic perspective on the industry's performance. The development of harmonised and standardised metrics across the diverse sectors within the bio-based industry is imperative for facilitating meaningful comparisons and tracking progress towards sustainability goals. The development of robust and reliable metrics is essential for evaluating the true environmental benefits and trade-offs of bio-based products and processes, as well as for informing policy decisions and guiding investments towards the most sustainable options.

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6.7.2 Challenges in balancing environmental impact with techno-economic viability

The bio-based sector in Europe is currently facing the ongoing challenge of balancing environmental performance with techno-economic viability. While bio-based processes do offer the potential for reduced environmental impact compared to fossil-based alternatives, achieving this without compromising economic competitiveness requires innovative technological solutions. There is a need for careful consideration of potential trade-offs between environmental performance and economic factors, including production costs and market prices. Optimising resource and energy efficiency is pivotal in achieving both sustainability and economic goals within the sector. Technological innovation is imperative to devise win-win solutions that simultaneously minimise environmental impacts and enhance the economic viability of bio-based production. The development and adoption of cost-effective technologies that prioritise resource efficiency, waste reduction and the use of sustainable feedstocks will be essential to ensure the long-term success and sustainability of the European bio-based sector.

6.8 Summary By Country

6.8.1 Belgium[1109]

Belgium is committed to achieving climate neutrality by 2050, in line with EU targets. This transition requires not only the decarbonisation of energy systems but also a fundamental transformation in the way biomass is produced, allocated and utilised. Biomass is increasingly recognised as a key resource for replacing fossil-based feedstocks in materials, chemicals, industry and energy, placing the bioeconomy at the centre of Belgium's climate transition.

6.8.1.1 Process Efficiency and Resource Utilisation

Belgium currently benefits from relatively high biomass productivity. In 2020, the country produced approximately 16.1 million tonnes of dry matter (DM) of primary biomass, of which 86% originated from crop agriculture and 14% from forestry and landscape management. Domestic productivity reaches approximately 5.2 tonnes DM per hectare. However, the current utilisation of biomass reveals important efficiency challenges. Almost two-thirds of crop biomass is currently used as animal feed rather than for direct human consumption or higher-value bio-based applications. While the bioeconomy already accounts for 20.8% of apparent biomass use, a significant proportion of available biomass continues to be allocated to low-value applications, creating challenges for future resource optimisation.

[1109]Rapport bio-economie (FOD Volksgezondheid, 2024): Bio-economie en klimaattransitie in België: hoe kunnen vraag en aanbod van biomassa op lange termijn op elkaar worden afgestemd? 2024 – POLICY PAPER.

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Future development of a climate-neutral bioeconomy will require more efficient allocation of biomass resources and greater adherence to biomass cascading principles, ensuring that food, materials and high-value products are prioritised before energy recovery.

6.8.1.2 Scalability and Industrial Deployment

The most significant challenge facing Belgium is the projected imbalance between future biomass demand and available supply. Under the CORE-95 scenario, total biomass demand is projected to increase by between 260% and 430% by 2050 compared with 2018 levels. This increase is primarily driven by:

- Decarbonisation of the chemical sector, where fossil feedstocks are expected to be fully replaced by biomass-based alternatives.
- Increased use of bio-based materials in construction, with biomass potentially replacing up to 40% of cement and 20% of steel in selected applications.
- Growing demand for bioenergy in sectors that are difficult to electrify, including specific industrial activities, buildings, and maritime transport.

Demand patterns are also expected to change significantly. While demand for solid biomass is projected to decrease by 58% compared with 2018 levels, demand for biogas is expected to increase by 333% and demand for biofuels by 90%. At the same time, biomass availability is expected to stabilise or decline slightly. Future supply will increasingly depend on forests, non-food crops, waste streams, and by-products from food-processing industries. Since Belgium's strategy seeks to maintain food production, additional biomass supply is expected to come from land-use reallocation, reduced consumption of animal products, lower food waste, and reduced dependence on synthetic fertilisers. Even under these assumptions, the projected increase in demand substantially exceeds expected supply, creating major scalability challenges for future bio-based industries.

6.8.1.3 Product Development and Differentiation

Belgium has already established several bio-based value chains. The bioeconomy currently accounts for 20.8% of apparent biomass use. Forestry-based products currently represent more than 70% of the country's bioeconomy-related biomass use, while important sectors include construction materials, chemicals, textiles, biogas production, and biofuels. Future competitiveness will depend on directing available biomass towards higher-value applications capable of generating greater economic and environmental returns from limited domestic resources. As biomass availability becomes increasingly constrained, product differentiation and value maximisation will become critical factors in maintaining industrial competitiveness.

6.8.1.4 Process Innovation and Technology Development

Achieving climate neutrality will require continued innovation in biomass conversion, biorefining technologies and integrated valorisation pathways. The projected mismatch between biomass demand and supply highlights the need for technologies capable of:

- Improving biomass conversion efficiencies.
- Increasing resource recovery from waste streams.

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- Supporting cascading biomass utilisation.
- Maximising the use of by-products and secondary biomass streams.
- Reducing feedstock losses throughout value chains.

Innovation will also be essential for enabling greater substitution of fossil-based materials in sectors such as chemicals and construction while minimising pressure on primary biomass resources.

6.8.1.5 Digital Transformation

No major digitalisation barriers were explicitly identified in the reviewed source. However, digital tools can play an important enabling role in managing future biomass constraints. Digital systems for biomass mapping, resource monitoring, logistics optimisation and supply-chain management could support more efficient allocation of biomass between competing sectors. In particular, advanced monitoring and forecasting systems may become increasingly important as Belgium seeks to balance demand and supply under climate-neutral scenarios.

6.8.1.6 Circularity and Waste Management

Circularity is expected to become a central pillar of Belgium's future bioeconomy strategy. Future biomass supply will increasingly depend on waste streams, food-processing by-products, forestry residues and other secondary biomass resources. In order to reduce pressure on primary biomass production, it is essential to implement:

- **Reallocation of Land**: the process requires the transition of land from feed crops to biomass crops or forests. To achieve this goal, a multifaceted approach is necessary, including dietary changes, reducing food waste, and lowering animal protein intake. This contributes to the preservation of natural carbon sinks and improves ecological resilience.
- **Efficiency and Sobriety Measures**: a bioeconomy that is aligned with climate change must be supported by material efficiency, behavioural change and a reduction in overall energy and material consumption. It is vital that bioenergy use is strictly limited to essential sectors and implemented in accordance with cascading principles. In accordance with these principles, priority should be given to food and materials before energy.
- **Circular Bioeconomy and Governance**: the future bioeconomy must embrace the integration of recycling, reuse, and cascading strategies. A key priority for the new administration will be the design of policy that is holistic, inclusive and transparent, aligning the priorities of agriculture, industry, land use and environmental protection. The issue at hand is not just technical; it is also deeply societal and political.

Greater integration of recycling, reuse and cascading utilisation strategies will therefore be required to optimise resource efficiency and reduce dependency on imported biomass. Particular emphasis should be placed on ensuring that biomass is used according to cascading principles, prioritising food and material applications before energy recovery.

6.8.1.7 Environmental Performance and Sustainability

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The projected demand-supply imbalance introduces several important sustainability risks. First, increasing dependence on imported biomass may externalise environmental impacts to other regions, potentially shifting rather than reducing environmental pressures. Second, growing competition between food, materials and energy applications may intensify pressure on available biomass resources and increase land-use conflicts. Third, as more countries pursue bioeconomy development pathways, international competition for biomass resources may generate broader global trade and sustainability challenges. Belgium's climate-neutrality pathway therefore depends not only on increasing biomass utilisation but also on maintaining ecological resilience and preserving natural carbon sinks. This requires substantial land-use adjustments, including the transition of land currently dedicated to feed production towards biomass crops or forests. Such changes are supported by assumptions including a 56% reduction in meat consumption, reductions in food waste, and lower reliance on synthetic fertilisers.

6.8.1.8 Strategic Recommendations

To align its bioeconomy ambitions with climate-neutrality objectives, Belgium should prioritise:

- More efficient allocation of biomass resources across competing sectors.
- Greater deployment of circular economy practices, including recycling, reuse and cascading biomass utilisation.
- Technological innovation to improve biomass conversion efficiency and valorisation of wastes and by-products.
- Land-use reforms that support sustainable biomass production while preserving food security and ecosystem services.
- Behavioural changes aimed at reducing overall material and energy consumption, including reductions in food waste and animal protein consumption.
- Integrated governance frameworks capable of coordinating agricultural, industrial, climate, land-use and environmental policies.

The long-term success of Belgium's bioeconomy will depend on balancing increasing biomass demand with finite biomass availability. Strengthening resource efficiency, circularity, cross-sector collaboration and sustainable trade policies will be essential to ensure that the bioeconomy contributes to both climate neutrality and long-term resilience.

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6.8.2 Bulgaria[1110] [1111]

Bulgaria's bioeconomy is facing a range of technological challenges that hinder its ability to develop competitive, high-value bio-based industries. While the country possesses strong potential in biomass utilisation, agricultural production and forestry-based resources, the lack of advanced technological infrastructure, process innovation and industrial-scale biorefining facilities is constraining growth. In order to enable a more robust and competitive bioeconomy in Bulgaria, several key issues must be addressed, including inefficiencies in bioconversion processes, limited scalability of bio-based production, insufficient investment in product development, weak process innovation, slow adoption of digital technologies, and inadequate circularity and waste management strategies.

6.8.2.1 Process Efficiency Constraints and Resource Utilisation

Bulgaria's bioconversion efficiency is not as high as it could be due to the use of outdated and energy-intensive processing technologies. Many bioprocessing facilities rely on traditional batch-processing methods rather than continuous production models, with the result that overall yield is reduced and costs increased. The high energy consumption inherent in the manufacturing of bio-based products presents a significant challenge when attempting to compete with fossil-based alternatives. For instance, the food and agricultural industries, which form a substantial part of Bulgaria's bioeconomy, often struggle with inefficient supply chains and logistics, leading to biomass losses before reaching processing facilities. Addressing these efficiency constraints requires investments in modern, high-yield bioprocessing technologies that can optimise resource use while minimising environmental impact.

6.8.2.2 Scalability Issues and Industrial Deployment in Bio-Based Production

A significant bottleneck in Bulgaria's bioeconomy is the inability to scale up bio-based innovations from laboratory or pilot scale to industrial production. In contrast to leading bioeconomy nations, Bulgaria lacks sufficient biorefining infrastructure to support large-scale biomass valorisation. A significant number of promising bio-based technologies are not being commercialised due to a lack of support. The underdevelopment of processing facilities for emerging bio-based materials, such as lignocellulosic biomass and algae-based biofuels, limits the country's capacity to integrate bioeconomy solutions into mainstream industrial sectors. Furthermore, while the country has significant biomass potential, logistical challenges are preventing efficient feedstock mobilisation, which is further restricting scalability.

[1110] Strategy for the Digitalisation of Agriculture and Rural Areas of the Republic of Bulgaria | Preparatory Action on Smart Rural Areas in the 21st Century

[1111] At a glance: Bulgaria's CAP Strategic Plan | Agriculture and Rural Development | European Commission

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6.8.2.3 Limitations in Bio-Based Product Development

The development of high-value bio-based products in Bulgaria is being hindered by several factors. These include limited R&D funding, weak industry-academia collaboration, and a lack of commercialisation mechanisms. Despite the emergence of Bulgaria's biopharmaceutical sector, which produces essential oils, biofertilisers and bio-based textiles, these industries face challenges in competing with lower-cost synthetic alternatives. The absence of well-established product certification frameworks and sustainability labelling further weakens the market adoption of bio-based goods. In the absence of adequate financial incentives and effective support mechanisms to encourage the transition from fossil-based to bio-based products, many companies remain reluctant to invest in the bioeconomy.

6.8.2.4 Process Innovation and Technology Development

Process innovation in Bulgaria's bioeconomy is underdeveloped due to limited access to funding for advanced biorefinery technologies. Many companies lack the financial means to invest in cutting-edge fermentation, enzymatic conversion, and microbial processing techniques necessary for producing advanced biofuels, bioplastics, and bio-based chemicals. The lack of pilot and demonstration plants further hinders the validation of new bio-based production methods before full-scale deployment. In order to enhance process innovation, it is essential that Bulgaria establishes technology transfer hubs. These hubs will connect research institutions with industry players, thereby fostering collaboration on bio-based product development.

6.8.2.5 Slow Digital Transformation in the Bioeconomy

Despite the growing importance of digitalisation in industrial bioprocessing, Bulgaria's bioeconomy has been slow to adopt Industry 4.0 solutions such as AI-driven process automation, blockchain for biomass traceability, and big data analytics for optimising biorefining operations. Many bio-based businesses lack the digital expertise and financial resources to implement smart manufacturing solutions that could improve efficiency and reduce operational costs. Furthermore, the full potential of digital tools for biomass supply chain management is not being realised, resulting in inefficiencies in the procurement of feedstock and logistics. It is vital that the Bulgarian government implements targeted incentives and technical training programmes to accelerate the digital transformation of the bioeconomy. Nevertheless, Bulgaria has a number of policy instruments that could support the digital transition of its bioeconomy. The country's Digital Transformation Strategy 2024–2030 places particular emphasis on the following areas: (i) the development of digital skills, (ii) the digitalisation of enterprises, (iii) innovation capacity, (iv) data utilisation, and (v) the deployment of advanced digital technologies.

However, recent assessments of Bulgaria's digital performance continue to highlight challenges related to SME digitalisation, adoption of advanced technologies, and shortages of digital skills, which remain significant constraints for sectors relying on innovation and technological upgrading. In the biomass-producing sectors, digitalisation remains uneven. Bulgaria's Strategy for the Digitalisation of Agriculture and Rural Areas (2019–2027) is a comprehensive plan that aims to promote the adoption of precision agriculture, smart rural development, digital infrastructure and

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innovative technologies such as IoT systems, remote sensing, data-driven farm management and automated monitoring solutions. However, the implementation of these systems remains concentrated in larger enterprises and specific regions, while many smaller operators continue to face barriers related to financing, infrastructure availability and technical expertise. These limitations have a detrimental effect on opportunities to improve biomass traceability, optimise logistics, and increase resource efficiency across bioeconomy value chains.

6.8.2.6 Circularity and Waste Management

While Bulgaria has made progress in promoting circular economy principles, biowaste valorisation remains a major challenge. The country generates substantial agricultural, forestry, and food processing waste, but much of it remains underutilised due to the lack of biogas production facilities, composting infrastructure, and waste-to-bioenergy conversion technologies. The bioeconomy strategy emphasises the need for improved waste management systems, particularly in rural areas where agricultural residues could be converted into bio-based products. Increased investment in waste valorisation facilities, anaerobic digestion plants and biochar production technologies would enhance Bulgaria's ability to close material loops and optimise the value extracted from biological resources.

6.8.2.7 Environmental Performance and Sustainability

The technological limitations affecting Bulgaria's bioeconomy also have important environmental implications. The efficiency of biomass processing technologies, the high energy consumption of manufacturing processes, and the underutilisation of agricultural, forestry and food-processing residues all have a negative impact on the overall sustainability performance of bio-based value chains. The wider deployment of advanced bioprocessing technologies, modern biorefineries, anaerobic digestion systems and waste valorisation infrastructure could contribute to lower greenhouse gas emissions, improved resource efficiency and reduced dependence on fossil-based materials. Furthermore, greater adoption of circular bioeconomy principles would support biodiversity protection, sustainable resource management and the transition towards climate neutrality. The effective utilisation of biomass resources in accordance with cascading-use principles, along with the promotion of sustainable management practices in the agricultural and forestry sectors, will be pivotal in ensuring the optimal environmental benefits of Bulgaria's bioeconomy are realised, while concurrently fostering long-term economic growth.

6.8.2.8 Strategic Recommendations

To overcome the technological challenges identified above, Bulgaria should implement specific policy measures aimed at strengthening bioeconomy infrastructure, improving process efficiency and accelerating technology transfer. Key recommendations include:

- Investing in large-scale biorefineries and modernising existing processing facilities to support industrial-scale biomass valorisation.
- Providing financial incentives for bio-based product development, commercialisation and certification.

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- Supporting digital transformation initiatives such as AI-based process control, blockchain traceability and smart logistics solutions.
- Increasing investments in biowaste valorisation and cascading biomass utilisation models.
- Fostering stronger collaboration between universities, research institutions and industry players to accelerate innovation.

By addressing these technological barriers, Bulgaria can establish a more sustainable, efficient and competitive bioeconomy, contributing to long-term economic growth and alignment with EU sustainability objectives.

6.8.3 Croatia[1112] [1113] [1114] [1115] [1116] [1117] [1118] [1119]

Croatia's bioeconomy sector is still in a developmental phase, facing numerous structural, technological and operational barriers. While the country possesses abundant biomass resources from agriculture, forestry and related sectors, its ability to convert these resources into high-value bio-based products remains limited. The absence of a dedicated bioeconomy strategy, inadequate policy coordination, and limited research and innovation investments have contributed to a fragmented and underdeveloped sector. Despite these challenges, Croatia has significant opportunities to strengthen its bioeconomy. European Union funding mechanisms provide access to financial resources that can support the establishment of biorefineries, encourage private-sector investment, and improve technological innovation. Furthermore, alignment with the European Green Deal and the EU Bioeconomy Strategy could facilitate the transition towards a more sustainable and circular bioeconomy.

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[1113] Glavan, D., Bioekonomija: izazovi i potencijali za održivi razvoj ruralnih područja. Master's thesis (2022) University of Zagreb. Repository Faculty of Agriculture University of Zagreb. **https://urn.nsk.hr/urn:nbn:hr:204:906798**

[1114] Institute for Development and International Relations (IRMO) aktualno "Bioeconomy in Croatia - do we know where we are going?" (2022) | Institut za razvoj i međunarodne odnose

[1115] Kulišić, B., Sectoral analysis: Bioeconomy (2020) Energy Institute Hrvoje Požar.

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[1117] Ministry of Economy and Sustainable Development. Strategic framework for circular economy and bioeconomy in Croatia (2022) Government of the Republic of Croatia.

[1118] Ministry of Regional Development and EU Funds. Smart Specialization Strategy 2021–2027 (2021) Government of the Republic of Croatia.

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6.8.3.1 Process Efficiency and Resource Utilisation

Croatia benefits from an abundance of biomass resources; however, the efficiency with which these resources are converted into value-added products remains relatively low. Existing biomass value chains often prioritise primary resource utilisation over advanced valorisation pathways, which have the potential to generate higher-value products and generate greater economic returns. The limited deployment of advanced biomass processing technologies reduces the overall efficiency of resource utilisation, while fragmented value chains constrain opportunities for maximising the value extracted from available feedstocks. Improving the efficiency of biomass processing and promoting higher-value applications are therefore essential to strengthen competitiveness and optimise the utilisation of domestic biological resources.

6.8.3.2 Scalability and Industrial Deployment

A key challenge for Croatia's bioeconomy is the limited availability of industrial-scale infrastructure capable of supporting biomass valorisation and large-scale production of bio-based products. Despite Croatia's significant biomass resources, the absence of dedicated biorefineries and processing facilities hinders the scaling up of bio-based innovations and the transition from resource availability to industrial deployment. This discrepancy negatively impacts the country's potential to commercialise innovative bio-based solutions and compete with more established European bioeconomy regions. EU funding mechanisms provide a valuable opportunity to address these limitations by supporting biorefinery development, infrastructure investments, and industrial modernisation. Expanding industrial-scale biomass processing capacity will be essential for transforming Croatia's resource potential into economic growth and competitive bio-based industries.

6.8.3.3 Product Development and Differentiation

Croatia has the potential to develop and commercialise high-value bio-based products, but this capacity remains relatively limited at present. While significant quantities of biomass are available, the conversion of these resources into differentiated bio-based materials, chemicals, fuels and other value-added products is still underdeveloped. The country would benefit from stronger support mechanisms that encourage innovation and facilitate the commercialisation of research results. Greater emphasis on product differentiation could help Croatian companies improve competitiveness in both domestic and international markets while capturing greater value from available biomass resources. The development of innovative bio-based products should therefore become a strategic priority alongside efforts to strengthen industrial deployment and market creation.

6.8.3.4 Process Innovation and Technology Development

Insufficient investment in research, development and innovation continues to limit technological progress in Croatia's bioeconomy. A significant number of biomass resources that show great potential are not being used to their full potential. This is due to a lack of the necessary technology, limited facilities where the technology can be tested, and poor links between research institutions and industrial actors. The development of advanced biomass conversion technologies, biorefining processes, and integrated valorisation systems will be essential for increasing resource efficiency and creating new market opportunities. Improved technology transfer mechanisms can facilitate the

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movement of innovations from research environments into commercial applications. Furthermore, stronger collaboration between universities, research organisations and businesses will be necessary to accelerate technological development and support the emergence of innovation-driven bio-based industries.

6.8.3.5 Digital Transformation

Digital transformation is a component of Croatia's bioeconomy ecosystem that is still in its development phase. While digital technologies have the potential to improve biomass resource management, supply-chain coordination, process optimisation and industrial competitiveness, their integration within bio-based industries remains limited. The Croatian bioeconomy is characterised by a fragmented structure, compounded by the absence of a dedicated bioeconomy strategy, which has hindered the development of coordinated digitalisation initiatives across the sector. Consequently, there are significant untapped opportunities to enhance efficiency through the implementation of digital solutions. The implementation of digital technologies has the potential to facilitate a range of processes, including biomass mapping, feedstock traceability, logistics optimisation, real-time monitoring of biomass flows, and enhanced management of bio-based production systems. Such technologies would be particularly valuable given the dispersed nature of biomass resources and the need to improve resource mobilisation and industrial utilisation. Digital platforms have the potential to enhance collaboration between research institutions, public authorities and private-sector stakeholders by facilitating knowledge exchange, technology transfer and innovation management. Greater integration of digital technologies within agriculture, forestry, biomass processing and circular economy value chains could therefore contribute to enhanced productivity, resource efficiency and competitiveness.

6.8.3.6 Circularity and Waste Management

Croatia has significant opportunities to strengthen circular economy approaches within its bioeconomy development pathway. In alignment with the European Green Deal, the EU Bioeconomy Strategy and national circular economy initiatives, the transition towards more sustainable resource utilisation models can be supported. A stronger focus on biomass valorisation, cascading use of resources, and the integration of waste streams into productive value chains would improve resource efficiency while reducing environmental pressures. Agricultural residues, forestry by-products and organic waste streams represent significant opportunities for the development of circular bio-based solutions. The further integration of circular economy principles into industrial development strategies could contribute to both environmental sustainability and economic competitiveness.

6.8.3.7 Environmental Performance and Sustainability

The transition towards a bio-based economy offers significant opportunities for Croatia to enhance environmental sustainability while fostering economic growth. The efficient utilisation of biomass, higher-value valorisation pathways and greater circularity can contribute to reduced resource waste and improved environmental performance. Croatia's capacity to develop environmentally responsible bio-based industries could be further strengthened by alignment with European sustainability objectives. However, achieving these objectives will require stronger policy

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coordination, targeted investments and long-term planning to ensure that economic development is aligned with environmental goals. The sustainable management of Croatia's abundant biological resources will be critical to ensuring that future bioeconomy growth contributes positively to climate, environmental and rural development objectives.

6.8.3.8 Strategic Recommendations

To overcome existing barriers and accelerate bioeconomy development, Croatia should establish the following priorities:

- The development of dedicated bioeconomy policies and improved coordination across government sectors.
- Greater investment in research, development and innovation activities.
- The establishment of biorefineries and industrial-scale biomass processing facilities.
- Stronger collaboration between research institutions and private-sector actors.
- The creation of bioeconomy clusters to facilitate knowledge transfer and industrial cooperation.
- Increased financial incentives to encourage private-sector participation and technological investments.
- Improved biomass processing efficiency and resource valorisation.
- Greater integration of digital technologies across biomass value chains.
- Wider adoption of circular economy principles in bio-based industries.

Without immediate policy interventions and strategic investments, Croatia risks falling further behind in the European bioeconomy landscape. However, through targeted actions, stronger governance and enhanced innovation capacity, Croatia has the potential to leverage its rich natural resources and transition towards a more sustainable, competitive and innovative bioeconomy.

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6.8.4 *Cyprus*[1120] [1121] [1122] [1123] [1124] [1125]

Cyprus faces several technological barriers that limit its ability to develop and commercialise bio-based industries. While the country has strong research capabilities, particularly in biotechnology and circular economy applications, the lack of industrial integration, technology transfer, and adequate processing facilities prevents efficient bioeconomy development. Key challenges include inefficiencies in bioconversion processes, scalability constraints, limitations in bio-based product development, gaps in process innovation, slow digital transformation, and difficulties in waste valorisation. Addressing these barriers is essential for Cyprus to strengthen its bioeconomy and align with EU sustainability targets.

6.8.4.1 *Process Efficiency Constraints and Resource Utilisation*

The efficiency of bioconversion processes in Cyprus is not yet optimal, primarily due to outdated technologies and high energy consumption. Many bio-based production methods require significant energy inputs, which can reduce their competitiveness against fossil-based alternatives. The absence of integrated multi-step processing in existing bioprocessing facilities is also problematic, as most plants focus on single-step biomass conversion rather than cascading use approaches that maximize feedstock value. Furthermore, restricted access to state-of-the-art bioprocessing technologies restricts the optimisation of enzymatic and microbial conversion pathways, which are pivotal for the production of high-value bio-based products. The lack of investment in low-energy, high-yield bioprocesses contributes to elevated production costs, making it challenging for Cyprus to develop cost-competitive bio-based industries.

6.8.4.2 *Scalability Issues and Industrial Deployment in Bio-Based Production*

A significant technological challenge in Cyprus' bioeconomy is the difficulty of scaling up bio-based innovations from laboratory or pilot scale to full industrial production. The country lacks the necessary biorefining infrastructure to process biomass efficiently, which limits the commercialisation of bio-

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[1124] Republic of Cyprus. Cyprus' draft integrated National Energy and Climate Plan for 2021-2030 | Department of Environment | Ministry of Energy, Commerce and Industry | STIP Compass

[1125] Shaping the future bioeconomy across sectoral, governmental and geographical levels | ShapingBio | Projekt | Fact Sheet | HORIZON | CORDIS | European Commission

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based products. While there is interest in bio-based energy and bioplastics, there are few large-scale biorefineries capable of producing these materials at a commercially viable scale. Additionally, the bio-based industry in Cyprus is dominated by batch-based production models, which hinders the adoption of continuous processing methods that could enhance efficiency and reduce costs. In the absence of targeted investments in large-scale biorefinery infrastructure and supply chain integration, the country will face considerable challenges in transitioning from small-scale experimental projects to competitive bioeconomy operations.

6.8.4.3 Bio-Based Product Development and Differentiation

The development of high-value bio-based products in Cyprus is constrained by insufficient R&D funding, limited market opportunities, and high production costs. While universities and research institutes are actively studying bio-based materials, these findings rarely translate into commercially viable products due to a lack of industrial partnerships and technology transfer mechanisms. Furthermore, the challenge for bio-based products from Cyprus is to differentiate themselves from fossil-based alternatives, which remain cheaper and more widely available. The absence of incentives for businesses to invest in novel bio-based materials further slows the growth of this sector. To overcome these barriers, there is a need for stronger industry-academia collaboration, financial support for bio-based product development, and market-driven policies promoting sustainable alternatives.

6.8.4.4 Process Innovation and Technology Development

Cyprus faces challenges in developing cost-effective and sustainable industrial bioprocesses due to a lack of investment in process innovation. Many biorefining technologies are still in the development stage, which limits the ability to produce high-value bio-based products at competitive costs. The country lacks dedicated testing and demonstration hubs where new bioeconomy technologies can be piloted before commercialisation. To address this gap, Cyprus should enhance its support for research-driven process innovation and develop financial mechanisms that encourage companies to invest in technological advancements. In the absence of adequate support mechanisms to facilitate the large-scale deployment of bio-based technologies, a significant number of promising bioeconomy innovations are likely to remain at the laboratory research stage.

6.8.4.5 Digital Transformation in the Bioeconomy

The adoption of digital technologies is progressing at a gradual pace in the Cypriot bioeconomy, despite the potential benefits of enhancing process efficiency, automation, and data-driven decision-making. Many bioprocessing facilities are not equipped with advanced automation systems, resulting in inefficiencies in production and high labour costs. Furthermore, digital tools such as AI-driven process control, blockchain for biomass traceability, and smart monitoring systems remain underutilised. Whilst digital transformation is increasingly recognised as a key factor in improving competitiveness, many companies lack the technical expertise and financial resources to implement digital innovations. Government support for Industry 4.0 solutions in the bioeconomy, along with targeted investment in digital infrastructure, could help overcome the challenges currently being faced and enhance Cyprus' position in the European bioeconomy landscape.

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6.8.4.6 *Circularity and Waste Management*

Despite Cyprus' growing emphasis on circular economy principles, its bioeconomy still faces major difficulties in waste valorisation and closed-loop biomass utilisation. Despite the Cyprus Action Plan for the Transition to a Circular Economy (2021-2027) promoting sustainable resource management, the country's waste valorisation systems are underdeveloped. Many bio-based industries fail to generate maximum value from biological resources, leading to inefficiencies in waste reuse and biorefining side-stream utilisation. The country also lacks investment in waste-to-bioenergy technologies, particularly anaerobic digestion facilities for the conversion of organic waste into biogas. In the context of Cyprus' bioeconomy, there are crucial factors to consider achieving enhanced circularity: the expansion of waste valorisation infrastructure, the development of incentive mechanisms for the cascading use of biomass, and the promotion of investment in biowaste recovery solutions.

6.8.4.7 *Environmental Performance and Sustainability*

Cyprus faces significant environmental challenges associated with its limited natural resources, arid climate, and dependence on imported energy and raw materials. These conditions increase the importance of developing resource-efficient and low-carbon bioeconomy solutions capable of reducing environmental pressures while enhancing resource security. The underutilisation of biomass resources and inadequate waste valorisation infrastructure currently limit the environmental benefits that could be achieved through a more developed bioeconomy. Greater deployment of advanced bioconversion technologies, waste-to-bioenergy systems, anaerobic digestion facilities and cascading biomass utilisation models could contribute to reducing greenhouse gas emissions, improving resource efficiency, and diverting organic waste from disposal pathways. Furthermore, the transition towards a circular bioeconomy could support the implementation of Cyprus' National Energy and Climate Plan and Circular Economy Action Plan by promoting sustainable resource management, reducing dependence on fossil-based products, and increasing the recovery and valorisation of biological resources. It is vital to ensure that biomass resources are used according to cascading-use principles to maximise environmental benefits while maintaining long-term sustainability.

6.8.4.8 *Strategic Recommendations*

To overcome these technological challenges, Cyprus should implement targeted policy measures to support bioeconomy development:

- Investment in large-scale biorefinery infrastructure and advanced biomass processing facilities.
- Adoption of cutting-edge bioconversion technologies to improve process efficiency and productivity.
- Financial support for bio-based product development, certification and commercialisation.
- Deployment of Industry 4.0 technologies, including AI-driven process optimisation, automation and blockchain-based traceability systems.
- Expansion of biowaste recovery, anaerobic digestion and waste-to-bioenergy infrastructure.

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- Wider implementation of cascading biomass utilisation models and circular economy practices.
- Stronger collaboration between research institutions, universities and industrial stakeholders to facilitate technology transfer and market uptake.

The implementation of these measures by Cyprus has the potential to enhance the competitiveness of its bioeconomy, stimulate innovation, and contribute to the achievement of European sustainability and climate objectives.

6.8.5 Czechia[1126] [1127] [1128] [1129] [1130] *[1131] [1132]*

The Czech Republic has excellent potential to facilitate the circular bioeconomy through the production of new feedstocks such as agricultural residues, industrial hemp, forest wood biomass, food processing residues, and energy crops. However, the processing of raw biomass into high-value bio-based products is limited by a range of technological hurdles. In addition, pre-treatment difficulties with feedstocks, modular technology availability, technical specifications, and the lack of a sufficient skilled workforce further restrict Czech bio-based solution commercialization and competitiveness. The removal of these barriers is critical in an effort to capitalise on regional biomass resources and facilitate rural innovation-driven development.

6.8.5.1 Process Efficiency and Maturity and Resource Utilisation

Low conversion efficiency remains a significant barrier to the deployment of biomass valorisation technologies such as anaerobic digestion, pyrolysis, and enzymatic hydrolysis, especially when processing heterogeneous feedstocks like straw, manure, or food waste. Variability in biomass properties, including moisture content, lignin levels, and contamination, can adversely affect process performance and lead to inconsistent product yields. Moreover, many of these technologies are still at intermediate stages of development (TRL 4–6), requiring further optimisation and scale-up efforts

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before widespread industrial implementation. The high energy demand associated with several conversion processes, particularly torrefaction and pyrolysis, can reduce both their overall efficiency and environmental benefits. At the same time, limited integration of resource recovery strategies, such as waste heat utilisation, water recycling, and nutrient recirculation, constrains the sustainability of biomass processing facilities. These challenges are especially relevant in the Czech Republic, where high energy costs and limited access to renewable electricity can further affect the economic viability of such technologies.

6.8.5.2 Scalability and Industrial Deployment

Technologies developed by research institutions (e.g. membrane separation, microbial fermentation) often lack pathways for scale-up, especially for SMEs. There is a limited amount of pilot infrastructure available. There are only a few demonstration plants in the Czech Republic that are capable of testing industrial-scale biomass conversion. Additionally, integration into existing facilities (e.g., breweries, sugar refineries) is constrained by technical incompatibilities and regulatory hurdles.

6.8.5.3 Product Development and Differentiation

The preponderance of R&D focus on low-value outputs, such as biogas, compost, and heat, rather than high-value products, including bio-based chemicals, polymers, and nutraceuticals, is a salient concern. The absence of standardisation and quality control measures has the effect of hindering the ability to differentiate Czech bio-based products in EU markets. Furthermore, downstream applications (e.g., for cosmetics, pharmaceuticals, packaging) are frequently not integrated with biomass producers and processors.

6.8.5.4 Process Innovation and Technology Development

Many existing biomass technologies are imported and lack adaptation to local feedstock types or the small-scale use cases that are characteristic of Czech agriculture and forestry. The pace of innovation is hindered by a narrow focus on applied research within Czech universities, resulting in numerous breakthroughs remaining confined to academic discourse without the implementation of commercialisation strategies. The challenges encountered during multi-feedstock processing (for example, the combination of hemp, hops waste and straw) are attributable to the absence of flexible processing lines.

6.8.5.5 Digital Transformation and Smart Systems

The uptake of advanced digital technologies in biomass value chains remains limited, particularly in logistics, storage, and conversion operations. Tools such as real-time sensors, automation systems, and remote monitoring solutions are not yet widely implemented, while digital twins, process modelling platforms, and AI-based monitoring systems are largely absent from biomass processing facilities. As a result, many operators continue to depend on manual procedures and conventional management practices, reducing opportunities for process optimisation, operational efficiency, and supply-chain traceability. Another important challenge is the lack of a centralised and easily accessible source of information on biomass resources, conversion pathways, by-product valorisation options, and technology performance. This information gap can hinder transparency,

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slow the transfer of innovation, and complicate decision-making for new market entrants seeking appropriate technologies or business models. In addition, open-access knowledge-sharing platforms and technology matchmaking mechanisms remain underdeveloped within the Czech innovation ecosystem, limiting collaboration and the wider dissemination of best practices.

6.8.5.6 Circularity and Waste Management Integration

By-products from biomass processing (e.g. digestate, ash, lignin-rich residues) are frequently treated as waste rather than being utilised as inputs for new value chains. There is a lack of circular system design that connects bioenergy, agriculture, waste, and material loops. There are limited opportunities to integrate waste from the food, beverage, or forestry sectors into new cycles. This is due to technical, logistical and legal issues.

6.8.5.7 Environmental Performance and Sustainability Metrics

Many processing methods (e.g. combustion, traditional biogas) provide limited GHG savings or circularity benefits when not optimized. A significant challenge in evaluating the environmental impact of Czech biomass-based processes is the scarcity of LCA data. This hinders the ability to substantiate their environmental value. Technologies are often not equipped with closed-loop water use, emissions control or nutrient recovery systems, which has a negative impact on overall sustainability.

6.8.5.8 Strategic Recommendations

To address the technological barriers identified above, Czechia should prioritise:

- Establishing regional pilot and testing facilities focused on locally available feedstocks such as hop residues, industrial hemp and agricultural straw.
- Supporting SMEs and research institutions in the validation and scale-up of bio-based technologies under real operating conditions.
- Funding cross-industry R&D teams to develop scalable multi-feedstock biomass processing platforms.
- Strengthening collaboration between agricultural producers, biotechnologists and engineering experts.
- Supporting digital innovation hubs in rural bioeconomy clusters to accelerate the adoption of automation, sensors and data analytics.
- Developing knowledge-sharing platforms that improve technology dissemination and biomass resource mapping.
- Promoting LCA studies and eco-labelling schemes for Czech bio-based products.
- Encouraging process optimisation and sustainability performance improvements through environmental certification frameworks.

By implementing these measures, Czechia can strengthen rural innovation systems, improve biomass valorisation and establish a stronger competitive position within the European bioeconomy.

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6.8.6 *Estonia*[1133] [1134] [1135] [1136] [1137]

Estonia's ambition to establish itself as a leading development centre for bioeconomy in Europe is set to be tested by a range of technological challenges, despite the country's abundant bioresources. Estonia boasts one of Europe's most significant bioeconomies, underpinned by a wealth of expertise in forest-based activities and supported by high-quality natural resources. Approximately half of the country's total land area is covered in forests, making Estonia one of the most forest-rich countries in Europe. This natural advantage provides substantial biomass resources for the development of the bioeconomy, with arable land per capita almost twice the EU-27 average (0.69 and 0.37 ha, respectively). Despite the favourable natural conditions, Estonia faces significant challenges in optimising the value of its biological resources, particularly in terms of processing capacity and value addition. As outlined previously in this report, the Ministry of Rural Affairs has identified a key challenge in bioeconomy-related areas: the low value added per employee (€23,000-25,000 compared to the EU average of €61,000). Additionally, Estonia lacks a unified strategic approach, despite having more than 20 different bioeconomy-related strategies across various sectors. This fragmentation hinders the country's ability to fully utilise existing land, forest, and water resources or support effective and environmentally friendly production and biomass use. In light of this untapped potential, the Estonian government has developed a Circular Bioeconomy Roadmap. This was a joint initiative between the Ministries of Regional Affairs and Agriculture and Climate, as well as various stakeholders, including researchers, entrepreneurs and interest groups. The roadmap has short-term (2023-27) and long-term (until 2035) implementation goals. The analysis of the innovation landscape in Estonia's bioeconomy reveals several persistent barriers that hinder technological advancement and limit competitive advantage in international markets.

6.8.6.1 *Process Efficiency and Resource Utilisation*

The efficient utilisation of biological resources remains a major challenge for Estonia's bioeconomy. Significant volumes of agricultural products, including cereals and raw milk, as well as biodegradable waste streams, residues and by-products, are not fully valorised. This underutilisation represents a substantial loss of economic value and limits the overall efficiency of resource use. A key factor behind this challenge is the limited capacity of existing processing systems to maximise value

[1133] Jaakma, U., Opportunities and challenges in implementing a bio-economy strategy – university perspective. Estonian University of Life Sciences - Euragri [online].

[1134] Klimaministeerium & Regionaal-Ja Põllumajandusministeerium - Estonian Circular Bioeconomy Roadmap 2030 (ringbiomajanduse teekaart)

[1135] Estonian Agriculture and Fisheries Strategy 2030 | Ministry of Regional Affairs and Agriculture, Republic of Estonia

[1136] Pikner, T., et al., Methodological framework for developing a regional circular bioeconomy roadmap, Tallinn University in cooperation with Ministry of Regional Affairs and Agriculture (2023) ISBN 978-9949-29-766-5

[1137] Production and deploying of high purity lignin and affordable platform chemicals through wood-based sugars | SWEETWOODS | Projekt | Fact Sheet | H2020 | CORDIS | European Commission

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extraction from available biomass. The Estonian Ministry of Rural Affairs and Agriculture has highlighted that both bioresources and production potential are not being used efficiently, indicating persistent gaps in resource utilisation across multiple sectors. The geographical distribution of biomass resources further complicates efficient utilisation. Biomass is often dispersed across different regions, resulting in low feedstock densities and high transportation costs. These logistical constraints can reduce processing efficiency and affect the economic viability of biomass valorisation projects. In addition, many biomass conversion technologies require significant energy inputs. High energy consumption, combined with limited implementation of waste heat recovery, water reuse and nutrient recycling systems, reduces overall resource efficiency. Strengthening process integration and circular resource management practices would improve both environmental and economic performance across Estonia's bioeconomy value chains.

6.8.6.2 Scalability and Industrial Deployment

A major challenge for Estonia's bioeconomy is the transition from research, pilot and demonstration activities to commercially viable industrial-scale operations. Although several innovative technological solutions have been developed, many remain at intermediate levels of technological readiness and face difficulties progressing towards full market deployment. The Circular Bioeconomy Roadmap identifies the need for dedicated financing mechanisms to support start-ups and spin-offs originating from research institutions as they move from proof-of-concept to industrial implementation. This highlights existing weaknesses within Estonia's innovation pipeline and the challenges associated with scaling promising technologies. Industrial deployment is also constrained by insufficient processing infrastructure. Existing facilities are often unable to support large-scale implementation of innovative bioeconomy solutions, creating a need for additional investments in biorefineries, demonstration plants and specialised processing capacity. Regional differences add further complexity. Variations in biomass availability, infrastructure quality and socioeconomic conditions mean that technological solutions cannot always be replicated uniformly across the country. Consequently, successful industrial deployment requires region-specific investment strategies and implementation models. Without stronger financing mechanisms, demonstration opportunities and infrastructure investments, many bioeconomy innovations risk remaining at pilot scale rather than achieving sustainable commercial operation.

6.8.6.3 Product Development and Differentiation

Enhancing value creation from Estonia's abundant biological resources remains a strategic priority for the bioeconomy sector. Although the country possesses extensive forest resources and substantial biomass availability, a significant proportion of current production is concentrated in relatively low-value applications, limiting the economic benefits generated from available feedstocks. The forestry sector illustrates this challenge particularly clearly. The wood value chain remains largely focused on mechanical processing, which restricts opportunities to develop higher-value products such as biochemicals, biomaterials and specialised bio-based ingredients. Similar limitations can be observed in agricultural value chains, where the development of diversified bio-based products remains comparatively limited. Advanced biorefinery concepts, including technologies such as the Sunburst™ fractionation process applied within the SWEETWOODS project, demonstrate the potential to convert biomass into higher-value outputs, including speciality chemicals and advanced biomaterials. These approaches can significantly increase economic value

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generation without requiring additional biomass extraction. At the same time, Estonia faces challenges in developing emerging sectors such as synthetic biotechnology, cellular agriculture, hydroponics and vertical farming. These fields offer important opportunities for product diversification, market differentiation and access to higher-value market segments but currently remain underdeveloped due to technological and investment constraints. Strengthening value-added production pathways and expanding the range of bio-based products will be essential for improving Estonia's competitiveness in European and international bioeconomy markets.

6.8.6.4 Process Innovation and Technology Development

The development of innovative bioeconomy technologies is constrained by limited R&D investment. Many companies lack the financial resources needed to undertake long-term innovation activities, reducing their capacity to develop, test and commercialise new technological solutions. The research ecosystem also faces structural challenges. Bioeconomy-related research capacities remain fragmented across institutions, with varying levels of expertise, infrastructure and research capability. As a result, scientific knowledge generation is not always effectively aligned with industrial needs and market opportunities. The development of advanced technological solutions is further hindered by limited demonstration opportunities and weak commercialisation pathways. These constraints are particularly evident in emerging fields such as synthetic biotechnology, cellular agriculture and advanced bioprocessing technologies, where market-ready applications remain relatively scarce. Knowledge transfer between universities, research institutes and industry remains another important challenge. Stronger collaboration mechanisms are needed to accelerate the transformation of scientific results into commercial products, industrial processes and business opportunities. Furthermore, Estonia faces a shortage of specialists with the interdisciplinary expertise required to connect biomass resources, biotechnology, engineering and market development. Addressing these human-capital gaps will be essential for strengthening innovation capacity and accelerating technology deployment across the bioeconomy sector.

6.8.6.5 Digital Transformation

The integration of digital technologies presents significant opportunities to enhance competitiveness, productivity and resource efficiency across Estonia's bioeconomy. Nevertheless, the adoption of advanced digital solutions remains uneven throughout the sector. The Circular Bioeconomy Roadmap identifies digital agriculture, precision farming, agridrone technologies, robotics and data-driven management systems as strategic priorities, highlighting the need to accelerate their deployment across agricultural and bio-based value chains. The limited use of digital tools constrains the ability of businesses to optimise resource use, improve operational decision-making and increase productivity. This challenge is particularly relevant in agriculture, forestry and biomass supply chains, where digital technologies could support more efficient resource management and improve the traceability of biological resources. Data infrastructure and analytical capabilities also represent important areas for improvement. Advanced data management systems are essential for precision agriculture, forestry management, biomass logistics and industrial process optimisation. However, the availability, integration and accessibility of relevant datasets remain insufficient to fully support digital transformation efforts. Within bio-based processing industries, greater adoption of automation, process monitoring systems, predictive analytics and advanced control technologies could substantially improve production efficiency, quality assurance and operational scalability. Current

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levels of implementation remain relatively low, limiting opportunities to increase competitiveness and technological performance. Digital transformation is further hindered by the absence of a centralised and easily accessible platform providing information on biomass availability, processing technologies, by-product utilisation pathways and pilot-scale technology performance. This fragmentation reduces transparency, slows knowledge transfer and makes it more difficult for businesses, investors and new market entrants to identify suitable technologies, partners and business opportunities. The development of open technology platforms, digital knowledge-sharing systems and integrated data infrastructures would strengthen innovation diffusion and support the continued growth of Estonia's bioeconomy ecosystem.

6.8.6.6 Circularity and Waste Management

Circularity is a core pillar of Estonia's Circular Bioeconomy Roadmap and is defined as the efficient, needs-based use of resources while maximising environmental, social and economic value throughout their lifecycle. Despite this strategic commitment, the implementation of circular bioeconomy principles remains limited in several sectors. The adoption of closed-loop production models, industrial symbiosis approaches and advanced resource recovery systems is still insufficient, reducing opportunities to retain materials and nutrients within the economy for longer periods. A key challenge is the limited deployment of technologies that enable the recovery and valorisation of secondary resource streams. Strengthening the capacity to convert agricultural, forestry and industrial by-products into valuable inputs for new processes would help reduce waste generation and increase overall system sustainability. Further progress will depend on the development of integrated biorefinery concepts and technologies that support biomass cascading, resource reuse and product life-cycle optimisation. Designing products and production systems with circularity principles in mind can improve material efficiency, reduce environmental impacts and generate additional economic value across bioeconomy value chains. In addition, stronger linkages between producers, processors and end-users will be required to facilitate the circulation of materials, by-products and recovered resources. Enhancing collaboration across value chains can support the transition from linear production models towards more resilient and resource-efficient circular bioeconomy systems.

6.8.6.7 Environmental Performance and Sustainability

Environmental sustainability is a fundamental objective of Estonia's bioeconomy strategy, which seeks to balance economic growth with climate goals, biodiversity conservation and long-term ecosystem resilience. The Circular Bioeconomy Roadmap identifies the bioeconomy as a key contributor to the green transition and highlights its potential to support decarbonisation and more sustainable patterns of resource use. Realising these ambitions requires the deployment of technologies and management approaches capable of minimising environmental impacts throughout bioeconomy value chains. In particular, there is a growing need for solutions that can reduce greenhouse-gas emissions, improve carbon management and strengthen climate-change mitigation efforts while maintaining economic competitiveness. A major challenge is ensuring that increased biomass production and utilisation do not adversely affect soil quality, biodiversity, water resources or ecosystem functioning. Addressing these risks requires more advanced environmental monitoring systems, robust sustainability assessment methodologies and adaptive management tools capable of supporting evidence-based decision-making. The roadmap explicitly highlights the importance of

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avoiding significant negative impacts on ecosystems. Consequently, the development of comprehensive sustainability monitoring and impact-assessment frameworks will be essential for evaluating environmental performance and ensuring responsible biomass utilisation across different sectors. Continued innovation in environmental monitoring, ecosystem assessment, sustainable land management and low-impact biomass processing technologies will therefore play a critical role in supporting the long-term sustainability and resilience of Estonia's bioeconomy.

6.8.6.8 Policies and Strategies Recommendations for Technological Advancement

In consideration of the aforementioned information, the following points should be prioritised by Estonia in order to address the technological challenges identified above:

- Full implementation of the Estonian Circular Bioeconomy Roadmap to improve coordination across sectors and reduce policy fragmentation.
- Increased investment in advanced biorefining technologies and higher-value biomass processing pathways.
- Development of specialised processing infrastructure and demonstration facilities capable of supporting technology scale-up.
- Strengthening technology transfer mechanisms between universities, research institutions and industry.
- Expanding financing instruments for start-ups and spin-offs seeking to progress from lower to higher TRLs.
- Accelerating the adoption of digital agriculture, precision forestry, automation systems and advanced data infrastructures.
- Supporting regional bioeconomy strategies adapted to local biomass resources and territorial needs.
- Promoting knowledge-sharing platforms and collaborative networks involving researchers, businesses, local authorities and NGOs.
- Encouraging advanced biotechnology applications, including synthetic biology, cellular agriculture and novel bioprocesses.
- Improving sustainability monitoring systems to support biodiversity protection, resource efficiency and climate objectives.

By implementing these measures, Estonia can improve resource utilisation, increase value addition, strengthen innovation capacity and consolidate its position as a leading bioeconomy development centre in Europe.

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6.8.7 *France*[1138] [1139] 1140 [1141] [1142] [1143] [1144] [1145]

France's bioeconomy strategy, which is anchored in its 2017 national policy and regional initiatives such as Hauts-de-France's Bioeconomy Plan, faces persistent technological challenges despite advancements in biorefining and soil preservation technologies.

6.8.7.1 *Process Efficiency and Resource Utilisation*

The ambitious targets set to improve the efficiency and sustainability of agricultural resource use are proving difficult to implement. Amongst these objectives are a 50% reduction in pesticide usage by 2025 and the enhancement of nitrogen management practices. These objectives are critical for reducing environmental impact and improving soil health. However, progress is being hindered by the limited adoption of key innovations, such as anaerobic digestion (methanisation) and the integration of bio-based alternatives into mainstream agricultural practices. Despite significant biomass availability and strong agricultural production systems, biomass resources remain underutilised in several regions. The effective conversion of biomass into high-value products continues to face technical and organisational barriers, limiting the overall efficiency of resource utilisation. Improvements in biomass processing pathways, nutrient management systems and resource recovery technologies will be necessary to maximise the value generated from France's biological resources.

6.8.7.2 *Scalability and Industrial Deployment*

A significant challenge for the French bioeconomy is the transition from pilot-scale innovation to large-scale industrial implementation. While the Hauts-de-France region has demonstrated leadership in promoting bio-based construction materials and biomass valorisation, many innovations continue to face difficulties in scaling up to commercial operations. Pilot projects such as BBoBB's biosourced road materials illustrate the challenges associated with bridging the gap

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between laboratory development and market deployment. The successful commercialisation of these technologies requires stronger multi-actor partnerships and more effective collaboration between research organisations, industrial stakeholders and regional authorities. Furthermore, the SCALE-UP initiative has identified a lack of industrial symbiosis networks capable of supporting circular bio-based systems. In particular, the aggregation of biomass feedstocks for biorefineries remains insufficiently developed, limiting opportunities for industrial-scale deployment and reducing the competitiveness of emerging bio-based value chains. Even where promising technologies exist, biomass valorisation pathways remain underdeveloped and industrial uptake remains slower than required to support France's bioeconomy ambitions.

6.8.7.3 Product Development and Differentiation

France has developed several promising bio-based value chains, particularly in the fields of bio-based construction materials and advanced biomass valorisation. However, significant opportunities remain to increase value creation through the development of higher-value bio-based products and advanced material applications. The experience of the Hauts-de-France region demonstrates the potential for innovative bio-based construction materials and alternative biomass-derived products. Nevertheless, many technologies remain at an early stage of commercialisation, limiting their contribution to economic growth and industrial competitiveness. Strengthening the development of differentiated bio-based materials, chemicals and industrial products capable of replacing fossil-based alternatives will be essential to maximise the value generated from available biomass resources and improve France's position within European and international bioeconomy markets.

6.8.7.4 Process Innovation and Technology Development

The ongoing fragmentation of France's R&D ecosystem represents a significant impediment to technological and scientific progress. Since 2018, efforts to restructure innovation clusters have inadvertently created coordination gaps between key institutions such as INRAE and Axelera, a French competitiveness cluster focused on chemistry and environmental technologies. This fragmentation has weakened opportunities for integrated innovation and reduced synergies that are critical for advancing bioeconomy technologies. While IFPEN (Institut Français du Pétrole–Énergies Nouvelles) has been actively developing advanced tools for soil carbon assessment and technologies aimed at optimising nutrient enrichment to support sustainable agriculture, the uptake of these innovations by industry has been constrained by bureaucratic impediments associated with access to EU funding. Evidence from the SCALE-UP project demonstrates that administrative barriers can delay implementation timelines and reduce incentives for industrial stakeholders to engage in collaborative R&D activities. Therefore, promising technologies often require longer periods to progress from research environments to commercial deployment. Strengthening cooperation between research centres, competitiveness clusters, regional authorities and industrial actors will be essential to accelerate innovation and improve technology transfer within the French bioeconomy.

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6.8.7.5 Digital Transformation

Although France's national precision agriculture plan supports research, innovation and training, digital integration remains uneven across the bioeconomy sector. Rural connectivity represents a particularly important constraint, with only 53% of agricultural areas having reliable broadband access. This limitation restricts the deployment of IoT-enabled smart irrigation systems, despite their potential to reduce water consumption by approximately 25%. While initiatives such as Ekylibre's farm-management data platforms and Naio Technologies' agricultural robots demonstrate France's innovation capacity in digital agriculture, their broader deployment remains constrained by fragmented digital ecosystems and limited interoperability. Data interoperability also represents a major challenge. Approximately 72% of farmers continue to use incompatible software systems, restricting opportunities to implement predictive analytics, precision agriculture solutions and integrated farm-management approaches. Although the 2018–2020 Bioeconomy Action Plan emphasised the valorisation of non-food biomass, it did not establish interoperable data standards. As a result, digital integration across bioeconomy value chains has progressed more slowly than anticipated. Accelerating digital transformation will therefore require improvements in connectivity, data sharing, automation, interoperability and digital infrastructure across rural areas.

6.8.7.6 Circular and Waste Management

The development of circular bioeconomy systems in France continues to face structural challenges. According to the SCALE-UP initiative, industrial symbiosis networks remain insufficiently developed, particularly in relation to biomass aggregation and the efficient supply of feedstocks to biorefineries. Furthermore, circular production systems face increasing competition for biomass resources. Approximately 34% of agricultural residues are currently allocated to energy production, limiting their availability for higher-value material and biochemical applications. This creates tensions between competing biomass uses and reduces opportunities for cascading utilisation. Stronger integration of biomass producers, processors and end users, together with improvements in feedstock logistics and industrial symbiosis, will be necessary to support more efficient and circular bioeconomy systems.

6.8.7.7 Environmental Performance and Sustainability

Despite significant progress in developing sustainability-oriented technologies, important environmental trade-offs continue to be unresolved within the French bioeconomy. The coexistence of IFPEN’s soil carbon assessment tools and nutrient enrichment technologies with unaddressed biodiversity risks in intensive agricultural regions remains a significant concern. The sustainability criteria established under France’s 2017 bioeconomy strategy do not include sufficiently robust monitoring mechanisms for practices such as maize monoculture, which contributes to soil degradation in regions supplying approximately 60% of biorefinery feedstocks. The allocation of biomass resources also presents sustainability challenges. The diversion of 34% of agricultural residues towards energy production can reduce feedstock availability for higher-value and potentially more resource-efficient bio-based products. Although the national Bioeconomy Action Plan strongly supports agroecological approaches, it does not provide sufficiently robust metrics for assessing

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trade-offs between biomass utilisation and ecosystem preservation. This issue is particularly relevant in water-stressed areas, where balancing biomass production, ecosystem health and resource efficiency remains a significant long-term challenge.

6.8.7.8 Strategic Recommendations

France should prioritise the following measures in order to address the technological challenges that have been identified above:

- Strengthening coordination between research organisations, competitiveness clusters and industrial stakeholders to reduce fragmentation across the innovation ecosystem.
- Accelerating pilot-scale deployment and industrial implementation through dedicated public-private financing mechanisms.
- Expanding industrial symbiosis networks and feedstock aggregation systems to support the scale-up of circular bio-based value chains.
- Increasing the adoption of anaerobic digestion, bio-based alternatives and resource-efficient agricultural practices.
- Expanding broadband and 5G coverage across rural and agricultural areas, including the planned rollout in more than 30 French agro-valleys by 2027.
- Providing financial incentives for interoperable farm management systems and data-sharing platforms.
- Developing harmonised sustainability assessment frameworks that integrate biodiversity, soil health and ecosystem impacts.
- Implementing standardised sustainability metrics supported by real-time environmental monitoring tools.

The implementation of these measures by France has the potential to enhance innovation capacity, optimise resource efficiency, expedite industrial deployment, and augment the long-term sustainability of its bioeconomy.

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6.8.8 Greece[1146] [1147] [1148] [1149] [1150] [1151] [1152] [1153] [1154] [1155] [1156] [1157] [1158] [1159] [1160]

The bioeconomy of Greece is confronted with numerous technological challenges that impede the scalability, automation, and sustainability of bio-based industries. Despite the existence of robust academic research in the domains of biotechnology, bioenergy, and circular economy applications, Greece encounters significant challenges in translating innovation into industrial-scale production. The primary technological barriers encompass process efficiency constraints, scalability limitations, gaps in product development, slow digital transformation, circularity challenges, and environmental sustainability concerns. It is imperative that these challenges are addressed to ensure that Greece maintains its competitiveness within the European bioeconomy landscape and aligns with the objectives of the EU Green Deal and Horizon Europe.

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6.8.8.1 Process Efficiency and Resource Utilisation

The efficiency of bio-based production in Greece is not yet optimal, largely due to high energy consumption, outdated processing methods and limited technological optimisation. Many biorefineries and biomass processing facilities operate on a batch-based production model, which often results in low yields and high operational costs. In particular, the generation of bioenergy from agricultural residues is currently inefficient due to three main factors. Firstly, the high moisture content of the residues means that the energy yield is low. Secondly, the logistics of transportation are not optimised, which results in high costs for the end user. Thirdly, there is a lack of pre-treatment facilities, which hinders the process even further. For instance, in Western Macedonia, the utilisation of agricultural residues for energy generation has not yet reached its full potential due to suboptimal combustion technologies, low feedstock collection efficiency, and limited infrastructure for biomass logistics. Additionally, Greece lacks multi-step biomass valorisation systems, meaning that waste streams from bioconversion processes are often discarded rather than re-used for further bio-based product development. Investments in cutting-edge bioconversion techniques are essential for enhancing process efficiency. These include thermochemical conversion, enzymatic hydrolysis and microbial fermentation, which offer high yields while utilising minimal energy. Furthermore, the integration of cascading biomass uses strategies, where one feedstock is converted into multiple high-value products, could significantly improve the efficiency and profitability of bio-based production.

6.8.8.2 Scalability Limitations and Industrial Deployment

One of the most significant challenges currently being faced by Greece's bioeconomy is the limited scalability of bio-based innovations. Many bioeconomy-related R&D projects remain at the laboratory or pilot-scale level, with only a few successfully reaching commercial production. The absence of large-scale biorefineries and bioprocessing facilities hinders Greece's competitiveness with major European bioeconomy hubs such as Germany, the Netherlands, and Finland. For instance, Greece lacks the required infrastructure for large-scale biofuel and bioplastic production, resulting in over-reliance on fossil-based imports despite the availability of abundant biomass resources. In the context of potential investment in Western Macedonia, medium-scale biomass power plants have been identified as a financially viable proposition, though investment in such projects is currently constrained by a lack of resources and logistical difficulties. In the absence of industrial-scale biorefining facilities, Greek bio-based industries will encounter significant challenges in their transition from research-driven pilot projects to market-ready commercial applications. Government incentives, public-private partnerships and targeted EU funding mechanisms are all essential to support the development of scalable bio-based industries.

6.8.8.3 Product Development and Differentiation

Greece's bioeconomy innovation pipeline is hindered by limitations in product development, commercialisation and market differentiation. While Greek research institutions have successfully developed a range of promising bio-based products, including bioplastics, bio-based fertilisers and biochemicals, many of these innovations remain at early stages of market deployment. Particularly

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noteworthy are bioplastics derived from olive industry residues, which have demonstrated significant technical potential in research and pilot-scale applications. However, the absence of large-scale production facilities and commercial manufacturing capacity limits the ability to bring these products to market. Similar challenges affect waste-based biofertilisers and animal-feed supplements produced from dairy-industry by-products, which continue to be manufactured at relatively small scales despite growing market demand. The limited availability of commercial-scale production facilities reduces opportunities to develop specialised bio-based product portfolios capable of competing with conventional alternatives. As a result, much of the value embedded within Greece's agricultural, agro-industrial and food-processing residues remains untapped. Strengthening product differentiation will therefore require greater emphasis on the development of value-added bio-based products, stronger support for commercialisation activities, and the creation of market incentives that encourage the uptake of sustainable alternatives. In addition, bio-based product branding, certification schemes and quality-assurance systems could help Greek companies improve market visibility, reinforce consumer confidence and strengthen competitiveness in European and international markets. Expanding the range of commercially available bio-based materials, fertilisers, biochemicals and other bio-based products will be critical for increasing value creation, diversifying revenue streams and improving the overall competitiveness of Greece's bioeconomy.

6.8.8.4 Process Innovation and Technology Development

Process innovation remains a significant challenge within the Greek bioeconomy. Although Greek universities and research institutions have demonstrated strong capabilities in biotechnology, bioenergy and circular bioeconomy applications, the transfer of research outputs into commercially viable technologies remains limited. Many innovations successfully demonstrated at laboratory or pilot scale fail to progress towards industrial implementation due to insufficient technology transfer mechanisms and weak collaboration between academia and industry. Several promising bio-based products, including bioplastics derived from olive industry residues, bio-based fertilisers and biochemical products, have demonstrated significant technical potential. However, the absence of dedicated demonstration facilities and large-scale validation platforms limits opportunities to test, optimise and commercialise these technologies under real operating conditions. The innovation ecosystem is further constrained by limited investment in pilot-scale biorefineries and demonstration plants. As a result, many bioeconomy-related technologies remain trapped at intermediate development stages, preventing their transition towards full-scale market deployment. Strengthening process innovation therefore requires targeted support for technology transfer, demonstration infrastructure, industrial piloting and collaborative innovation programmes linking research organisations, industrial stakeholders and public authorities. The development and deployment of advanced bioconversion technologies, including thermochemical conversion, enzymatic hydrolysis and microbial fermentation systems, will be particularly important for improving process performance, increasing biomass valorisation rates and supporting the production of higher-value bio-based products.

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6.8.8.5 *Digital Transformation*

Digitalisation and automation are vital for enhancing process efficiency and scalability in the bioeconomy, yet Greece is falling behind in adopting Industry 4.0 solutions for biorefining, biomass logistics and bio-based manufacturing. Many bioeconomy enterprises still rely on manual processes, resulting in high labour costs, inefficiencies and inconsistencies in production quality. Specifically, Greek biorefineries are characterised by a lack of automation in key areas such as feedstock processing, fermentation control, and downstream purification. This deficiency leads to suboptimal process optimisation. The application of AI-driven process control, blockchain-based biomass traceability, and IoT-enabled precision agriculture has the potential to enhance efficiency and reduce costs, yet these technologies are not being fully utilised in Greece. To compete in the European bioeconomy, Greece needs to invest in automation, AI-driven optimisation, and digital monitoring systems. These investments will improve bioprocess efficiency, reduce resource consumption, and enhance production scalability. Furthermore, training programmes for digital skills should be developed to enable bioeconomy professionals to adopt and implement smart manufacturing technologies.

6.8.8.6 *Circularity and Waste Valorisation*

Despite growing awareness of the principles of the circular economy, there remains a significant challenge in Greece regarding the effective valorisation of biomass waste and the implementation of closed-loop bioeconomy practices. Large volumes of agricultural and industrial waste streams remain underutilised, with low levels of recycling and upcycling in bio-based industries. For instance, Western Macedonia produces over 550,000 tons of agricultural residues annually, yet only a fraction of this is currently processed into bio-based energy or materials. The lack of advanced waste valorisation technologies, such as anaerobic digestion, pyrolysis, and biochemical extraction, hinders Greece's ability to fully utilise its biomass resources. To enhance circularity, Greece should consider investing in integrated biowaste valorisation systems, including composting facilities, biochar production units and nutrient recovery technologies. Furthermore, policy incentives for bio-based material recycling and upcycling are required to support closed-loop biomass utilisation.

6.8.8.7 *Environmental Performance and Sustainability*

Ensuring the environmental sustainability of bio-based industries is a major challenge, as many bioprocessing technologies have high energy and water consumption requirements. Greece lacks standardised sustainability metrics and LCA frameworks for evaluating the environmental impact of bio-based products, making it difficult to ensure eco-friendly production practices. Furthermore, the cultivation of biomass for bio-based applications can create land-use conflicts with food production, raising concerns over sustainable resource allocation. The absence of a national bioeconomy certification system also limits the ability of Greek companies to differentiate sustainable bio-based products in the market. To improve sustainability, Greece needs to set clear environmental guidelines, invest in green processing technologies, and implement bioeconomy-specific sustainability certification programmes. Additionally, the integration of renewable energy sources

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into bio-based production facilities can contribute to a reduction in carbon emissions and an enhancement in overall environmental performance.

6.8.8.8 Strategic Recommendations

To overcome Greece's technological barriers in the bioeconomy, Greece should prioritise:

- Modernising biorefineries and biomass-processing infrastructure through the deployment of multi-step biomass valorisation technologies.
- Establishing regional biomass hubs to improve feedstock collection, logistics and supply chain efficiency.
- Providing incentives for industrial-scale biorefineries and bio-based manufacturing facilities.
- Expanding targeted EU funding mechanisms that support the transition from pilot projects to commercial-scale production.
- Strengthening public-private partnerships to accelerate investment in bio-based industries.
- Supporting technology transfer and stronger collaboration between research organisations and industry.
- Accelerating digital transformation through the deployment of AI, IoT and blockchain solutions across biomass value chains.
- Implementing workforce-training programmes focused on digital skills and smart manufacturing technologies.
- Expanding investments in anaerobic digestion, biochemical extraction and nutrient recovery systems.
- Establishing a national bioeconomy sustainability certification framework for bio-based products.

By implementing these measures, Greece can strengthen industrial scalability, improve resource efficiency, accelerate technological innovation and reinforce its competitiveness within the European bioeconomy.

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6.8.9 Hungary[1161] [1162] [1163] [1164] [1165] [1166] [1167] [1168]

Hungary is increasingly interested in developing its bioeconomy sector as part of broader European sustainability initiatives. With significant biomass potential, a strong agricultural sector, and a strategic geographic position within Central and Eastern Europe, the country possesses substantial resources to establish a competitive bio-based economy. However, despite these advantages, Hungary continues to face challenges related to infrastructure development, innovation capacity, market integration, policy coherence and industrial deployment.

6.8.9.1 Process Efficiency and Resource Utilisation

Hungary's agricultural sector is well-developed, generating substantial quantities of biomass from crops such as wheat, maize and sunflower, as well as forestry residues. Furthermore, the country has significant untapped potential in alternative feedstocks, including oil crops, algae and lignocellulosic biomass. While there is plenty of biomass available, full utilisation is still limited by supply chain inefficiencies, land use restrictions and technological barriers. Feedstock mobilisation and logistics systems are not yet sufficiently optimised to ensure the efficient delivery of biomass to processing facilities, reducing overall resource efficiency. Improving biomass utilisation will require investments in advanced processing technologies, improved logistics systems and more efficient resource-management practices capable of converting available biological resources into higher-value products.

6.8.9.2 Scalability and Industrial Deployment

The Hungarian bioeconomy remains in a relatively early stage of industrial development. Although the country has established a number of biomass-processing facilities and biorefineries, large-scale production of high-value bio-based products remains limited. The expansion of industrial-scale bio-based production is constrained by high capital requirements, limited infrastructure availability and

[1161] Advancing Sustainable Circular Bioeconomy in Central and Eastern European countries: BIOEASTsUP | BIOEASTsUP | Project | Fact Sheet | H2020 | CORDIS | European Commission

[1162] Buday, Z., et al., National Bioeconomy Dossier: Hungary (2020) | Central European Leaders of Bioeconomy Network | CELEBIO

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[1165] Ministry of Rural Development. National Environmental Technology Innovation Strategy 2011-2020 | NETIS | Budapest, Hungary

[1166] National Clean Development Strategy 2020-2050 | Hungarian Ministry of Innovation and Technology

[1167] Juhász, A., Bioeconomy in Hungary: Opportunities and Challenges (2023) Ministry of Agriculture, Hungary.

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insufficient long-term market certainty. Many emerging bioeconomy initiatives encounter difficulties progressing from pilot-scale activities towards fully commercial operations. Furthermore, the absence of strong market incentives and long-term purchase agreements increases investment risks for bio-based businesses. Competition from established fossil-based industries and conventional agricultural value chains further complicates industrial deployment. Expanding industrial infrastructure, strengthening investment frameworks and improving market conditions will be essential for accelerating the scale-up of Hungary's bioeconomy.

6.8.9.3 Product Development and Differentiation

The development of high-value bio-based products remains a key challenge for Hungary. While the country possesses substantial biomass resources and strong scientific capabilities, market development for bio-based products remains relatively limited. High production costs continue to affect the competitiveness of many bio-based alternatives, while consumer awareness and demand remain comparatively low. These factors reduce incentives for companies to invest in product diversification and the development of specialised bio-based materials, chemicals and other value-added products. Strengthening product differentiation, increasing market visibility and supporting the development of innovative bio-based product portfolios will be essential for improving competitiveness and generating greater value from domestic biomass resources.

6.8.9.4 Process Innovation and Technology Development

Hungary benefits from a strong academic and research base, particularly in agricultural sciences, biotechnology and environmental technologies. However, the country's innovation ecosystem faces several structural barriers that limit the commercial impact of scientific research. Collaboration between academia and industry remains insufficient, hindering the transfer of knowledge and the conversion of research results into market-ready products and industrial solutions. These challenges are compounded by limited investment in bio-based research and innovation, as well as fragmented technology-transfer and commercialisation mechanisms, which slow the scale-up and market uptake of promising technologies. To strengthen innovation performance, Hungary would benefit from closer industry–research cooperation, enhanced incubation and acceleration programmes, and greater access to venture capital for bio-based start-ups and SMEs. The policy framework already recognises the strategic importance of innovation through instruments such as the Smart Specialisation Strategy (S3) 2021–2027, the National Environmental Technology Innovation Strategy (NETIS), and the Circular Biomass-Based Economy Strategic Concept Document. Nevertheless, stronger alignment between policy objectives, funding instruments and implementation mechanisms is needed to maximise their contribution to industrial innovation, technology deployment and the long-term competitiveness of Hungary's bioeconomy sector.

6.8.9.5 Digital Transformation

Digitalisation represents an important opportunity for improving productivity, efficiency and competitiveness within Hungary's bioeconomy. However, the current policy framework places limited emphasis on the digital transformation of biomass value chains and bio-based industries. The wider deployment of precision agriculture technologies, digital monitoring systems, automated biomass

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logistics, data-driven resource management and Industry 4.0 solutions could substantially improve the efficiency of biomass production and processing activities. Digital technologies could also strengthen traceability, supply-chain coordination, resource optimisation and process control across the bioeconomy sector. Achieving these benefits will require investments in digital infrastructure, digital skills and the adoption of advanced technologies by businesses throughout the value chain.

6.8.9.6 Circularity and Waste Management

The transition towards a circular bioeconomy remains an important priority for Hungary. The transition towards a circular bioeconomy remains a key priority for Hungary. The Circular Biomass-Based Economy Strategic Concept Document promotes the integration of circular economy principles into biomass utilisation and resource management, aiming to improve resource efficiency and maximise value generation from biological resources. However, implementation remains uneven across sectors and regions. One of the key challenges is the lack of infrastructure for waste management, recycling and biomass valorisation. Significant opportunities remain to increase the utilisation of agricultural residues, food-processing by-products and other secondary biomass streams. Stronger integration of circular economy principles into bioeconomy development could improve resource efficiency, reduce waste generation and create additional value from existing biological resources. Continued investment in waste-processing infrastructure, resource recovery technologies and integrated circular value chains will be essential to accelerate the transition towards a more circular and competitive bioeconomy in Hungary.

6.8.9.7 Environmental Performance and Sustainability

Hungary has made significant progress in incorporating sustainability objectives into national policy frameworks through initiatives such as the National Clean Development Strategy 2020–2050, the S3 2021–2027 and NETIS 2011-2020. These policies promote low-carbon development, environmental protection and resource efficiency as key pillars of the country's bioeconomy transition. Despite this progress, several environmental challenges continue to affect the sustainable expansion of the sector. Increased biomass utilisation may generate risks related to deforestation, soil degradation and pressure on ecosystem services if feedstock production and resource extraction are not managed responsibly. Water availability also represents a limiting factor for certain bio-based activities, particularly algae cultivation and some biofuel production pathways. In addition, shortcomings in waste-management and resource-recovery infrastructure reduce the environmental benefits that could be achieved through greater circularity and more efficient use of biological resources. While the strategic framework provides a clear direction, translating policy objectives into large-scale implementation remains challenging in areas such as sustainable biomass management, water stewardship and ecosystem protection. Strengthening environmental monitoring systems, improving resource-management practices and investing in circular infrastructure will be essential to ensure that Hungary's bioeconomy develops in a manner that is both economically competitive and environmentally sustainable over the long term.

6.8.9.8 Strategic Recommendations

With the purpose of addressing the challenges identified above, Hungary should prioritise:

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- Developing a cohesive national bioeconomy strategy that improves coordination across existing policy frameworks.
- Increasing investments in advanced biomass-processing facilities and industrial-scale bio-based production infrastructure.
- Improving biomass supply-chain management and feedstock logistics systems.
- Strengthening support for high-value bio-based product development and market creation.
- Expanding R&D funding for bioeconomy-related technologies.
- Enhancing collaboration between universities, research organisations and industrial stakeholders.
- Accelerating technology transfer and commercialisation mechanisms.
- Supporting the adoption of digital technologies, precision agriculture and Industry 4.0 solutions across biomass value chains.
- Expanding waste-management, recycling and biomass-valorisation infrastructure.
- Promoting sustainable biomass utilisation practices that minimise risks to soils, forests and water resources.

By implementing these measures, Hungary can strengthen its innovation ecosystem, improve resource efficiency, enhance industrial competitiveness and accelerate the transition towards a sustainable, competitive and resilient bioeconomy.

6.8.10 Italy[1169] [1170] [1171] [1172] [1173]

The obstacles and technological challenges currently being experienced by the Italian bioeconomy are chiefly a result of the limited availability of advanced technologies that are applicable and usable by the SMEs that constitute the plurality of the national production fabric. Many Italian companies, especially SMEs, lack the resources to adopt innovative bioeconomy technologies, such as those for biomass processing or producing bioproducts. Given the predominantly rural nature of the territory and the consequent logistical difficulties, it will be necessary in the near future to consider replicable rural biorefinery models that can be implemented by small companies. The absence of pilot and demonstration plants also hinders large-scale experimentation and the transition from research to industrial production. Another technological challenge lies in the management of raw

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materials: it will be essential to identify technologies applicable to different input materials, given the variety of biological solutions available in the area.

6.8.10.1 Process Efficiency and Resource Utilisation

Energy costs are a key factor in the efficiency of bioeconomic production processes, and optimising processes and combining them with other existing activities can play a key role in the economic sustainability of the development of the bioeconomy. Many industrial processes in the Italian bioeconomy are inefficient in terms of energy and raw materials usage, which limits the competitiveness of companies. Furthermore, the transition to more sustainable technologies requires significant investments in innovation to upgrade existing infrastructures, improve the management of material flows and adopt advanced solutions such as digitalisation and automation.

6.8.10.2 Scalability Issues and Industrial Deployment

The challenges associated with scalability primarily pertain to the complexity of transferring innovative solutions from research and development to large-scale production. In particular, SMEs, which dominate the Italian industrial landscape, face significant challenges in implementing advanced technologies that can guarantee both sustainability and competitiveness. The lack of capital to invest in industrial plants and the high risk associated with adopting new technologies are preventing companies from expanding their production processes. Fragmentation of the sector and the lack of an integrated supply chain between research, production and distribution also limit the possibility of optimising processes on an industrial scale. The absence of adequate infrastructure, including facilities for the valorisation of biological waste and the large-scale production of bioproducts, represents a significant hurdle. Finally, the challenges associated with accessing foreign markets and the lack of standardisation in organic products are key factors that hinder the international expansion of the Italian bioeconomy.

6.8.10.3 Product Development and Differentiation

The development and differentiation of products in the Italian bioeconomy is mainly linked to the need to adapt technologies and processes to the specific characteristics of biological materials, which can vary according to factors such as origin, seasonality and production conditions. This complicates the development of standardised yet innovative products, particularly for SMEs, which often lack the resources to invest in large-scale R&D initiatives. Furthermore, the bioeconomy requires a strong commitment to product differentiation, both in functional and aesthetic terms, to meet the needs of different markets. However, innovation in this sector is hampered by a still insufficient level of collaboration between universities, research centres and industry, which slows down access to new scientific and technological knowledge. The complexity of the global market and increasing international competition pose an additional challenge in the creation of unique and distinctive products that can be successfully established both nationally and internationally.

6.8.10.4 Process Innovation and Technology Development

The Italian bioeconomy is facing challenges due to a lack of adequate infrastructure and pilot and demonstration plants, which are hindering the adoption of advanced technologies. Additionally, there

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is a reluctance amongst SMEs to invest in digitalisation and automation, which is affecting the progress of the bioeconomy. Moreover, the significant initial costs associated with adopting new technologies, coupled with the complexity of transferring technology to small businesses, impede the translation of innovations into large-scale industrial applications. The standardisation of processes is complicated by the variability of biological materials and the slowness of technology transfer, which further complicates the efficiency of production processes and prevents a rapid expansion of innovative solutions in the sector. Process innovation should not only focus on industrial models, but also on SMEs.

6.8.10.5 Digital Transformation

The digital transition in Italy has been promoted through several policy instruments, particularly the National Recovery and Resilience Plan (PNRR), which provides funding to accelerate the adoption of digital technologies across industrial value chains. However, the uptake of these opportunities remains uneven, especially amongst SMEs that continue to face financial and skills-related barriers. However, it is struggling to be adopted by small and medium-sized enterprises, which make up a significant part of the sector. These companies are finding it difficult to seize the opportunity offered by new advanced technologies such as the Internet of Things (IoT), artificial intelligence and big data. Many companies lack the necessary digital skills and the financial resources to invest in advanced technological infrastructure, which slows down the integration of digitalisation into production processes. The digital transition is also being hindered by a lack of cultural acceptance of change. This is making it difficult for many companies to adopt a more technologically advanced and sustainable business model.

6.8.10.6 Circularity and Waste Management

Italy has adopted various policies for the management and reuse of waste, and in 2022 published a specific 'National Waste Management Programme' by the Ministry for the Environment and Energy Safety (MASE). The Programme, with a time horizon of six years, starting from the European reference framework, is designed to guide public policies and incentivise private initiatives for the development of a sustainable and circular economy, for the benefit of society and the quality of the environment. The Programme is one of the strategic and implementing pillars of the National Strategy for the Circular Economy, in conjunction with the National Waste Prevention Programme and other policy instruments. The critical issues that emerged from the PNGR (Programma Nazionale per la Gestione dei Rifiuti) principally concern the inadequacy of management infrastructures, with deficiencies in recycling and treatment systems, especially for organic and hazardous waste. The fragmentation of the system, marked by substantial disparities between Italian regions, and the complexity of transitioning towards a circular economy, serve to impede the efficacy of policies designed for the recovery and reuse of materials. Finally, disparities in regional policies and the lack of uniform implementation of regulations further complicate the achievement of national and European objectives for sustainable waste management.

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6.8.10.7 Environmental Performance and Sustainability

The technological barriers affecting the Italian bioeconomy have important implications for environmental performance and long-term sustainability. Although the bioeconomy has significant potential to reduce reliance on fossil-based resources and support circular resource use, many bio-based production technologies do not yet consistently deliver optimal environmental performance throughout their life cycle. Several production processes remain characterised by high energy consumption and limited resource recovery, reducing their overall environmental and economic efficiency. In many cases, available technologies do not fully valorise biomass streams, resulting in the loss of potentially valuable materials and nutrients. Furthermore, the absence of advanced monitoring and assessment systems makes it difficult to accurately evaluate environmental impacts across different stages of production. This limits the ability of companies to measure, compare and continuously improve sustainability performance. Technologies for biological waste management, emissions reduction and resource recovery are still evolving and often face challenges related to scalability, economic viability and wider industrial deployment. As a result, the implementation of sustainable practices remains uneven across regions and sectors. Italy has adopted important policy instruments aimed at improving environmental sustainability, including the PNGR and the National Strategy for the Circular Economy. However, further investment in advanced environmental technologies, sustainability monitoring systems and resource-efficient production processes will be necessary to translate these strategic objectives into large-scale industrial practice. The wider adoption of green technologies, improved biomass valorisation systems and harmonised sustainability assessment frameworks will be essential for strengthening the environmental performance and resilience of Italy's bioeconomy.

6.8.10.8 Strategic Recommendations

To address the Italian technological challenges identified above, Italy should prioritise:

- Supporting the deployment of replicable rural biorefinery models adapted to the needs of SMEs and geographically dispersed biomass resources.
- Expanding pilot and demonstration facilities capable of accelerating technology validation and industrial scale-up.
- Increasing investments in energy-efficient processing technologies, automation and advanced biomass valorisation systems.
- Strengthening collaboration between universities, research centres, innovation hubs and industrial stakeholders to improve technology transfer.
- Accelerating the uptake of digital technologies supported through the PNRR, including IoT, artificial intelligence and data-driven process optimisation.
- Supporting SMEs in adopting advanced technologies through targeted financial instruments and technical assistance programmes.
- Enhancing waste-management and recycling infrastructure in accordance with PNGR and the National Strategy for the Circular Economy.

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- Developing technologies capable of processing diverse biomass feedstocks and improving the flexibility of bio-based production systems.
- Promoting harmonised sustainability monitoring systems that evaluate environmental performance throughout produce life cycles.
- Encouraging the adoption of circular economy practices that maximise resource recovery and minimise waste generation.

By implementing these measures, Italy can strengthen industrial competitiveness, improve resource efficiency, accelerate innovation uptake and enhance the long-term sustainability of its bioeconomy.

6.8.11 Latvia[1174] [1175] [1176] [1177] [1178] [1179] [1180] [1181] [1182]

Latvia possesses significant bioeconomy potential based on its extensive forest resources, agricultural production, emerging biotechnology capabilities and growing innovation ecosystem. However, despite notable progress in several areas, the country continues to face a range of technological, infrastructural and organisational challenges that limit the efficient utilisation of biomass resources, the scale-up of innovative solutions and the transition towards a fully circular and sustainable bioeconomy.

6.8.11.1 Process Efficiency and Resource Utilisation

Improving process efficiency and resource utilisation remains an important challenge for Latvia's bioeconomy. Although the country benefits from substantial biomass resources, there is still considerable scope to improve the efficiency of production systems, optimise resource use and increase value creation from available feedstocks. To support these objectives, the Latvian Industry

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Development Confederation (LIAK) was established as a collaboration platform bringing together five industrial associations representing the electrical engineering and electronics, mechanical engineering and metalworking, information and communication technology, chemicals and pharmaceuticals, and wood-processing sectors. LIAK aims to strengthen cooperation between industrial actors, promote efficient production processes, stimulate innovation and improve technological competitiveness. Nevertheless, many sectors continue to face challenges related to the optimisation of production processes, resource efficiency and the deployment of advanced technologies capable of increasing productivity while reducing material and energy consumption. Continued technological upgrading and stronger integration between industrial sectors will be required to improve overall process performance across Latvia's bioeconomy.

6.8.11.2 Scalability Issues and Industrial Deployment

The scalability of bioeconomy activities remains constrained by structural and logistical challenges affecting both agriculture and forestry. Following the restoration of independence, the transition from collective farming to private ownership resulted in a highly fragmented agricultural landscape. Although Latvia's accession to the European Union contributed to agricultural modernisation, export growth and farm consolidation, many smaller farms continue to face difficulties achieving the scale required for competitive participation in bio-based value chains. As a result, cooperation mechanisms between producers remain essential for improving biomass mobilisation and market integration. In the forestry sector, ownership fragmentation and infrastructure limitations continue to affect the efficient utilisation of forest resources. Latvia's forest-road network currently reaches approximately 13.1 thousand kilometres, equivalent to 0.75 km per 100 hectares of forest, which remains below the recommended level of 1 km per 100 hectares. Consequently, an estimated additional 4,300 km of forest roads would be required to support efficient forest management and biomass mobilisation. These logistical constraints limit the scalability of biomass supply chains and can hinder the deployment of larger-scale bioeconomy initiatives dependent on reliable feedstock availability.

6.8.11.3 Product Development and Differentiation

Latvia benefits from a dynamic and rapidly evolving innovation ecosystem that supports the development of new bio-based products and technologies. The country has gained international recognition for its start-up environment and was identified as one of the world's most start-up-friendly countries. By the end of 2024, Latvia hosted more than 500 start-ups, with almost one-quarter founded by international entrepreneurs. Government support measures, including start-up visas, tax incentives and start-up-friendly stock-option policies, have contributed to the growth of innovative companies and increased foreign investment. This favourable business environment creates opportunities for the development and commercialisation of bio-based products, services and technologies. Despite these strengths, challenges remain in transforming innovative concepts into commercially successful bio-based products. Many start-ups and emerging companies still face difficulties accessing industrial-scale production capacity, securing long-term financing and competing in international markets. Strengthening pathways from innovation to commercialisation will therefore be essential for increasing product differentiation and expanding Latvia's bioeconomy portfolio.

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6.8.11.4 Process Innovation and Technology Development

Latvia has established one of the most advanced bioeconomy innovation ecosystems within the Baltic region. The country's rapidly expanding biorefinery ecosystem brings together 22 collaborating organisations working to promote sustainable biomass utilisation, advanced biotechnologies and the production of higher-value bio-based products. Several innovative solutions have already reached commercial deployment. These include technologies capable of converting more than 90% of wood feedstock into functional biomaterials and biochemicals, an online biomass trading platform serving producers, traders and heat-supply companies, the production of biopolyols from renewable feedstocks such as rapeseed oil and tall oil, and microalgae-based wastewater treatment systems that generate biomass suitable for multiple applications. Despite these achievements, further efforts are required to accelerate technology transfer, expand pilot and demonstration capacities and support the broader commercialisation of innovative solutions. Continued investment in advanced biorefining, industrial biotechnology and biomass valorisation will be essential for maintaining Latvia's competitive position within the European bioeconomy.

6.8.11.5 Digital Transformation

Latvia has made significant progress in digitalisation in recent years. In 2023, notable advances were achieved in the digitalisation of SMEs, increased cloud adoption and the development of digital public services for businesses. However, several important barriers remain. Only 45.3% of the population possesses at least basic digital skills, below the EU average of 55.6%. Additionally, ICT specialists represent only 4.4% of total employment, and almost 60% of enterprises report difficulties recruiting suitably qualified ICT professionals. Connectivity also remains a challenge, particularly regarding the rollout of gigabit infrastructure and 5G networks. These limitations affect the widespread adoption of digital technologies and reduce opportunities to deploy advanced solutions such as digital supply-chain management, process automation, precision resource management and data-driven industrial optimisation. Addressing skills shortages and strengthening digital infrastructure will be critical for accelerating digital transformation across Latvia's bioeconomy value chains.

6.8.11.6 Circularity and Waste Management

Latvia continues to advance its transition towards a more circular economy. Since 2022, the country has been implementing measures included within its Circular Economy Action Plan with the objective of improving resource efficiency and reducing environmental impacts. The Action Plan establishes targets to increase material circularity to 11% and improve resource productivity to €1.55 per kilogram by 2027. At the same time, national waste-prevention programmes include objectives aimed at reducing waste generation, minimising hazardous substances and improving environmental performance. Nevertheless, important challenges remain. Latvia's material footprint increased from 12 tonnes per capita in 2010 to 20 tonnes per capita in 2023, indicating growing resource demand. Although municipal waste generation remains below the European average, further investments in circular business models, resource recovery systems and waste valorisation infrastructure will be necessary to improve circularity performance and maximise biomass utilisation.

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6.8.11.7 Environmental Performance and Sustainability

Environmental sustainability remains a key element of Latvia's bioeconomy transition. However, the country continues to face several environmental challenges associated with energy use, transport systems and resource management. The European Union has expressed concerns regarding the absence of a comprehensive strategy for the phase-out of fossil fuels. Latvia continues to lag behind many EU Member States in electric vehicle adoption, partly due to limited charging infrastructure and affordability constraints. At the same time, Latvia has a long-standing commitment to environmental protection. Significant efforts have been undertaken to address historical pollution associated with industrial activities and military infrastructure during the Soviet period, resulting in substantial improvements in air, water and soil quality. Recent measures, including the introduction of a tax on plastic bags and broader environmental initiatives supported through EU policies, demonstrate continued commitment to improving environmental performance. Nevertheless, further progress will require investments in low-carbon technologies, sustainable transport systems, resource-efficient industries and comprehensive climate-transition strategies.

6.8.11.8 Strategic Recommendations

To address the technological challenges identified here, Latvia should prioritise the following actions:

- Improving biomass mobilisation infrastructure, including the expansion of forest-road networks and logistics systems supporting agricultural and forestry feedstocks.
- Strengthening technology-transfer mechanisms and accelerating the commercialisation of innovations emerging from Latvia’s growing bioeconomy ecosystem.
- Supporting the wider deployment of advanced biorefinery technologies capable of producing high-value biomaterials, biochemicals and bio-based products.
- Expanding pilot and demonstration facilities that enable industrial validation and scale-up of innovative bioeconomy technologies.
- Strengthening collaboration through organisations such as the Latvian Industry Development Confederation (LIAK) and existing bioeconomy innovation networks.
- Addressing shortages of digital skills and ICT professionals through targeted education and workforce-development programmes.
- Accelerating the deployment of digital technologies across bioeconomy value chains, including data-driven resource management, automation and digital platforms.
- Strengthening implementation of the Circular Economy Action Plan to improve material circularity and resource productivity.
- Supporting sustainable forest management and expanding biomass logistics infrastructure to ensure efficient resource mobilisation.
- Developing a comprehensive strategy supporting low-carbon technologies and fossil-fuel substitution within the bioeconomy sector.

By implementing these measures, Latvia can strengthen innovation capacity, improve biomass utilisation, accelerate industrial deployment and enhance the long-term sustainability of its bioeconomy.

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6.8.12 Lithuania[1183]

Lithuania has a well-developed agricultural and forestry sector, providing a strong foundation for bioeconomy development. The country possesses significant biomass resources and favourable conditions for the expansion of bio-based industries. Nevertheless, several technological and structural barriers continue to limit the sector's competitiveness, including insufficient processing capacity, limited industrial deployment of innovative technologies, weak market development and an underdeveloped innovation ecosystem. In addition, Lithuania continues to export a considerable proportion of its biomass resources rather than processing them into higher-value bio-based products, reducing opportunities for value creation within the domestic economy.

6.8.12.1 Process Efficiency and Resource Utilisation

Lithuania benefits from abundant agricultural and forestry resources, yet the utilisation of biomass remains suboptimal. A significant proportion of available feedstocks is exported or used in lower-value applications rather than being converted into advanced bio-based products. This limits resource efficiency and reduces the potential economic value generated from biomass resources. The lack of sufficient domestic processing capacity further constrains the efficient utilisation of biomass. Expanding resource-efficient conversion technologies and strengthening domestic biomass-processing capabilities would improve value creation and support a more competitive bioeconomy.

6.8.12.2 Scalability and Industrial Deployment

One of the main barriers to the Lithuanian bioeconomy is the limited availability of industrial-scale processing infrastructure. The country lacks a sufficiently developed network of biorefineries capable of converting biomass into a broad range of high-value products at commercial scale. As a result, many bioeconomy-related opportunities remain underexploited, and innovations often face difficulties progressing from development stages to industrial deployment. Strengthening industrial infrastructure and supporting large-scale processing facilities will be essential for improving competitiveness and reducing dependence on biomass exports.

6.8.12.3 Product Development and Differentiation

Lithuania faces challenges in developing and commercialising differentiated bio-based products. The limited domestic processing capacity restricts opportunities to diversify production and move towards higher-value applications. Competition from more technologically advanced bioeconomy sectors in Western Europe places additional pressure on Lithuanian producers. Strengthening product

[1183] Vitunskienė, V., and Aleksandravičienė, A., Executive summary of the strategic concept paper for bioeconomy: Lithuania (2023) BIOEASTsUP H2020 Project

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development capabilities and supporting the creation of specialised bio-based products will be important for enhancing market positioning and increasing value generation across the sector.

6.8.12.4 Process Innovation and Technology Development

The Lithuanian bioeconomy continues to face challenges in innovation and technology deployment. Research and innovation activities are not yet fully integrated with industrial needs, limiting the commercialisation of new technologies and bio-based solutions. Insufficient collaboration between research institutions and businesses slows knowledge transfer and reduces the ability of companies to adopt innovative production processes. Increasing support for research and development and strengthening technology-transfer mechanisms will be crucial for accelerating technological advancement and industrial innovation.

6.8.12.5 Digital Transformation

Digital technologies have the potential to improve efficiency, traceability and resource management across Lithuania's bioeconomy value chains. However, the integration of advanced digital solutions within bio-based industries remains limited. Greater adoption of digital tools, automation systems and data-driven management approaches could help improve productivity, optimise biomass supply chains and strengthen the competitiveness of Lithuanian bio-based industries.

6.8.12.6 Circularity and Waste Management

Lithuania possesses significant opportunities to strengthen circular biomass utilisation through the improved processing of agricultural and forestry resources. However, current biomass flows are not always utilised according to circular economy principles, with substantial value often lost through raw material exports and limited domestic valorisation. The development of integrated supply chains, biomass-processing networks and circular business models would improve resource efficiency and support the transition towards a more circular bioeconomy.

6.8.12.7 Environmental Performance and Sustainability

The development of a stronger domestic bioeconomy could contribute to improved environmental performance by increasing resource efficiency and reducing dependence on fossil-based products. However, achieving these benefits requires sustainable biomass management and the deployment of environmentally efficient processing technologies. In addition, Lithuania must ensure that future bioeconomy growth is supported by sustainability-oriented practices capable of balancing economic development with responsible resource use and long-term environmental protection.

6.8.12.8 Strategic Recommendations

To overcome the challenges identified above, Lithuania should prioritise:

- Developing and expanding domestic biorefinery infrastructure to process biomass locally and increase value creation.
- Encouraging investment in bio-based industries through targeted tax incentives, grants and subsidy schemes.

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- Strengthening research and development activities and increasing funding for bioeconomy-related innovation.
- Improving knowledge transfer mechanisms and collaboration between universities, research organisations and industry.
- Supporting the commercialisation of innovative bio-based products and technologies.
- Creating bioeconomy clusters and integrated supply-chain networks to improve efficiency and reduce production costs.
- Promoting digitalisation, automation and advanced resource-management systems across bioeconomy value chains.
- Reducing dependence on biomass exports by increasing domestic processing and higher-value biomass utilisation.
- Supporting circular economy approaches that maximise resource efficiency and biomass valorisation.
- Strengthening Lithuania's technological competitiveness within the European bioeconomy landscape.

By implementing these measures, Lithuania can improve resource utilisation, strengthen innovation capacity, increase industrial competitiveness and reduce its dependence on raw-material exports while creating greater value from domestic biomass resources.

6.8.13 Malta[1184] [1185] [1186]

Malta's bioeconomy is in its formative stages and is closely linked to the country's broader circular economy and sustainability agendas. The island's unique spatial, economic and demographic characteristics create a distinct set of technological and systemic challenges affecting innovation, efficiency, scalability, digitalisation and sustainability. Despite progress through various circular economy initiatives and investments in waste management infrastructure, Malta continues to face constraints related to limited resources, restricted economies of scale and a fragmented innovation ecosystem.

6.8.13.1 Process Efficiency and Resource Utilisation

The efficient utilisation of biological resources remains a challenge due to Malta's limited natural resource base, high population density and restricted land availability. The country's reliance on imported materials further limits opportunities for controlling product life cycles and maximising

[1184] Pace, L.A., Eco-innovation in Malta - Country Profile 2018-2019: Malta | Eco-Innovation Observatory. Retrieved from [online].

[1185] Circular Economy Country Profile 2024 - Malta | ETC-CE Report 2024/Malta | European Topic Centre – Circular economy and resource use | European Environment Agency

[1186] Strengthening EU Rural Ecosystems: MCAST's Contributions to Innovation Guide Project – Malta daily. Visited on 2025-05-08. Retrieved from [online].

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resource efficiency through domestic value chains. Although investments have been made in advanced facilities such as ECOHIVE for waste-to-energy and organic waste processing, overall resource-recovery capacity remains limited relative to national requirements. Improving process efficiency will require greater optimisation of resource recovery systems, enhanced waste valorisation pathways and wider deployment of technologies that maximise material and energy recovery from biological resources.

6.8.13.2 Scalability and Industrial Deployment

Malta's limited geographical size and high degree of urbanisation create significant barriers to industrial scalability. The construction of large-scale bio-based processing facilities is often economically unviable, limiting opportunities to achieve economies of scale comparable to those available in larger European countries. As a result, certain waste streams must be exported for treatment or further processing. While investments in infrastructure have improved national capabilities, the development of large industrial bioeconomy facilities remains constrained by spatial limitations, market size and feedstock availability. Future deployment strategies will therefore need to focus on modular, decentralised and highly efficient bio-based production systems adapted to local conditions.

6.8.13.3 Product Development and Differentiation

The development of innovative bio-based products is constrained by the limited R&D capacity of many Maltese enterprises, particularly microenterprises and SMEs that dominate the national economy. Most companies lack the technical expertise, financial resources and market scale necessary to develop new products or commercialise innovative solutions. Furthermore, Malta's reliance on imported materials reduces opportunities to influence product design, material selection and end-of-life management, creating additional barriers to the development of differentiated circular and bio-based products. Strengthening product innovation will require targeted support mechanisms, improved access to research expertise and stronger links between innovation actors and market stakeholders.

6.8.13.4 Process Innovation and Technology Development

Malta faces significant challenges in process innovation due to limited research and development capacity, fragmented innovation networks and weak knowledge-transfer systems. Although examples such as MCAST's participation in rural innovation ecosystems demonstrate the value of collaboration between academia, industry, government and civil society, these interactions remain insufficiently institutionalised. Many businesses, particularly SMEs, lack the capacity to develop or adopt advanced bioeconomy technologies. As a result, innovation activities often remain fragmented and disconnected from industrial deployment. Strengthening research-industry collaboration, increasing investment in applied research and supporting technology-transfer mechanisms will be essential to accelerate innovation within the Maltese bioeconomy.

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6.8.13.5 Digital Transformation

The adoption of digital technologies within Malta's bioeconomy remains slower than in many other EU Member States. Although awareness of the benefits of digitalisation is increasing, uptake remains limited, particularly amongst SMEs and businesses operating in traditional sectors such as agriculture, fisheries and waste management. The lack of digital infrastructure, digital skills and specialised expertise restricts the implementation of automation systems, precision technologies and data-driven management approaches. Malta also lacks comprehensive national frameworks for monitoring bioeconomy and circular-economy indicators, limiting opportunities to optimise operations through data-based decision making. Improving digital infrastructure, strengthening workforce capabilities and expanding digital monitoring systems will be critical to improving productivity and competitiveness across bioeconomy value chains.

6.8.13.6 Circularity and Waste Management

Malta has made progress in advancing circular economy principles through initiatives such as the Beverage Container Refund Scheme and investments in waste-processing infrastructure. However, significant challenges remain in achieving higher levels of circularity and resource recovery. Limited domestic processing capacity, spatial constraints and high dependence on imported goods restrict the development of fully circular material flows. In addition, the absence of comprehensive monitoring systems limits the ability to evaluate progress and identify opportunities for improvement. Strengthening circular economy implementation will require improved waste valorisation technologies, enhanced recycling systems and stronger integration of circular principles into product and process design.

6.8.13.7 Environmental Performance and Sustainability

Environmental sustainability remains a major challenge for Malta due to high levels of urbanisation, limited natural resources and continued dependence on imported products and fossil fuels. These factors place pressure on natural capital and complicate efforts to develop resilient bio-based systems. The integration of sustainability considerations into product and process design remains relatively limited, while policy frameworks and enforcement mechanisms are still evolving. Achieving long-term sustainability objectives will require stronger regulatory incentives, improved environmental monitoring and greater adoption of green technologies across economic sectors. Additional efforts will also be needed to strengthen environmental education, support sustainable consumer behaviour and ensure that future bioeconomy development contributes to broader climate and sustainability objectives.

6.8.13.8 Strategic Recommendations

To address the technological and systemic challenges identified above, Malta should prioritise:

- Increasing investment in bioeconomy-related R&D activities, particularly for SMEs and microenterprises.
- Strengthening collaboration between academia, industry, government and civil society through formalised innovation networks and knowledge-transfer mechanisms.

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- Supporting the deployment of modular and decentralised bio-based processing systems adapted to Malta's spatial constraints.
- Expanding resource-recovery and waste-valorisation infrastructure to improve biomass utilisation and circularity.
- Accelerating the adoption of digital technologies, automation systems and data-driven management approaches across bioeconomy sectors.
- Developing comprehensive monitoring frameworks for circular economy and bioeconomy indicators to support evidence-based decision making.
- Improving digital and green skills through targeted education, training and workforce-development programmes.
- Strengthening policy incentives and regulatory frameworks that encourage eco-innovation and sustainable business models.
- Supporting sustainable product design and circular value chains that reduce dependence on imported materials.
- Promoting the wider adoption of green technologies and low-carbon solutions across the economy.

By implementing these measures, Malta can strengthen innovation capacity, improve resource efficiency, accelerate digital transformation and support the sustainable development of a resilient and competitive bioeconomy.

6.8.14 Poland[1187] [1188]

Poland benefits from substantial availability of underutilised biomass resources originating from agriculture, livestock production, forestry, the food industry and organic municipal waste streams. The country also possesses significant scientific expertise and research capabilities. However, despite this strong resource base, Poland remains less developed than many neighbouring countries in terms of industrial bioeconomy deployment. Key barriers include an uncertain regulatory environment, low innovation adoption rates, limited industrialisation of research outcomes, weak cross-sectoral collaboration, insufficient scaling infrastructure and a lack of mature business models capable of supporting long-term bioeconomy growth.

6.8.14.1 Process Efficiency and Resource Utilisation

The efficient utilisation of available biomass resources remains one of the main challenges affecting the Polish bioeconomy. Although large volumes of agricultural, forestry, livestock and food-

[1187] Mapping Poland's bio-based potential | Country-Report-Poland-2023 | Bio-based Industries Consortium (BIC)

[1188] Kránitz, L., and Kunya, Z., Executive summary of the strategic concept paper for bioeconomy: Polonia (2023) BIOEASTsUP H2020 Project

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processing biomass are available, resource utilisation is often suboptimal, limiting value generation and economic returns. The identification of the most promising end uses for available feedstocks is essential to maximise resource efficiency and support viable bio-based value chains. Particular attention must be paid to improving biomass pre-treatment technologies, conversion efficiency and feedstock selection to reduce production costs and increase competitiveness. Current challenges are compounded by relatively high energy costs and low rates of innovation adoption, which affect the economic performance of biomass-processing activities. Greater deployment of low-energy conversion technologies and improved resource-management practices could significantly improve process efficiency and profitability.

6.8.14.2 Scalability and Industrial Deployment

The transition from research and development activities to large-scale industrial deployment remains a major challenge for Poland. Investors require robust business models capable of demonstrating technological feasibility, economic sustainability and attractive returns on investment before committing significant resources to bioeconomy projects. At present, the country lacks sufficient demonstration facilities, proof-of-concept installations and industrial-scale infrastructure capable of validating and commercialising innovative technologies across different TRLs. This slows the progression of innovations from laboratory environments to commercial production. The development of demonstration plants, pilot facilities and industrial-scale processing infrastructure will therefore be essential to support technology validation, de-risk investments and facilitate industrial scale-up. Dedicated incentives can play a critical role in reducing the high level of risk perceived by investors during the early stages of bioeconomy projects and can support the transition from pilot activities to commercial deployment.

6.8.14.3 Product Development and Differentiation

Poland has significant opportunities to create higher-value bio-based products from its diverse biomass resources. Feedstocks derived from agriculture, livestock production, forestry, the food industry and organic municipal waste streams could support the development of a broad portfolio of food and non-food applications. However, the country continues to face difficulties in generating sufficient added value from these resources. Many bio-based products struggle to compete with conventional alternatives due to production costs, limited market awareness and insufficient differentiation strategies. Expanding the development of higher-value products, improving market positioning and identifying commercially attractive applications for domestic biomass resources will be essential to strengthening the competitiveness of the Polish bioeconomy.

6.8.14.4 Process Innovation and Technology Development

Although Poland possesses strong scientific capabilities and recognised research centres, the industrial uptake of research results remains limited. Technology transfer mechanisms are often insufficient to facilitate the transition from applied research to market-ready innovation. A key challenge is the weak interaction between the different sectors involved in emerging bioeconomy value chains, including primary production, industry and services. These gaps reduce opportunities for collaborative innovation and hinder the industrialisation of promising technologies. Innovation

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intermediaries, including bioeconomy cluster-management organisations, can play an important role in bridging the gap between academia and industry. These organisations can facilitate the industrialisation and scaling-up of validated processes while establishing interlinkages across sectors involved in emerging bioeconomy value chains. Strengthening these organisations and supporting collaborative innovation programmes would accelerate technology transfer, process validation and the commercialisation of innovative bio-based solutions.

6.8.14.5 Digital Transformation

The transformation of Poland's bioeconomy also depends on the wider adoption of advanced technologies capable of improving productivity, reducing production costs and enhancing resource efficiency. Digital technologies, automation systems and data-driven resource-management tools could support more efficient biomass utilisation, logistics optimisation and industrial process control. However, the relatively low level of innovation adoption observed across parts of the agricultural and industrial sectors limits the deployment of these technologies. Accelerating digitalisation, particularly within biomass supply chains and processing industries, would contribute significantly to increasing competitiveness and improving overall system performance.

6.8.14.6 Circularity and Waste Management

Poland possesses significant opportunities to strengthen circular bioeconomy models through the valorisation of agricultural residues, livestock by-products, forestry biomass, food-industry side streams and the organic fraction of municipal solid waste. Utilising these resources more effectively could reduce waste generation, improve resource productivity and increase value creation throughout bioeconomy value chains. However, stronger interconnections between sectors are required to enable cascading biomass use and create integrated circular systems. The development of collaborative cross-sectoral initiatives and joint ventures would support a more efficient utilisation of biomass resources and facilitate the creation of circular business models. Additional opportunities exist in the development of biomass sources for biogas and biomethane production, as well as products and by-products originating from inland aquaculture.

6.8.14.7 Environmental Performance and Sustainability

The long-term sustainability of the Polish bioeconomy will depend on its capacity to generate higher-value products while reducing environmental impacts and improving resource efficiency. Current challenges include the relatively low productivity of parts of the agricultural sector and the need to ensure that biomass utilisation pathways remain economically viable and environmentally sustainable. The development of cost-effective technologies capable of processing domestic biomass resources efficiently will be essential for maintaining competitiveness while supporting sustainability objectives. Strengthening resource efficiency, reducing dependence on external value chains and promoting sustainable biomass utilisation practices will play a crucial role in the future development of Poland's bioeconomy.

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6.8.14.8 Strategic Recommendations

To address the technological and structural challenges identified above, Poland should prioritise:

- Adopting a comprehensive national bioeconomy strategy with clear priorities, implementation mechanisms and dedicated financial resources.
- Strengthening the regulatory and incentive framework supporting bio-based industries and investments.
- Improving biomass pre-treatment, conversion and resource-efficiency technologies to reduce production costs and increase competitiveness.
- Expanding proof-of-concept facilities, pilot plants, demonstration infrastructure and industrial-scale production capacity across different TRLs.
- Increasing investment in research, innovation and technology-transfer activities to accelerate the commercialisation of bio-based solutions.
- Supporting bioeconomy cluster organisations and innovation intermediaries that strengthen collaboration between academia, industry and public authorities.
- Promoting cross-sectoral partnerships and integrated value chains linking agriculture, forestry, food industries, waste management and industrial processing sectors.
- Supporting the development of high-value bio-based products based on the most promising domestic biomass feedstocks.
- Accelerating the adoption of digital technologies, automation systems and data-driven resource-management tools across bioeconomy value chains.
- Raising awareness amongst businesses and investors regarding the economic opportunities associated with circular and bio-based business models.

By implementing these measures, Poland can strengthen innovation capacity, improve biomass utilisation, accelerate industrial deployment and enhance the competitiveness and sustainability of its bioeconomy.

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6.8.15 Portugal[1189] [1190] [1191] [1192] [1193] [1194]

Portugal remains a Moderate Innovator within the European Union, with innovation performance reaching approximately 83.5% of the EU average. National R&D expenditure has increased in recent years and reached approximately 1.70% of GDP in 2023, although it remains below the EU average of approximately 2.22% of GDP. While the country possesses recognised scientific capabilities and a growing network of innovation actors, several technological and structural barriers continue to limit the ability of the bioeconomy sector to transform research results into large-scale industrial and commercial applications.

6.8.15.1 Process Efficiency and Resource Utilisation

The relatively low industrial adoption of innovative technologies remains a constraint on process efficiency within the Portuguese bioeconomy. Although Portugal has developed significant scientific expertise in biotechnology and bio-based sectors, many innovations fail to reach operational deployment, limiting opportunities to improve resource efficiency and reduce production costs. The wider implementation of advanced bioprocesses, resource-efficient technologies and industrial optimisation measures is hindered by limited commercial uptake and insufficient investment from industry. As a result, scientific advances are not always translated into measurable improvements in industrial productivity, biomass utilisation efficiency and resource management.

6.8.15.2 Scalability and Industrial Deployment

One of the most significant technological challenges is the lack of pilot and demonstration facilities capable of bridging the gap between laboratory research and industrial deployment. Pilot plants and demonstration-scale facilities are essential for validating bio-based technologies under real operating conditions and supporting progression across different TRLs. Portugal currently lacks sufficient open-access infrastructure to support biotechnology scale-up and bio-refinery deployment.

[1189] Directorate-General for Research and Innovation. European Innovation Scoreboard 2024 | Country Profile Portugal | European Commission.

[1190] FCT/DGEEC.. Inquérito ao Potencial Científico e Tecnológico Nacional. Fundação para a Ciência e a Tecnologia (2023) | Direção-Geral de Estatísticas da Educação e Ciência.

[1191] Eurostat. (2023). Gross domestic expenditure on R&D (GERD) as % of GDP.

[1192] Directorate-General for Research and Innovation. Research and Innovation analysis in the European Semester 2020 Country Reports | Country Report Portugal 2020 | European Commission.

[1193] Mascarenhas C., et al., Analyzing technology transfer offices' influence for entrepreneurial universities in Portugal. Management Decision 57(12) 3473-3491. **https://doi.org/10.1108/MD-11-2018-1200**

[1194] Costa, H.R., and Cruz, K., A comprehensive analysis of Portuguese national and regional policy instruments for technology transfer offices. Information Society (2023).

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Consequently, many promising innovations enter a “valley of death” between research and commercialisation, where technologies are unable to secure the validation and optimisation required for market entry. The high costs associated with pilot-scale operations and demonstration activities further limit access for SMEs and innovative start-ups. Addressing these infrastructure deficiencies will be crucial for accelerating industrial deployment and attracting investment into the bioeconomy sector.

6.8.15.3 Product Development and Differentiation

Portugal faces challenges in converting scientific knowledge into commercially competitive products. Indicators such as patenting activity and high-technology exports remain below the EU average. Patent Cooperation Treaty (PCT) patent applications are estimated at approximately 55% of the EU per-capita average, while exports of medium- and high-technology products reach around 59% of the European average. These figures suggest that many innovations do not progress sufficiently far along development pathways to generate differentiated, market-ready products. Likewise, knowledge-intensive services exports remain relatively low, reaching approximately 38% of the EU average. Improving product development capabilities will require stronger commercialisation mechanisms, better access to scale-up infrastructure and stronger engagement of industry in innovation activities.

6.8.15.4 Process Innovation and Technology Development

Despite possessing a growing network of research organisations and innovation actors, Portugal's innovation ecosystem remains fragmented. The OECD has highlighted that the national research and innovation policy landscape is crowded and fragmented, reducing the efficiency of public investments and preventing the accumulation of critical mass in strategic technological domains. A persistent challenge concerns technology transfer and knowledge commercialisation. Although many universities have established Technology Transfer Offices (TTOs), these often operate with limited resources and insufficient funding for proof-of-concept activities, patenting processes and licensing support. Consequently, many innovations fail to progress towards levels of technological maturity suitable for industrial adoption. The country has nevertheless implemented several promising initiatives aimed at strengthening innovation capacity. A network of 35 Collaborative Laboratories (CoLABs) had been established by 2021, bringing together universities, research centres and businesses to address industry-driven challenges. The B2E (Blue Bioeconomy CoLAB), established in 2019, is a notable example focused on marine bioresources and blue bioeconomy innovation. In addition, RAIZ – Forest and Paper Research Institute, supported by The Navigator Company and academic partners, has become one of Portugal's leading bioeconomy research centres. RAIZ ranked amongst the top ten Portuguese institutions for international patent applications in 2024, recording 12 PCT applications and leading a forest-based bioeconomy R&D programme valued at approximately €14.6 million. Although these examples demonstrate the existence of strong innovation capacities, their impact remains largely concentrated in specific sectors. Achieving broader technology deployment will require stronger coordination mechanisms, increased support for innovation intermediaries and greater integration between academia and industry.

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6.8.15.5 Digital Transformation

Digital technologies represent an important opportunity for improving productivity, process optimisation and resource management across Portugal's bioeconomy value chains. However, innovation adoption rates remain relatively low across parts of the industrial sector, limiting the deployment of advanced digital tools. The wider integration of data-driven innovation systems, digital process monitoring, automation technologies and advanced analytics could support more efficient production systems and accelerate knowledge transfer between research institutions and businesses. However, these opportunities remain constrained by the broader weaknesses affecting innovation uptake and commercialisation.

6.8.15.6 Circularity and Waste Management

The transition towards a circular bioeconomy depends heavily on stronger innovation ecosystems and more effective valorisation of biological resources. However, fragmented research networks, weak industrial adoption and limited scale-up infrastructure reduce the capacity to develop integrated circular value chains. The development of demonstration facilities and improved industry-research collaboration would support the validation of technologies capable of transforming biological resources and waste streams into higher-value products. In this context, initiatives such as CoLABs and sector-focused research centres can contribute to the development of more integrated circular bioeconomy systems.

6.8.15.7 Environmental Performance and Sustainability

Portugal's bioeconomy has significant potential to contribute to sustainability objectives through the development of renewable biological resources, circular production systems and low-carbon technologies. However, realising these benefits depends on overcoming current weaknesses in innovation adoption and industrial deployment. The limited commercial uptake of bio-based innovations reduces the environmental benefits that could otherwise be achieved through wider use of sustainable technologies. Accelerating technology transfer, supporting industrial implementation and strengthening research-industry linkages will therefore be essential for ensuring that scientific advances contribute effectively to environmental and climate objectives.

6.8.15.8 Strategic Recommendations

To address the technological challenges identified above, Portugal should prioritise:

- Increasing investment in research and development activities to reduce the gap with the EU average and strengthen bioeconomy innovation capacity.
- Expanding pilot plants, demonstration facilities and industrial validation infrastructure to bridge the gap between research and commercial deployment.
- Strengthening technology-transfer mechanisms and increasing operational support for university Technology Transfer Offices (TTOs).
- Improving access to venture capital and other financing instruments that support bioeconomy start-ups, spin-offs and industrial scale-up activities.

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- Enhancing coordination across the innovation ecosystem through a coherent long-term national bioeconomy strategy.
- Reinforcing collaborative initiatives such as CoLABs and promoting stronger integration between academia, research organisations and industry.
- Supporting the wider deployment of advanced digital technologies, automation systems and data-driven production processes.
- Promoting the commercialisation of research outputs and the development of higher-value bio-based products.
- Strengthening innovation intermediaries capable of facilitating knowledge transfer and industrial uptake of emerging technologies.
- Building on successful models such as B2E and RAIZ to expand sector-specific innovation capacities across the bioeconomy.

By implementing these measures, Portugal can strengthen its innovation ecosystem, improve technology commercialisation, accelerate industrial deployment and enhance the competitiveness and sustainability of its bioeconomy.

6.8.16 Romania

Romania has significant potential to develop a strong bioeconomy due to its abundant agricultural and forestry resources. However, despite this resource base, the sector continues to face several structural and technological challenges, including high production costs, limited processing capacity, weak profitability, insufficient industrial deployment of innovative technologies and an underdeveloped research and innovation ecosystem. The country remains heavily dependent on the export of raw biomass instead of generating higher value through domestic processing and bio-based manufacturing.

6.8.16.1 Process Efficiency and Resource Utilisation

Romania possesses substantial agricultural and forestry biomass resources, providing a strong foundation for bioeconomy development. However, the utilisation of these resources remains inefficient, as a significant proportion of biomass is exported in raw or minimally processed form rather than being converted into higher-value products domestically. High production costs and limited resource-processing capabilities reduce the overall efficiency of biomass valorisation. Improving feedstock management, logistics systems and processing technologies will be essential to maximise value creation and strengthen the competitiveness of domestic bio-based value chains.

6.8.16.2 Scalability and Industrial Deployment

A major challenge for the Romanian bioeconomy is the lack of industrial-scale processing capacity. Investments in advanced biorefineries and large-scale bio-based production facilities remain limited, restricting the country's ability to convert biomass into higher-value products such as advanced biofuels, bio-based chemicals and biomaterials. The current shortage of processing infrastructure hinders the transition from biomass production to industrial bioeconomy development and limits

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opportunities for large-scale commercial deployment. Expanding industrial infrastructure and strengthening investment frameworks will be essential for supporting the scale-up of bio-based industries.

6.8.16.3 Product Development and Differentiation

Romania faces difficulties in developing diversified portfolios of high-value bio-based products. The predominance of biomass exports limits opportunities to generate greater added value within domestic value chains and restricts the development of differentiated products capable of competing in international markets. Greater emphasis on advanced bio-based chemicals, biomaterials and other innovative products would improve market positioning and increase economic returns from available biomass resources. Strengthening product-development capabilities will therefore be a key component of future bioeconomy growth.

6.8.16.4 Process Innovation and Technology Development

The Romanian bioeconomy continues to face challenges associated with a relatively underdeveloped research and innovation ecosystem. The current level of interaction between research organisations and industry remains insufficient to support the effective transfer and commercialisation of innovative technologies. Limited collaboration between academia and businesses reduces opportunities for technology adoption and slows the development of market-ready bioeconomy solutions. Strengthening technology-transfer mechanisms, increasing bioeconomy-related R&D investments and promoting collaborative innovation programmes will be critical for accelerating technological development.

6.8.16.5 Digital Transformation

Digital technologies offer significant opportunities to improve resource management, biomass logistics, industrial productivity and value-chain integration. However, the current level of technological modernisation within parts of Romania's bioeconomy remains relatively limited. Increasing the adoption of digital solutions, automation technologies and data-driven management systems could improve operational efficiency, reduce costs and strengthen the competitiveness of bio-based industries throughout the country.

6.8.16.6 Circularity and Waste Management

Romania possesses considerable opportunities to strengthen circular bioeconomy approaches through the valorisation of agricultural residues, forestry by-products and other organic waste streams. However, the limited availability of advanced processing infrastructure constrains the full utilisation of these resources. Improving biomass valorisation pathways and strengthening circular business models would increase resource efficiency, reduce waste generation and support the development of more integrated bioeconomy value chains.

6.8.16.7 Environmental Performance and Sustainability

The transition towards a stronger domestic bioeconomy has the potential to generate significant environmental benefits through more efficient use of renewable biological resources and reduced

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reliance on fossil-based materials. However, these benefits depend on the implementation of sustainable biomass-management practices and environmentally efficient processing technologies. Future development should therefore ensure that economic growth is accompanied by improvements in resource efficiency, sustainability performance and long-term environmental protection.

6.8.16.8 Strategic Recommendations

To address the technological and structural challenges identified above, Romania should prioritise:

- Investing in advanced biorefineries and expanding domestic biomass-processing infrastructure.
- Strengthening research, development and innovation activities related to the bioeconomy.
- Improving collaboration between universities, research organisations and industry to accelerate technology transfer.
- Supporting the development of higher-value bio-based products, including bio-based chemicals, biomaterials and advanced biofuels.
- Improving logistics systems and supply-chain integration to enhance biomass valorisation and reduce production costs.
- Introducing financial incentives and investment-support mechanisms that encourage greater private-sector participation.
- Promoting digitalisation, automation and advanced resource-management technologies across bioeconomy value chains.
- Supporting circular-economy approaches that maximise the utilisation of agricultural and forestry residues.
- Reducing dependence on raw biomass exports by increasing domestic processing and value creation.
- Establishing a comprehensive national bioeconomy strategy that provides clear priorities, incentives and long-term policy direction.

By implementing these measures, Romania can strengthen its innovation ecosystem, improve resource utilisation, accelerate industrial deployment and build a more competitive and sustainable bioeconomy.

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6.8.17 Slovakia[1195] [1196] [1197] [1198] [1199] [1200] [1201] [1202] [1203]

Slovakia is particularly rich in opportunities for the development of a viable bioeconomy based on its agricultural resources, extensive forest cover and by-products from food-production processes. However, despite the abundance of available biomass resources, including straw, manure, wood residues, grassland biomass and crops such as hemp and short-rotation coppice, the country continues to face significant technological barriers that limit the conversion of these feedstocks into higher-value and market-competitive products.

6.8.17.1 Process Efficiency and Resource Utilisation

Most bio-based technologies relevant to Slovakia, including anaerobic digestion, composting, torrefaction and hydrothermal carbonisation, continue to face challenges in achieving optimal conversion efficiencies when processing locally available biomass. One of the main constraints is the heterogeneous nature of feedstocks, particularly the differences in quality, composition and moisture content between biomass resources originating from lowland and mountainous regions. These variations complicate process optimisation, reduce conversion yields and increase operational costs. As a result, available biomass resources are not always utilised efficiently, limiting opportunities to maximise value creation from domestic feedstocks. Improving feedstock characterisation, process optimisation and resource-management systems will therefore be essential to increase biomass-conversion efficiency and improve the economic performance of bio-based value chains.

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6.8.17.2 Scalability and Industrial Integration

The transition from pilot-scale development to commercial deployment remains a major challenge for Slovakia's bioeconomy. Many technologies continue to operate at laboratory or pilot scale and have not yet reached TRLs 7–9 required for large-scale market deployment. The country lacks sufficient pilot-scale and demonstration facilities capable of validating technologies under real operating conditions. Furthermore, centralised bioprocessing systems continue to dominate the sector, reducing opportunities for the deployment of decentralised and modular processing solutions adapted to remote areas and small-scale producers. Industrial integration is further constrained by technical incompatibilities between emerging bio-based technologies and existing infrastructure within sectors such as food processing and forestry. Outdated equipment and insufficient incentives for retrofitting limit the adoption of innovative technologies and slow industrial scale-up.

6.8.17.3 Product Development and Differentiation

Many biomass-derived products currently produced in Slovakia remain concentrated in relatively low-value market segments. Examples include digestate, pellet fuels, compost and conventional biogas products. R&D activities focused on higher-value applications remain relatively limited, particularly in relation to feedstocks with significant untapped potential such as hemp, grape pomace and hop residues. Consequently, opportunities to produce advanced bioplastics, biochemicals, nutraceuticals and other high-value products are not yet being fully exploited. The limited availability of certification systems, branding strategies and product-differentiation mechanisms further reduces the competitiveness of Slovak bio-based products in both domestic and European markets. Expanding innovation activities linked to advanced bio-based products will be critical for increasing value creation and strengthening market position.

6.8.17.4 Process Innovation and Technology Development

A significant proportion of the bio-based technologies deployed in Slovakia are imported from abroad and are often not fully adapted to local biomass resources, climatic conditions or the requirements of small agricultural producers. The limited adaptation of technologies to regional conditions reduces process flexibility and constrains innovation in integrated multi-purpose systems capable of simultaneously delivering energy, material valorisation and nutrient recovery. In many cases, technology developers and equipment suppliers operate separately from end users, including farmers, foresters and food processors. This disconnect slows the development of technologies specifically tailored to Slovak biomass streams and limits opportunities for collaborative innovation. Strengthening interaction between technology developers, research institutions and end users will be essential for supporting locally adapted process innovation and increasing technology uptake.

6.8.17.5 Digital Transformation

The digital transformation of Slovakia's biomass value chains remains at an early stage of development. The adoption of smart monitoring systems, automation technologies, Internet of Things (IoT) solutions, blockchain-based traceability systems and digital process-control tools remains limited across much of the sector. Many rural stakeholders lack the digital infrastructure, technical capabilities and incentives required to adopt advanced technologies. As a result,

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opportunities to optimise biomass logistics, improve process monitoring and enhance supply-chain transparency remain underutilised. The limited interoperability between traditional agricultural and forestry machinery and emerging bio-based processing technologies further constrains digital transformation. Existing equipment is often difficult and costly to retrofit for integration with modern biomass-processing systems, particularly for on-farm pre-treatment operations such as shredding, compacting and pelletising. The limited availability of region-specific integration services and specialised technology providers further reduces the uptake of advanced technologies, particularly amongst small and medium-sized producers. Slovakia also lacks smart regional biomass logistics networks capable of aggregating, monitoring and delivering feedstocks from dispersed producers to processors. Furthermore, no national biomass-tracking system based on GIS or blockchain technologies is currently available. This limits feedstock traceability, reduces supply-chain transparency and increases investment risks for biomass-based ventures.

6.8.17.6 Circularity and Integration of Waste Management

The valorisation potential of side streams and by-products generated through bio-based processes remains largely underutilised. Valuable resources such as post-fermentation slurry, digestate and lignin-rich residues are not yet systematically integrated into circular bioeconomy systems. Similarly, the integration of municipal biowaste and food-sector residues into agricultural and industrial value chains remains limited due to a combination of technical, logistical and legislative barriers. Significant quantities of potentially valuable biomass, including market residues and kitchen waste, continue to be disposed of through landfill or incineration rather than being converted into useful products. Increasing processing capacity and strengthening circular-economy linkages between waste producers and biomass users would significantly improve resource utilisation and reduce environmental impacts.

6.8.17.7 Environmental Performance and Sustainability

Environmental performance remains constrained by the limited deployment of technologies designed to improve resource efficiency and reduce emissions. Many biomass-processing facilities are not equipped with advanced features such as waste-heat recovery systems, water-recycling systems or emissions-control technologies. The use of LCA methodologies and environmental-monitoring tools remains relatively limited, reducing the ability of stakeholders to measure, optimise and communicate environmental performance. Furthermore, the absence of LCA-based product labelling and eco-certification schemes can reduce the credibility and competitiveness of Slovak bio-based products, particularly within export markets. Greater use of environmental assessment tools, sustainability monitoring systems and resource-efficient technologies will therefore be essential to improve both environmental performance and market acceptance.

6.8.17.8 Strategic Recommendations

To address the technological challenges identified above, Slovakia should prioritise:

- Accelerating the deployment of locally adapted biomass-conversion technologies capable of processing heterogeneous feedstocks from agricultural, forestry and marginal areas.

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- Expanding pilot, demonstration and industrial-scale facilities to support technology validation and market deployment across TRL 7–9.
- Promoting modular and decentralised biomass-processing systems suitable for remote and smallholder applications.
- Supporting R&D activities focused on higher-value bio-based products, including bioplastics, biochemicals, nutraceuticals and advanced biomaterials.
- Strengthening collaboration between technology developers, farmers, forestry operators and industrial users to improve technology transfer and process adaptation.
- Expanding digital infrastructure and accelerating the adoption of IoT, smart monitoring systems, automation and blockchain-based traceability solutions.
- Developing national biomass-logistics platforms and feedstock-tracking systems to improve supply-chain transparency and resource mobilisation.
- Increasing the valorisation of biowaste, digestate, lignin-rich residues and other secondary biomass streams through circular-economy approaches.
- Promoting wider use of life-cycle assessment (LCA), environmental monitoring systems and eco-certification schemes.
- Supporting innovation clusters, advisory services and technical-support networks that facilitate technology uptake amongst SMEs and rural stakeholders.

By implementing these measures, Slovakia can improve resource efficiency, accelerate technology deployment, strengthen circular bioeconomy systems and increase the competitiveness of its bio-based sectors within the European bioeconomy.

6.8.18 Slovenia[1204] [1205] [1206] [1207] [1208] [1209]

Slovenia's bioeconomy faces multiple technological barriers that limit its capacity for innovation, scalability and sustainability. While the country possesses strong scientific capabilities and significant research potential in bio-based industries, insufficient industrial integration and weak technology-transfer mechanisms continue to slow the commercialisation of innovative solutions. Key

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challenges include process-efficiency constraints, scalability limitations, product-development barriers, process-innovation gaps, slow digital transformation, insufficient circularity and sustainability-related concerns. Addressing these bottlenecks will be essential for strengthening Slovenia's position within the European bioeconomy.

6.8.18.1 Process Efficiency and Resource Utilisation

The efficiency of bioconversion processes in Slovenia remains constrained by high energy and material costs, which reduce the competitiveness of bio-based production relative to fossil-based alternatives. Many bioeconomy enterprises continue to experience difficulties in reducing processing times and operational costs, limiting profitability and industrial attractiveness. In addition, the lack of integrated multi-step processing systems reduces opportunities to maximise resource utilisation. Most existing facilities focus on single-step biomass valorisation rather than cascading-use approaches capable of extracting multiple products and increasing value generation from the same feedstock. Improving bioconversion techniques and accelerating the adoption of low-energy, high-yield processing technologies will be essential for increasing resource efficiency and improving industrial competitiveness.

6.8.18.2 Scalability Issues and Industrial Deployment

A major challenge for Slovenia's bioeconomy is the limited transition of innovations from laboratory and pilot-scale environments to full industrial deployment. Many promising technologies remain trapped at intermediate stages of development and fail to reach commercial implementation. The lack of dedicated biorefining infrastructure further restricts Slovenia's ability to compete with more advanced bioeconomy hubs such as Germany and the Netherlands. In addition, batch-based production models continue to dominate, limiting opportunities to implement continuous processing systems capable of increasing productivity and reducing costs. Without targeted investments in industrial-scale facilities, demonstration infrastructure and technology-integration mechanisms, Slovenia will face difficulties in achieving large-scale deployment of bio-based innovations.

6.8.18.3 Product Development and Differentiation

The development of high-value bio-based products faces several challenges, including limited R&D funding, relatively high production costs and insufficient market differentiation. Although Slovenian research organisations have developed innovative bio-based materials and chemicals, many of these technologies fail to reach commercial markets due to barriers in commercialisation and industrial uptake. Existing bio-based products also face difficulties competing against established fossil-based alternatives, particularly when price competitiveness becomes a deciding factor. Strengthening industry-academia partnerships, expanding incentives for bio-based product adoption and increasing support for commercialisation activities will be necessary to accelerate the development of higher-value product portfolios.

6.8.18.4 Process Innovation and Technology Development

Slovenia must continue strengthening process innovation in order to develop cost-effective and sustainable industrial bioprocesses. However, technical due diligence and industrial validation

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remain insufficiently developed, contributing to low TRLs for many emerging bio-based solutions. Several biorefining technologies remain underdeveloped and have not yet achieved the maturity required for competitive industrial deployment. This limits opportunities to produce high-value bio-based products efficiently and at commercial scale. Addressing these limitations will require stronger support for research-driven process innovation, the establishment of testing and demonstration hubs and the provision of dedicated financing mechanisms that facilitate technology validation and scale-up.

6.8.18.5 Digital Transformation

The adoption of digital technologies across Slovenia's bioeconomy remains slower than required to fully exploit the benefits of automation, data-driven management and advanced industrial control systems. Many biorefining operations continue to rely on relatively low levels of process automation, resulting in higher labour costs and reduced operational efficiency. Advanced digital tools such as AI-based process control, predictive analytics, blockchain-enabled biomass traceability systems and Industry 4.0 solutions remain underutilised across much of the sector. Limited financial resources and technical capabilities also constrain the implementation of digital innovations. Accelerating digital transformation, particularly within the blue bioeconomy and marine biomass valorisation activities, could significantly improve competitiveness and operational performance.

6.8.18.6 Circularity and Waste Management

Although Slovenia has made notable progress in promoting circular economy principles, several challenges remain in relation to biomass valorisation and closed-loop resource utilisation. Many bio-based industries continue to underutilise biological resources and fail to maximise the value generated from side streams and biorefinery residues. As a result, opportunities for waste reuse, cascading biomass utilisation and higher-value applications remain unrealised. Addressing these shortcomings will require improved waste-valorisation technologies, stronger policy support for cascading biomass use and increased investment in biowaste recovery and resource-recovery systems.

6.8.18.7 Environmental Performance and Sustainability

Balancing environmental performance with techno-economic viability remains a significant challenge for Slovenia's bioeconomy. Many biorefining processes are characterised by relatively high energy and water requirements, creating pressure to improve sustainability performance without compromising economic competitiveness. The absence of standardised sustainability metrics and indicators limits the ability to accurately assess and compare the environmental impacts of bio-based products. Furthermore, Slovenia currently lacks a dedicated national bioeconomy certification framework, reducing transparency and limiting product differentiation within domestic and export markets. Strengthening eco-labelling systems, carbon-footprint assessments, sustainability reporting mechanisms and environmental monitoring tools will be essential for aligning the Slovenian bioeconomy with the objectives of the European Green Deal and broader sustainability goals.

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6.8.18.8 Strategic Recommendations

To address the technological challenges identified above, Slovenia should prioritise:

- Improving the efficiency of bioconversion processes through the adoption of low-energy, high-yield technologies and cascading biomass-utilisation approaches.
- Expanding pilot, demonstration and industrial-scale biorefining infrastructure to accelerate the transition from laboratory-scale innovation to commercial deployment.
- Supporting continuous processing technologies capable of increasing productivity and reducing operational costs.
- Strengthening collaboration between research institutions, universities and industry to improve technology transfer and commercialisation.
- Increasing support for the development of high-value bio-based materials, chemicals and specialty products.
- Establishing testing and demonstration hubs that facilitate validation and scale-up of technologies with low TRLs.
- Accelerating the adoption of Industry 4.0 technologies, including AI-based process control, automation systems, predictive analytics and blockchain-enabled biomass traceability.
- Strengthening circular bioeconomy practices through improved waste valorisation, cascading biomass use and biorefinery side-stream utilisation.
- Developing harmonised sustainability metrics, environmental monitoring systems and national bioeconomy certification mechanisms.
- Expanding eco-labelling, carbon-footprint assessment and sustainability-reporting frameworks to enhance market transparency and competitiveness.

By implementing these measures, Slovenia can improve industrial competitiveness, accelerate innovation uptake, strengthen circular resource utilisation and enhance the long-term sustainability of its bioeconomy.

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6.8.19 Spain[1210] [1211] [1212] [1213] [1214] [1215] [1216]

Spain's bioeconomy is a key component of the country's transition towards a more sustainable and circular economy. Spain also possesses unique characteristics that position it as a potential Mediterranean bioeconomy hub, including extensive agricultural production systems, significant forestry resources, a large coastline supporting blue bioeconomy activities, strong agri-food industries and a growing network of regional innovation ecosystems. However, several technological and structural barriers continue to limit the country's ability to fully realise this strategic potential. Supported by the National Comprehensive Bioeconomy Strategy (2015) and reinforced through regional initiatives such as Catalonia's Bioeconomy Strategy 2030 (EBC 2030) and Andalusia's Circular Bioeconomy Strategy, the sector generates approximately €75 billion annually across agriculture, forestry, fisheries, food systems and biotechnology. However, despite this strong resource base and institutional commitment, significant technological and structural barriers continue to limit innovation uptake, industrial deployment, digital integration and the large-scale commercialisation of bio-based solutions.

6.8.19.1 Process Efficiency and Resource Utilisation

Spain continues to face significant challenges in the efficient utilisation of biological resources. Large quantities of biomass remain underutilised, including approximately 61% of industrial biowaste and 17% of urban biowaste. In Asturias, only 12% of available biowaste originates from agri-food activities, illustrating the limited integration of biomass streams into higher-value applications. Mechanical processing remains dominant within forestry value chains, while more advanced biochemical conversion pathways remain relatively underdeveloped. This is particularly visible in Andalusia, where approximately 2.32 million tonnes of olive biomass are generated annually, yet less than 15% is currently valorised into high-value products such as bio-based chemicals.

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Resource-distribution patterns further reduce efficiency. In livestock-dominated regions such as Asturias, low biomass density increases logistics costs and reduces the viability of centralised biorefinery models. In addition, anaerobic digestion facilities operate at approximately 65% capacity compared with an EU average of 78%, highlighting opportunities for process optimisation and improved infrastructure utilisation. Improving feedstock valorisation, expanding advanced bioconversion technologies and optimising biomass logistics will be essential for increasing the efficiency and competitiveness of Spain's bioeconomy.

6.8.19.2 Scalability and Industrial Deployment

A major challenge affecting Spain's bioeconomy is the well-known "valley of death" between research and commercialisation. Although innovation activity is strong, many technologies fail to progress from pilot and demonstration phases towards industrial deployment. The European Circular Bioeconomy Fund (ECBF) has allocated significant financing to support scale-up activities. However, early-stage companies continue to face difficulties accessing funding, with fewer than 12% of beneficiaries corresponding to early-stage start-ups. Andalusia's experience with microalgae production illustrates these challenges: despite favourable climatic conditions, only two out of fifteen pilot projects developed between 2018 and 2023 successfully reached industrial scale. Regional disparities further complicate scaling efforts. While regions such as Catalonia have established ambitious bioeconomy deployment programmes, other regions continue to operate with limited infrastructure and weaker support frameworks. Catalonia's plan to establish fifteen regional biohubs by 2030 represents an important initiative, although only three were operational by 2024. Greater investment in demonstration facilities, distributed processing infrastructure and industrial symbiosis networks will be necessary to accelerate deployment and reduce regional disparities.

6.8.19.3 Product Development and Differentiation

Although Spain possesses a strong research base and extensive biomass resources, the commercialisation of innovative bio-based products remains constrained by fragmented innovation systems, insufficient private-sector investment and limited market uptake. New products often struggle to compete with fossil-based alternatives due to relatively high production costs and insufficient market differentiation. The absence of strong national mechanisms supporting adoption and commercialisation further limits the development of competitive bio-based product portfolios. Developing higher-value applications based on agricultural, forestry, marine and industrial biomass streams will be essential to improve market competitiveness and strengthen Spain's position within European bioeconomy value chains.

6.8.19.4 Process Innovation and Technology Development

Spain's innovation ecosystem faces persistent fragmentation and technology-transfer challenges. Although several regions have established advanced innovation programmes, coordination at the national level remains limited, leading to duplicated efforts and inefficiencies. Regional initiatives such as Catalonia's Bioeconomy Strategy 2030, BIOHUBCAT and Andalusia's Smart Specialisation Strategy for Sustainability (S4), together with its Circular Bioeconomy Action Plan for the Agri-food Value Chain 2025–2030, have promoted innovation and value-chain modernisation. However, low

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stakeholder engagement, fragmented research networks and weak national coordination continue to reduce their overall impact. Knowledge transfer between universities, technology centres and industry remains insufficient. The lack of interdisciplinary training programmes and limited private-sector R&D investment further constrain innovation uptake and technology commercialisation. In addition, Spain's National Comprehensive Bioeconomy Strategy (2015) has not evolved sufficiently to address emerging technologies such as synthetic biology, cellular agriculture, advanced biorefining and precision agriculture. Regulatory flexibility remains limited, restricting the validation and deployment of innovative technologies. Initiatives such as BIOHUBCAT and the Urban Sandbox of Valencia demonstrate the potential of regulatory sandboxes for emerging innovations. However, these initiatives remain largely regional and are not yet integrated into a coordinated national framework.

6.8.19.5 Digital Transformation

Digitalisation represents one of the most important opportunities for improving the performance of Spain's bioeconomy. However, significant barriers remain. Approximately 43% of farmers lack adequate digital skills, while only 53% of agricultural areas have reliable broadband connectivity. Although Spain's Digital Agenda aims to achieve widespread high-speed coverage, important gaps remain in rural regions. In Extremadura, for example, 5G penetration remains below 40%. These infrastructure and skills limitations reduce the adoption of precision agriculture technologies, including IoT-enabled irrigation systems that could significantly reduce water consumption in water-stressed areas. Cross-sectoral collaboration is also hindered by incompatible data architectures and the absence of national standards for data sharing. Many farm-management systems remain unable to exchange data efficiently, limiting opportunities for predictive analytics, automation and integrated value-chain management. Accelerating digital transformation will require investment in rural connectivity, digital skills, IoT deployment, AI-driven decision-support systems and interoperable data infrastructures.

6.8.19.6 Circularity and Waste Management

Despite progress in circular-economy policies, Spain continues to face significant challenges in biomass circularity and waste valorisation. Large quantities of agricultural, industrial and urban biowaste remain underutilised, while biomass-cascading approaches are not yet widely implemented. The absence of integrated industrial-symbiosis networks further limits opportunities to exchange by-products and maximise resource recovery. Regional initiatives such as Andalusia's Circular Bioeconomy Action Plan and Catalonia's bioeconomy programmes provide important examples of circular approaches. However, implementation remains uneven across the country. Expanding biomass-cascading systems, industrial symbiosis networks and advanced waste-valorisation technologies will be critical for achieving a fully circular bioeconomy.

6.8.19.7 Environmental Performance and Sustainability

Balancing biomass utilisation with biodiversity conservation remains one of Spain's most important sustainability challenges. Large-scale monoculture systems and intensified biomass extraction have contributed to habitat fragmentation and biodiversity loss in certain regions. For example, intensive

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olive cultivation across approximately 1.5 million hectares in Andalusia has been associated with significant declines in bird populations. At the same time, pressures associated with water abstraction, pesticide use and land-use intensification continue to affect ecosystems and pollinator populations. Spain also faces challenges associated with carbon management. Although pyrolysis-based biochar technologies show promise, pilot projects currently operate below the efficiencies achieved in leading Nordic countries. Likewise, cost-effective carbon capture and carbon-accounting solutions remain insufficiently deployed, particularly amongst SMEs. The lack of harmonised biodiversity metrics, environmental monitoring systems and carbon-accounting frameworks further limits the ability to assess and optimise sustainability performance. Strengthening eco-monitoring technologies, biodiversity-assessment tools, biochar deployment, carbon-accounting systems and climate-positive certification mechanisms will be critical to ensure that bioeconomy growth remains aligned with the objectives of the European Green Deal.

6.8.19.8 Strategic Recommendations

To address the technological and structural challenges identified above, Spain should prioritise:

- Updating the National Comprehensive Bioeconomy Strategy (2015) to address emerging technologies and evolving sustainability challenges.
- Increasing bioeconomy-related R&D investment and strengthening public-private partnerships.
- Establishing cross-regional technology-transfer platforms connecting national and regional innovation ecosystems.
- Expanding regulatory sandboxes for technologies such as synthetic biology, cellular agriculture and advanced biorefining.
- Accelerating deployment of demonstration plants, distributed processing systems and bio-based industrial infrastructure.
- Supporting advanced biomass-conversion technologies capable of increasing valorisation rates and reducing energy consumption.
- Improving rural connectivity through targeted broadband and 5G deployment programmes.
- Developing national standards for bioeconomy data interoperability and digital information exchange.
- Expanding precision-agriculture technologies, AI-based decision-support systems and IoT-enabled monitoring platforms.
- Promoting cascading biomass utilisation, industrial symbiosis networks and advanced waste-valorisation systems.
- Integrating biodiversity metrics, carbon-accounting systems and environmental monitoring tools into bioeconomy decision-making frameworks.
- Supporting the development of scalable biochar, carbon-capture and climate-positive bio-based technologies.

By implementing these measures, Spain can strengthen innovation capacity, reduce regional disparities, accelerate industrial deployment and improve resource efficiency. Leveraging its

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agricultural, forestry, marine and industrial biomass resources, together with stronger coordination across regional innovation ecosystems, Spain has the potential to establish itself as a leading Mediterranean hub for circular and sustainable bioeconomy innovation.

6.8.20 Sweden[1217] [1218] [1219] [1220] [1221] [1222] [1223]

Sweden is one of Europe's most advanced bioeconomy ecosystems, supported by a strong forestry sector, mature bio-based industries, advanced research capabilities and a long tradition of industrial innovation. However, despite its technological maturity, several barriers continue to limit the development of new bio-based value chains. The main challenges relate to the integration of emerging technologies into established industries, the scaling-up of novel biorefinery concepts, limited industrial absorptive capacity and the commercialisation of innovative products beyond pilot and demonstration stages.

6.8.20.1 Process Efficiency and Resource Utilisation

Sweden possesses highly efficient biomass-conversion systems resulting from more than a century of industrial development within the forestry, pulp and paper sectors. Modern biorefinery concepts allow several valuable product streams to be extracted simultaneously from the same biomass feedstock, maximising resource utilisation and value creation. However, emerging biorefinery initiatives still face challenges in optimising multiple value chains simultaneously while maintaining commercial viability. The technical challenge is no longer simply biomass conversion, but rather the economic optimisation of complex processing systems capable of generating several high-value products from the same feedstock. Further development of integrated biorefinery concepts and resource-efficient production systems will be important for increasing profitability and supporting new bio-based business models.

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6.8.20.2 Scalability Issues and Industrial Deployment

One of the main challenges facing Sweden's bioeconomy is the transition of emerging biorefinery technologies from pilot and demonstration phases to commercial deployment. The scalability of many biorefinery concepts depends heavily on the ratio between feedstock costs, product yields and the market value of final products. Projects integrated into existing pulp and paper infrastructures often face lower investment requirements because they can utilise existing industrial assets and side streams. In contrast, the development of entirely new production systems requires substantially higher capital investments and greater market certainty. Further barriers include limited industrial absorptive capacity and difficulties mobilising financial and human resources within established industries. These challenges continue to slow the deployment of innovative biorefinery solutions despite strong technological capabilities.

6.8.20.3 Product Development and Differentiation

The Swedish pulp, paper and sawmill industries have successfully developed numerous high-value bio-based products over recent decades. Nevertheless, newer bio-based materials, chemicals and innovative products continue to face commercialisation barriers. Many emerging products struggle with high production costs, limited market differentiation and strong competition from well-established fossil-based alternatives. As a result, technologies that perform successfully at demonstration scale often encounter difficulties entering larger markets. The wider deployment of bio-based products may require stronger market incentives, including policy measures that improve the competitiveness of renewable alternatives relative to fossil-based raw materials and products.

6.8.20.4 Process Innovation and Technology Development

Even though Sweden possesses strong innovation capabilities, the integration of new technologies into mature industrial sectors remains challenging. Existing production systems, organisational structures and investment priorities often favour incremental improvements to current operations rather than the deployment of disruptive technologies. Several key factors have been identified as important for increasing resource mobilisation and technology adoption within the pulp and paper sector. These include establishing loosely coupled divisions capable of supporting innovation activities, creating internal markets for new bioproducts, developing purchasing agreements with downstream users and investing in new managerial competencies related to emerging bioeconomy technologies. At the national level, studies have also highlighted weak industrial participation, insufficient collaboration across organisational boundaries and a lack of policy instruments specifically supporting market adoption and commercialisation beyond research and development activities.

6.8.20.5 Digital Transformation

Sweden is one of the most digitally advanced countries in Europe and has been a pioneer in the digitalisation of forestry and biomass management systems. Early adoption of Geographic Information Systems (GIS), Global Positioning Systems (GPS) and airborne laser scanning has significantly improved forest-resource monitoring and planning. Since 2009, national airborne laser-scanning programmes have contributed to the creation of highly detailed forest inventories. Another

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important development has been the standardisation of data collection from harvesting machines. Modern harvesters measure individual trees during operations, generating large volumes of data that can be integrated into forest-management systems. More recently, advances in artificial intelligence and increased data availability have enabled the use of AI-based tools for updating forest inventories, identifying environmental considerations, recommending forestry operations and predicting harvesting outcomes. These developments position Sweden amongst the leaders in digital forestry and data-driven biomass management.

6.8.20.6 Circularity and Waste Management

Despite its strong environmental reputation, Sweden continues to face important circularity challenges. The national circularity rate is approximately 3.4%, indicating that the vast majority of resources entering the economy originate from virgin material sources. The country's economy remains highly dependent on extractive industries, particularly forestry and mining, which generate substantial material flows and large quantities of waste. Mining waste alone contributes significantly to overall waste generation and has a major influence on national circularity indicators. Many extractive activities are in remote northern regions, where material recovery and recirculation are often economically challenging. Consequently, even substantial improvements in recycling and reuse rates in other sectors have limited influence on overall circularity performance. Nevertheless, Sweden's material footprint has improved, decreasing from 23 tonnes per capita in 2010 to 21 tonnes per capita in 2023, indicating gradual progress towards more efficient resource use.

6.8.20.7 Environmental Performance and Sustainability

Sweden demonstrates strong environmental performance, particularly within the forestry and pulp-and-paper sectors. In 2020, approximately 15.5 million hectares of productive forest land were certified under PEFC or FSC schemes, representing around 66% of the country's productive forest area. Significant environmental improvements have also been achieved in industrial operations. Since the late 1980s, emissions to air per tonne of paper produced have declined substantially due to reduced energy consumption, increased use of biofuels and improvements in emissions-control technologies. Wastewater treatment systems have also advanced considerably, incorporating sedimentation, biological treatment and chemical precipitation technologies. In addition, Swedish paper mills eliminated the use of elemental chlorine in bleaching processes during the 1990s, significantly reducing emissions of chlorinated compounds. Environmental investments remain substantial, with the pulp, paper and sawmill sectors investing between SEK 1.4 billion and SEK 2 billion annually in environmental protection measures.

6.8.20.8 Strategic Recommendations

To address the technological and structural challenges identified above, Sweden should prioritise:

- Strengthening industrial absorptive capacity to accelerate the adoption of emerging biorefinery technologies.
- Supporting the commercial deployment of technologies that have successfully completed pilot and demonstration phases.

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- Improving collaboration across industry, academia and public-sector organisations to facilitate knowledge exchange and technology transfer.
- Expanding policy instruments that support market uptake and commercialisation in addition to R&D activities.
- Encouraging investment in advanced biorefinery concepts integrated with existing pulp and paper infrastructures.
- Supporting the development of new managerial competencies and organisational models capable of managing disruptive innovation.
- Promoting market mechanisms that improve the competitiveness of bio-based products relative to fossil-based alternatives.
- Accelerating the deployment of circular-economy solutions capable of reducing dependence on virgin material extraction.
- Expanding the utilisation of digital technologies, AI-based analytics and advanced forestry data systems across bioeconomy value chains.
- Maintaining leadership in environmental sustainability through continued investment in certified forestry, clean industrial processes and resource-efficient production systems.

By implementing these measures, Sweden can strengthen its capacity to commercialise bioeconomy innovations, accelerate industrial deployment and consolidate its position as one of Europe's leading bioeconomy and biorefinery innovation ecosystems.

6.8.21 UK[1224]

The United Kingdom possesses one of Europe's strongest research and innovation ecosystems for bio-based industries, supported by leading universities, advanced engineering biology capabilities and specialised innovation centres. The country's bioeconomy strategy emphasises the use of renewable feedstocks and the valorisation of waste streams in order to reduce dependence on fossil resources and support sustainable industrial development. Initiatives such as the £14 million Sustainable Bio-based Materials and Manufacture (SusBioMM) programme demonstrate the UK's commitment to developing innovative biomanufacturing solutions based on non-food biomass resources, including agricultural residues and municipal waste. Despite these strengths, several technological, commercial and systemic barriers continue to limit the transition from research excellence to large-scale industrial deployment.

[1224]OECD. The Digitalisation of Science, Technology and Innovation: Key Developments and Policies (2020). OECD Publishing. Paris. https://doi.org/10.1787/b9e4a2c0-en

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6.8.21.1 Process Efficiency and Resource Utilisation

A major challenge affecting the UK bioeconomy is the efficient utilisation of heterogeneous biomass feedstocks. Many bio-based production pathways depend on non-food biomass sources, including agricultural residues and municipal waste streams, which exhibit significant variability in composition and quality. This heterogeneity creates difficulties for biomass pre-treatment and the generation of consistent feedstocks suitable for biological and biochemical conversion processes. Improving pre-treatment technologies and feedstock standardisation remains essential to maximise process efficiency and reduce operational costs. The UK has established several specialised bioeconomy innovation centres, including the Biorenewables Development Centre (BDC) in York, the Industrial Biotechnology Innovation Centre (IBioIC) in Scotland and the Centre for Process Innovation (CPI) in Teesside. These facilities provide pilot capabilities that help companies address feedstock-processing challenges and improve resource utilisation.

6.8.21.2 Scalability and Industrial Deployment

Although the UK demonstrates strong capabilities in research and innovation, many technologies remain concentrated within TRLs 3–5 and have not yet progressed to commercial-scale production. The transition from pilot-scale validation to industrial deployment is hindered by high capital requirements, technical risks and competition from established fossil-based industries. Many SMEs and emerging ventures lack access to the financial resources required for industrial-scale investments. Bridging this scale-up gap will require greater investment in demonstration facilities, commercial biorefineries and industrial validation infrastructure capable of supporting technologies throughout the later stages of development and commercial deployment.

6.8.21.3 Product Development and Differentiation

The UK benefits from strong expertise in engineering biology, industrial biotechnology and catalysis, providing an excellent foundation for the development of innovative bio-based products. However, many promising products developed within research institutions encounter difficulties reaching the market. Commercialisation pathways remain relatively slow and often struggle to transform technological breakthroughs into competitive products with sufficient market penetration. Market differentiation is further influenced by regulatory uncertainty and competition from established fossil-derived alternatives. Continued support for technology validation, market access and industrial partnerships will therefore be critical for expanding the UK's portfolio of high-value bio-based products.

6.8.21.4 Process Innovation and Technology Development

Process innovation remains one of the UK's major strengths. The country has developed a strong innovation ecosystem linking academia, SMEs and specialised technology-development organisations. Nevertheless, significant challenges remain in moving technologies from laboratory-level innovation to industrial deployment. Technology-readiness gaps continue to delay commercial implementation and increase development risks. Government-backed initiatives such as CPI's National Industrial Biotechnology Facility play an important role in addressing these challenges by supporting bioprocess development, industrial validation and FSSC 22000-certified scale-up

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activities. Such facilities provide essential support for companies seeking to transition innovative technologies towards commercial production. Further strengthening process innovation will require continued investment in industrial biotechnology, engineering biology platforms and scale-up infrastructure.

6.8.21.5 Digital Transformation

Digital technologies remain underutilised across many areas of the UK bioeconomy despite their substantial potential to improve process efficiency, reproducibility and operational performance. The OECD has highlighted challenges related to reproducibility within biotechnology research and the opportunities offered by automation, cloud computing, advanced analytics and blockchain technologies. These digital tools can improve process monitoring, optimise resource utilisation and support more efficient innovation pathways. However, the bioeconomy currently lacks fully integrated digital platforms capable of supporting process modelling, lifecycle assessment and data management across value chains. This limits predictive accuracy, process optimisation and scaling efficiency. Expanding digital integration therefore represents a significant opportunity for future development.

6.8.21.6 Circularity and Waste Management

The UK's bioeconomy strategy places strong emphasis on feedstock recycling and the valorisation of waste streams. Agricultural residues, municipal waste and other underutilised biomass resources are increasingly viewed as strategic feedstocks for future bio-based industries. However, achieving greater circularity requires improved integration across supply chains and stronger collaboration between agriculture, waste management, industrial biotechnology and downstream manufacturing sectors. The creation of closed-loop systems remains constrained by fragmented value chains and insufficient infrastructure for biomass collection, processing and utilisation. Strengthening circular business models and expanding resource-recovery systems will be essential for maximising biomass valorisation and reducing dependence on virgin fossil-based resources.

6.8.21.7 Environmental Performance and Sustainability

The development of bio-based industries is closely linked to the achievement of environmental and climate objectives. Bio-based feedstocks, waste valorisation pathways and circular production systems have the potential to reduce greenhouse-gas emissions and increase resource efficiency. However, environmental performance depends on the implementation of robust sustainability assessment methodologies. Lifecycle assessment frameworks are particularly important for demonstrating environmental benefits, supporting market differentiation and ensuring compliance with sustainability standards. Expanding the use of lifecycle assessment tools, sustainability metrics and traceability systems will help strengthen confidence in bio-based products and improve their contribution to long-term environmental goals.

6.8.21.8 Strategic Recommendations

To address the technological and structural challenges identified above, the United Kingdom should prioritise:

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- Expanding pilot, demonstration and commercial-scale biorefinery infrastructure to accelerate industrial deployment of technologies currently operating at TRLs 3–5.
- Improving biomass pre-treatment technologies capable of processing heterogeneous non-food feedstocks efficiently and consistently.
- Increasing access to financing mechanisms that support scale-up and commercialisation activities for SMEs and innovative ventures.
- Strengthening the role of specialised facilities such as BDC, IBioIC and CPI in supporting industrial validation and technology deployment.
- Supporting commercialisation pathways for products developed through engineering biology, industrial biotechnology and catalysis.
- Expanding the National Industrial Biotechnology Facility and related scale-up programmes to reduce commercialisation risks.
- Accelerating the adoption of automation, cloud computing, blockchain and advanced data-analytics systems throughout bioeconomy value chains.
- Developing interoperable digital platforms supporting process modelling, lifecycle assessment and industrial data sharing.
- Strengthening collaboration between agriculture, waste management, biotechnology and manufacturing sectors to create integrated circular value chains.
- Promoting lifecycle assessment frameworks and sustainability metrics that support environmental performance verification and market confidence.

By implementing these measures, the United Kingdom can strengthen its transition from research excellence to commercial leadership, accelerate the deployment of innovative bio-based technologies and reinforce its position as one of Europe's leading bioeconomy innovation ecosystems.

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7 ROADMAP FOR FUTURE DEVELOPMENT

This chapter sets out a detailed plan for the future development of the European bio-based industry, underlining its crucial function in achieving climate neutrality, enhancing energy independence, and promoting sustainable growth across Europe, as demonstrated in the current deliverable. It underscores the potential of the sector to serve as a substitute for industries relying heavily on fossil fuels, while concurrently highlighting its role as a catalyst for economic and societal advancement, notably through regional development and the generation of skilled employment opportunities in rural and coastal regions. The analysis emphasises the importance of innovation, the fostering of supportive policies, and the encouragement of collaboration, which are key drivers for consolidating the European Union's position as a global leader in the bio-based economy. The objective of this chapter is **two-fold**: firstly, to act as a **practical, strategical guide for policymakers and industry stakeholders**; **and** secondly, to **facilitate the growth of the European bio-based industry in a sustainable and robust manner**, shaping a sustainable robust future for Europe.

The European Union is unwavering in its commitment to the ambitious objectives of the European Green Deal, a comprehensive strategy aimed at transforming the continent into a climate-neutral economy by the year 2050. Moreover, the Clean Industrial Deal is acknowledged as a pivotal strategy for expediting decarbonisation and fortifying industrial competitiveness throughout Europe[1225]. This transformative vision is centred on accelerating the transition from a linear, fossil-based economic model to a circular, low-carbon one, thus positioning the bio-based industry as its cornerstone. This transition has the potential to conserve up to 2.5 billion tonnes of CO_2 equivalent annually by the year 2030. In addition to helping to mitigate climate change, this transition will increase Europe's energy security by reducing its dependence on finite and often geopolitically sensitive fossil resources. The implementation of these strategies is intended to facilitate the realisation of the full potential of the European bio-based industry.

The establishment of the bio-based industry is set to bring about a dual benefit to the European Union, both environmental and economic. As was previously outlined, the sector has the potential to stimulate the creation of new markets and generate numerous job opportunities, particularly in rural and coastal areas, where biomass resources are typically concentrated. This aspect of regional development is crucial for promoting economic cohesion and ensuring a just transition to a greener economy, leaving no region or citizen behind. Bio-based industries in Europe have already become a significant economic force, with a turnover of more than €2.3 trillion in 2020 and employment of more than 17.5 million people in 2017. Further strategic development and investment in this sector

[1225] The Clean Industrial Deal: a joint roadmap for competitiveness and decarbonisation | Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and The Committee of the Regions | European Commission

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is expected to generate significant economic impact, establish new value chains and enhance the EU's industrial competitiveness on a global scale.

7.1 STRATEGIES FOR TECHNOLOGY DEVELOPMENT

From a purely technological perspective, the future of the European bio-based industry is contingent on the strategic development and adoption of innovative technologies in various fields. As outlined in the report, there are several key technology areas (in both established and emerging fields) that show great potential for breakthroughs that could significantly impact the industry's sustainability, economic viability and societal benefits.

The bio-based sector in Europe is currently experiencing a period of rapid growth and innovation, driven by continuous improvements in cost-efficiency and technological capabilities. This growth is primarily driven by significant advancements in **diverse areas of biotechnology areas**, such as (but not limited to) genome editing (e.g., CRISPR-Cas9), genetic engineering (targeted modification of DNA for improved traits), synthetic biology (design of new biological functions), consolidated bioprocessing (integration of enzyme production, biomass hydrolysis, and fermentation in a single processing step) and metabolic engineering (optimisation of cellular metabolic pathways to boost product yields). The European Commission recognises the sector's strategic importance. For this reason, it has identified bio-based innovation as a priority area and is supporting its development through the Strategic Technologies for Europe Platform (STEP), thus fostering investment in critical technologies.

A key focus of these innovations is the **optimisation of biomass conversion processes**, which is essential to improve efficiency, reduce environmental impact and lower production costs of the bio-based industry. This optimisation is achieved **through advanced pretreatment techniques, continuous improvement processes, and the deployment of advanced biotechnological tools**. Notable examples include AI-assisted enzyme engineering, high-solid enzymatic hydrolysis (which allows for efficient sugar extraction from biomass at lower water content), high-throughput screening for strain and enzyme selection, and eco-efficient extraction methods that minimise energy and extractant use.

The role of **AI and digital technologies in accelerating research and industrial implementation is increasing**. AI enhances predictive modelling and decision-making, while also improving scalability and automation within the biomanufacturing sector. In addition, the implementation of integrated digital information systems facilitates enhanced monitoring of sustainability metrics and circularity performance throughout the bio-based value chain. This promotes transparency, enhanced control and tracking, and informed policy and business decision-making.

In a similar vein, researchers in academic and industrial sectors are actively developing **novel enzymes and microbial strains** through directed evolution and adaptative laboratory evolution, being able to enhance capability of biological systems to degrade complex biomass into valuable bio-based intermediates and end products. These products include biopolymers, advanced biofuels,

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biopharmaceuticals, antimicrobial agents, recombinant proteins, single-cell proteins, industrial enzymes, chemical platforms, fine chemicals, and specialty chemicals.

Furthermore, **recent advancements in the field of genetic engineering**, such as CRISPR-Cas9 technology, have significantly broadened the scope for designing microbial systems that are capable of processing of a diverse range of feedstocks, including lignocellulosic biomass, algal biomass, and various industrial and municipal waste. This genetic optimisation plays a key role in the production of sustainable materials and fuels, thus helping to reduce reliance on fossil-based resources. Concurrently, advancements in **synthetic biology and metabolic engineering** are continuously enabling the design and establishment of novel biological systems and the precise optimisation of existing ones, maximising the efficiency and selectivity of bio-based production processes. Furthermore, innovations in DNA synthesis infrastructure, including microarray-based and yeast-based synthesis methods, have accelerated the design-build-test-learn cycle in strain engineering. These technological advancements facilitate rapid iteration and optimisation of microbial strains for industrial applications

In addition to biotechnology, **thermochemical conversion technologies** offer versatile pathways for transforming different biomass feedstocks into advanced biofuels and biochemicals. Through conventional pretreatment techniques, gasification, pyrolysis or hydrothermal liquefaction, sometimes coupled with bioconversion techniques and sometimes integrated in different combinations of technologies, these technologies present opportunities for creating highly effective hybrid biorefineries. The integration of thermochemical pathways with biochemical methods has the potential to enhance the economic viability, production and recovery of bio-based plastics, biochemicals and platform chemicals, while utilising lignocellulosic residues.

It is increasingly acknowledged that **nanotechnology and advanced materials** have considerable potential for transforming bio-based products. In relation to bio-based packaging, the use of nanotechnology enables the creation of materials with improved barrier properties, antimicrobial activity, hydrophilicity/hydrophobicity, and enhanced mechanical strength, amongst numerous other benefits, depending on the targeted biomolecule, through nanocomposites. Beyond the field of packaging, the use of nanomaterials is driving innovation in catalysis for bioconversion, including the use of lignin-derived catalysts for efficient biofuel production and separation techniques that use nano-porous membranes to purify bio-based chemicals such as succinic acid and lactic acid. In the field of biomedicine, there is growing interest in the use of bio-based delivery systems for pharmaceutical products. These systems make use of nanocarriers, such as glycol-functionalized cellulose nanocrystals, to target specific areas of the body for the treatment of diseases. Collaborative ecosystems are a strategic approach to unifying R&D and industrial scaling, addressing challenges such as cost competitiveness and global market leadership.

The **integration of membrane processes into biorefineries** must address the challenge posed by membrane fouling. This issue contributes significantly to operating costs, accounting for 50–80% of expenses in separation steps. Recent advances in the field of membrane processes have been developed for the selective recovery and purification of bio-based compounds and biofuels, with a

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view to energy consumption savings when compared to thermal methods. In addition, the use of inorganic nanofillers, such as graphene oxide or MOFs, can extend the operational life in harsh conditions. Concurrently, SFE is undergoing optimisation for niche applications, such as the recovery of lipids, carotenoids and phenolic compounds from various complex feedstock, achieving 95% purity in pilot studies. In addition, **the combination of membranes with other separation techniques** (or **hybrid membrane-based separation systems**), such as isoelectric precipitation, adsorption, and ion-exchange or spray-drying techniques, has been demonstrated to be an effective solution for bio-based products and bioethanol. This approach has been shown to reduce impurity and inhibitor levels while achieving double flux rates, making it a highly efficient process. These innovations align with the objectives of the European Green Deal and Clean Industrial Deal, with a view to recovering high-quality water and enabling resource recovery loops to achieve near-zero waste biorefineries by 2030. Nevertheless, issues concerning the scalability of the process remain a major obstacle, emphasising the need for further validation through pilot-scale experimentation with modular membrane-integrated processes, such as membrane reactors, for the purpose of **continuous processing** (including biodiesel and bio-based chemical production).

As outlined in the report, the large-scale production of bio-based products to meet industrial demands is dependent on two key innovations: **advanced bioreactor innovations and process intensification**. Continuous flow bioreactors represent a significant advance on traditional batch systems, offering a range of benefits including enhanced productivity, improved control and the potential for continuous product harvesting. These advantages allow for the integration of advanced fermentation and separation methods as well as in situ product recovery, leading to substantial improvements in the efficiency of industrial platform molecule production. Novel bioreactor designs are being developed to optimise cell culture conditions and improve the efficiency of various bio-based production processes. Furthermore, the implementation of process intensification strategies is paramount in fostering a more economically competitive and environmentally sustainable bio-based production.

Finally, recent advancements have emphasised **structured and multicriteria LCA-driven process optimisation**, particularly for reducing GHG emissions in hard-to-decarbonise sectors. However, in order to successfully implement these technologies, it will be necessary to respond to the challenges of feedstock variability and production issues by computational modelling and artificial intelligence systems, in a targeted and continuous way.

The successful integration of these innovations, tailored to the specific needs of the bio-based industry, is essential for the full potential of the bio-based industry in Europe to be realised. Leveraging modular unit operations and cutting-edge R&D in pilot plants has strategically positioned Europe to lead the global effort towards a competitive and environmentally responsible bioeconomy.

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7.2 AREAS REQUIRING FURTHER RESEARCH AND DEVELOPMENT

The European bio-based industry is showing significant progress, but it is clear from the development of the present report that there are several areas where further **targeted research and development is needed at both the EU and national levels to fully realise the sector's potential**. Despite their complexity, correct addressing of these areas in a correct way would be of paramount importance to the EU bioeconomy, thereby strengthening the bio-based sector fabric.

Firstly, **feedstock diversification, sustainable sourcing, and its logistics** remain key priorities for almost all the regions analysed. Research should continue to explore and optimise the use of underutilised biomass resources, such as agricultural residues (e.g. straw, maize stover), forestry wastes (e.g. wood chips, bark), algae (both micro- and macro-algae) and marine biomass. The development of sustainable cultivation practices for energy crops, thus avoiding competition with food production, and the establishment of efficient and resilient supply chains are also essential. Given the heterogeneity of agricultural and forestry landscapes across the EU, research efforts should prioritise a regional focus, with particular attention to biomass availability and the suitability of diverse feedstocks for various bio-based production pathways.

The **valorisation of waste and by-products** (zero waste approaches) is an area that requires increased research and development efforts. The development and scaling up of technologies to convert different biowaste streams, including food waste, agricultural residues and forestry by-products, into valuable bio-based products, bioenergy or biofertilisers is crucial to achieve a circular bioeconomy. Furthermore, research should concentrate on the implementation of circular economy principles in all aspects of the bio-based industry, from the sourcing of feedstock to product design and end-of-life management. The development of standardised metrics is also essential for measuring waste reduction and resource efficiency in bio-based industries. This will allow progress towards a zero-waste bioeconomy to be tracked.

The **integration and optimisation of biorefineries** requires continuous research and development to maximise the value of biomass. The development of innovative and integrated biorefinery concepts that can process multiple feedstocks and produce a wide range of biobased products and bioenergy is crucial. Optimising process design and enhancing energy efficiency within biorefineries represent pivotal domains for future research endeavours. Exploration of tailored biorefinery approaches is essential for maximising resource utilisation and ensuring economic viability. These approaches involve the combination of two key elements: bottom-up expansion of existing biomass processing facilities, and top-down design of new, highly integrated systems tailored to regional contexts.

Furthermore, sustained research efforts must be made into the **development of novel bio-based products and materials**. Exploration of new, high-value applications for various biomass elements, including lignin, hemicelluloses and extractives, is imperative to diversifying the bio-based industry's product portfolio. Furthermore, research should concentrate on the development of bio-based alternatives to a wide range of fossil-based chemicals and materials, with comparable or superior

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performance and cost competitiveness. Moreover, it is vital to develop biodegradable and compostable bio-based products to tackle the issues of plastic pollution and promote a real circular economy.

Finally, the **advancements and new developments in downstream processing and purification** are essential for the economic viability of biorefineries. Consequently, efforts should focus on the development of more cost-effective and sustainable downstream processing technologies, with the aim of reducing both energy consumption and production costs while enhancing the environmental impact of bio-based industries. Achieving elevated levels of purity in biorefinery outputs and enhancing product recovery are also imperative for meeting market demands. The exploration and development of innovative separation and extraction methodologies, incorporating membrane technologies and bio-based solvents, holds significant potential to deliver processes that are more sustainable and efficient in the long term.

7.3 POLICY RECOMMENDATIONS FOR FOSTERING INNOVATION

With the purpose of achieving the full potential of the European bio-based industry, it is essential to establish a supportive and enabling policy environment. A number of key policy recommendations have been posited as potential catalysts for innovation, market uptake and sustainable growth in the sector.

To reduce market barriers and encourage investment, **regulatory frameworks and standards** must be tightened and harmonised across the EU, including non-EU members or third countries such as Switzerland and the UK. The simplification of regulatory procedures for the authorisation and marketing of bio-based products is imperative to accelerate innovation. The establishment of clear, consistent and science-based standards for bio-based products and materials, encompassing aspects such as bio-based content, biodegradability and environmental performance, is imperative to enhance consumer confidence and facilitate market access. Removing existing regulatory barriers and creating a more innovation-friendly regulatory environment is essential to unlock the full potential of the bio-based industry.

Furthermore, **funding and investment strategies** must be refined to provide adequate support for research, development and infrastructure for the bioeconomy. Investment in bio-based R&D, comprising fundamental research, pilot projects, and the establishment of industrial-scale biorefineries, is pivotal in translating technological advancements into market-ready solutions. The provision of financial incentives, such as tax credits, grants and loan guarantees, and the development of de-risking mechanisms, will encourage investment in the development of biorefineries and other bio-based projects. Furthermore, it is imperative to provide support to SMEs and start-ups operating within the bio-based sector, as they are often instrumental in catalysing innovation.

It is imperative that measures are implemented to increase **market uptake and raise consumer awareness** of bio-based products. Implementing policies that promote public awareness and acceptance of bio-based solutions, emphasising their environmental and economic benefits, will

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encourage consumer adoption. Furthermore, strategic utilisation of public procurement policies to favour bio-based products and materials is recommended, with the aim of creating stable markets and stimulating innovation. The utilisation of clear and trustworthy labelling, coupled with the implementation of robust certification schemes, is instrumental in empowering consumers to make informed decisions and fostering confidence in the sustainability of bio-based products.

The development of the bio-based industry should be underpinned by **policies that prioritise sustainability and circularity**. By incentivising the use of sustainably sourced biomass feedstocks and promoting circular economy principles, including waste valorisation and product recyclability, the environmental benefits of the sector can be maximised. The setting of ambitious targets for the replacement of fossil-based products with bio-based alternatives in key sectors is likely to drive innovation and market growth. Furthermore, the promotion of zero waste and zero pollution approaches in bio-based industrial processes will minimise environmental impacts and improve resource efficiency.

7.4 COLLABORATION OPPORTUNITIES WITHIN THE EU.

The European bio-based industry is characterised by a wide range of stakeholders, including research institutions, industry players (from large corporations to SMEs and start-ups), policy makers and regional clusters. It is crucial to foster strong collaboration amongst these actors to accelerate innovation, scale up technologies and ensure the successful development of the sector.

Public-private partnerships and joint ventures have been identified as key drivers in the advancement of the bio-based industry. The CBE JU serves as a prime exemplar of a fruitful public-private partnership, representing a collaboration between the European Union and the Bio-based Industries Consortium (BIC) with the objective of funding projects that foster the development of competitive circular bio-based industries on a pan-European scale[1226]. It is vital to encourage and support further collaborations between research institutions and industry players to bridge the gap between scientific discoveries and their commercial application, thereby accelerating the translation of innovative bio-based technologies into the marketplace.

Cross-border initiatives and regional clusters provide valuable platforms for collaboration and knowledge exchange. Initiatives such as BIOEAST, which focuses on Central and Eastern Europe, facilitate the development of sustainable bioeconomies in specific regions[1227]. Furthermore, the establishment and growth of regional bioeconomy clusters across the EU has the potential to foster localised innovation ecosystems, drawing on the specific strengths and resources of different regions. Transnational cooperation in research and innovation projects enables the pooling of

[1226] Home | Circular Bio-based Europe Joint Undertaking (CBE JU)

[1227] Central and Eastern European Initiative for Knowledge-based Agriculture, Forestry and Aquaculture in the Bioeconomy – BIOEAST

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diverse expertise and resources, accelerating the development and deployment of bio-based solutions across national borders.

EU-funded R&D projects play a pivotal role in fostering collaboration and knowledge sharing within the European bio-based industry. A plethora of successful projects funded through programmes such as Horizon Europe and CBE JU have demonstrated the potential of bio-based innovation across different sectors[1228] [1229]. These projects frequently involve consortia of partners from different countries and sectors, thereby fostering knowledge transfer and the development of pan-European value chains. It is vital that these funding mechanisms are used strategically to drive innovation and expand bio-based technologies throughout the continent.

The concepts of **industrial symbiosis and value chain integration** present significant opportunities to enhance resource efficiency and establish new bio-based value chains. By fostering collaboration between diverse sectors, such as agriculture, forestry, food processing and chemical manufacturing, it is possible to effectively valorise waste streams and by-products, thus optimising the use of biological resources. The integration of biorefineries into existing industrial complexes, such as pulp and paper mills or sugar factories, has the potential to leverage existing infrastructure and expertise, accelerate the adoption of bio-based production, and generate new revenue streams for established industries.

7.5 Challenges to Roadmap Success and Structural Solutions

As was extensively evidenced in the present work, the technological barriers and challenges heavily hinder the successful future development and implementation of the existing roadmaps. The causes for potential ineffectiveness of the current strategic vision at both national and regional levels, as indicated by the barriers, include:

1. **Lack of cohesion and fragmentation**: fragmented national strategies and policy coordination impede unified progress (e.g., Czechia, Hungary, Italy). Some countries need to establish stronger policy frameworks, including adopting national bioeconomy with clear priorities and resource allocation. Aligning national and regional strategies with EU objectives must be a priority. Similarly, R&D&I ecosystems are fragmented, hindering collaboration (e.g., France, Estonia, Spain), and sectorial interactions are weak (e.g., Poland). The current regulatory landscape, such as the standardised methodology for measuring water footprint or transport emissions, can also create market uncertainty and confused statements to stakeholders.

[1228] Horizon Europe the EU's funding programme for research and innovation | European Commission

[1229] CORDIS | European Commission

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2. **Inadequate infrastructure and scalability issues**: limited industrial-scale biorefining facilities, lack of pilot/demonstration plants, lack of technological actors able to carry out technical due diligence, and inadequate infrastructure for feedstock logistics and processing hinder scaling up innovative technologies (e.g., Bulgaria, Greece, Slovakia, Slovenia). Additionally, transitioning from batch to continuous processing is complex and costly. Similarly, overall processing infrastructure requires improvement and adaptation for bio-based alternatives, such as biomethane or biofuels. Reconciling different plant capacities (e.g., biogas production and secondary refining) is an obstacle.
3. **Limited investment and financial barriers**: high production costs, lack of investment incentives, limited access to finance (especially for SMEs and high-risk projects), and competition from established fossil-based industries create financial hurdles (e.g., Cyprus, Hungary, Italy, Lithuania).
4. **Slow digital transformation and lack of data**: underutilisation of digital tools, lack of digital expertise/resources, incompatibility of legacy systems, and data fragmentation impede efficiency, optimisation, and traceability (e.g., Cyprus, Greece, Latvia, UK).
5. **Product development and market integration barriers**: R&D focus on low-value outputs, difficulties achieving desired material properties and functionalities, lack of standardisation and quality control, insufficient market support, and challenges in differentiating bio-based products hinder market uptake (e.g., Bulgaria, Czechia, Italy, Slovenia).
6. **Sustainability and circularity implementation gaps**: inefficient resource utilisation (e.g., lignin, hemicellulose), difficulties in waste valorisation and recycling, lack of investment in waste-to-bioenergy technologies, and absence of comprehensive sustainability metrics and certification hinder progress towards a circular bioeconomy (e.g., Bulgaria, Greece, Hungary, Spain).
7. **Social and awareness challenges**: a shared understanding and awareness of the circular bioeconomy are still in early stages in some regions, such as Estonia. Public perception and social compatibility must be considered, especially concerning potentially conflicting aims like land-use changes or the use of genetically modified plants. Skilled professionals are needed across the value chains, requiring new education and training programmes adapted to interdisciplinary needs.

The structural solutions that can be applied to these challenges, thereby unleashing the vast potential of bio-based processes and the bioeconomy in Europe:

1. To overcome the lack cohesion and fragmentation:
    - Implementing cohesive national bioeconomy strategies with clear priorities and resource allocation.
    - Strengthening policy frameworks and coordination across government departments (e.g., agriculture, industry, environment).
    - Fostering stronger industry-academia collaboration and interlinkages across value chain.

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- Establishing and strengthening innovation intermediaries and bioeconomy clusters to bridge research and market.

2. To overcome both inadequate infrastructure and scalability issues:
   - Improving infrastructure for biomass logistics, including collection, storage, and transport.
   - Developing and expanding pilot and demonstration plants covering different TRLs.
   - Investing significantly in industrial-scale biorefineries and integrated processing facilities.
   - Supporting the transition to continuous integrated biorefineries.
3. To overcome limited investment and financial barriers:
   - Providing targeted financial incentives, grants, subsidies, and tax incentives for bio-based industries and product development.
   - Leveraging EU funding mechanisms strategically (e.g., Horizon Europe, CBE JU).
   - Encouraging private-sector investment and accessing to venture capital through de-risking strategies and data from pilot projects.
   - Supporting public-private partnerships.
4. To overcome slow digital transformation and lack of data:
   - Providing incentives and training programmes for adopting Industry 4.0 solutions.
   - Investing in digital infrastructure, integrated platforms, and open data platforms for biomass availability, traceability, process modelling, and LCA.
   - Addressing rural digital divides.
5. To overcome product development and market integration barriers:
   - Shifting R&D focus towards high-value products.
   - Developing standardised sustainability certification schemes and eco-labelling to differentiate products and build credibility.
   - Enhancing market-driven policies promoting sustainable alternatives.
   - Improving technology transfer mechanisms.
6. To overcome sustainability and circularity implementation gaps:
   - Investing in waste valorisation facilities and integrated biowaste systems.
   - Developing and scaling up technologies for converting diverse biowaste streams.
   - Implementing circular economy principles across the value chain.
   - Developing harmonised and standardised sustainability metrics, indicators, and LCA frameworks.
   - Establishing national bioeconomy certification systems.
   - Promoting cascading use of biomass.

7.6 Implementation phases (aligned with Green Deal objectives)

This report presents the findings of an in-depth analysis of the technological barriers facing the EU bioeconomy. This analysis includes a major review of established and emerging technologies related to the bio-based industrial sector at these levels. The analysis was conducted at both the European and national levels and resulted in the formulation of a strategic roadmap for developing the EU

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bioeconomy, outlining actions in the short-term (2025-2027), medium-term (2028-2032) and in the long term (beyond 2032).

While the roadmap does not explicitly address adaptability to future crises, its defined elements inherently contribute to enhancing systemic resilience. These elements promote energy independence by reducing reliance on fossil fuels and strengthening energy security against supply disruptions. They support a diversified feedstock supply by optimising the utilisation of various biomass sources, including those from agriculture, forestry, marine, and industrial and municipal sources. This reduces dependence on single sources and mitigates risks associated with regional disruptions, including climate-related events and geopolitical shifts. Furthermore, a regional focus is encouraged by tailoring biorefinery strategies to local contexts and resources, enhancing local resilience and diminishing reliance on long-distance transport systems vulnerable to unexpected interruptions. The principles of a circular economy are also embedded in the strategy, with the aim of minimising waste, retaining resources within the system, and fostering greater self-sufficiency. Finally, digitalisation enhances system resilience by improving monitoring, traceability, and predictive modelling capabilities, thereby strengthening supply chain management and responsiveness to variability.

7.6.1 Short-term actions (2025-2027).

These initiatives aim to establish a foundational infrastructure and to prioritise the scaling up of promising technologies, the fostering of collaboration and the implementation of supportive policies. Their specific goal is to substitute a minimum of 30% of the existing fossil-based products with sustainable alternatives.

Key actions:

- **Policy and Regulation:**
  - Harmonising regulatory frameworks and standards across the EU and with third countries.
  - Simplifying regulatory procedures for bio-based products.
  - Implementing policy recommendations to promote market uptake.
  - Allocating appropriate resources to national bioeconomy strategies where they exist or developing them where they are lacking.
  - Implementing financial incentives for production and consumption of bio-based products.
  - Supporting regional roadmap development using established methodologies.
- **Technology:**
  - Focusing on scaling promising bio-based technologies, particularly those at TRL 6-8.
  - Investing in regional pilot and testing facilities adapted to local feedstocks.
  - Mobilising funding sources and exploring blending finance.
  - Supporting public-private partnerships to accelerate pilot-scale augmentation.
  - Initiating the integration of cutting-edge bioconversion technologies to enhance processing efficiency.

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  - Prioritising technologies focused on scaling existing knowledge: optimising bioconversion processes, improving the efficiency of thermochemical conversion, integrating membrane technologies for separating and recovering targeted bio-based products, and standardising the implementation of digital tools for process monitoring and basic data analysis.
- **Infrastructure:**
  - Focusing on the development of industrial-scale biorefineries and enhancing processing infrastructure.
  - Catalysing the establishment or strengthening of regional biomass hubs and optimising logistics infrastructure.
- **Resource allocation:**
  - Fostering the targeted EU and national funding for pilot/demonstration projects and boosting industrial infrastructure.
  - Incentivising private investment.
  - Developing resources for policy harmonisation and development.
- **Collaboration:**
  - Fostering stronger collaboration across the value chain, including research institutions, industry (SMEs and large corporations), policymakers, and regional clusters.
  - Strengthening industry-academia collaboration.
  - Defining complete mapping of potential bio-based innovations.
- **Digitalisation:**
  - Addressing methodological and data challenges for environmental and economic assessment, particularly for biomass as a hotspot.
  - Providing incentives and training for the adoption of basic digital tools for process monitoring and data collection.
  - Addressing rural digital divides to enable digital technology uptake.
  - Strengthening monitoring systems.
- **Sustainability:**
  - Developing standardised sustainability certification schemes.
  - Starting to implement standardised metrics for waste management and resource efficiency.

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7.6.2 Mid-term actions (2028-2032).

The primary goal of these initiatives is to promote greater integration across sectors and value chains, optimise biorefinery operations, accelerate digital transformation, and strengthen circularity principles. Their specific aim is to bridge the gap between short-term scaling and long-term climate neutrality goals.

Key actions:

- **Policy and Regulation:**
  - Continuing to streamline regulations.
  - Implementing policies that promote circularity (e.g. the upcoming Circular Economy Act).
  - Introducing policies that support industrial symbiosis and value chain integration.
  - Providing sustained incentives for the development and commercialisation of bio-based products.
  - Driving rapid deployment of local bioeconomies across diverse territories, including piloting urban bioeconomy strategies.
- **Technology:**
  - Investing in industrial reference plants for hight technological maturity concepts.
  - Focusing on integrating novel technologies into existing and new infrastructures.
  - Developing innovative and integrated biorefinery concepts capable of processing multiple feedstocks.
  - Optimising process design and energy efficiency within biorefineries.
  - Supporting research into novel separation/extraction methods.
  - Priority technologies focused on integration and optimisation: integrating hybrid biorefinery concepts, implementing advanced thermochemical processes for diverse feedstocks, optimising hybrid separation techniques, fostering process automation and Big Data analytics, and maximising the use of AI for process optimisation.
- **Infrastructure:**
  - Continuing investment in industrial-scale biorefineries.
  - Developing infrastructure for waste management and recycling, including waste valorisation facilities.
- **Resource allocation:**
  - Continued significant EU and national investment in industrial scaling and integration projects.
  - Funding for R&D focusing on multi-feedstock processing and process optimisation.
  - Fostering the access to resources for digital infrastructure development and skills training.
- **Collaboration:**
  - Deepening public-private partnerships to leverage diverse expertise and resources.
  - Fostering industrial symbiosis networks that promote resource efficiency and shared opportunities.

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  - Establishing cross-industry R&D&I teams to develop multi-feedstock platforms that leverage synergies and address global challenges.
  - Implementing new educational and training programmes tailored to bioeconomy needs across sectors.
  - Exploring opportunities for technology exports.
- **Digitalisation:**
  - Accelerating the adoption of advanced digital technologies, including automation, AI-driven optimisation, predictive models, and integrated digital platforms for process modelling and LCA.
  - Investing in digital infrastructure and open-access data platforms.
- **Sustainability:**
  - Implementing comprehensive indicators including environmental, social, and economic dimensions.
  - Strengthening eco-labelling and water and carbon footprint assessments.
  - Developing robust and standardised approaches to technical due diligence incorporating sustainability considerations.

7.6.3 Long-term actions (2033-2040).

The fundamental goal of these initiatives is to achieve carbon-neutral industrial processes, establish a fully circular bioeconomy where waste is minimised, resources are kept in the loop, and dependence on fossil fuels is significantly reduced. Their specific aim is to maximise the value generated from biological resources.

Key actions:

- **Policy and Regulation:**
  - Ensuring regulatory frameworks are in place to fully support a circular, low-carbon bioeconomy.
  - Implementing policies promoting green public procurement and carbon-intensity labelling to drive demand.
  - Embedding regulatory mechanisms for continuous monitoring, periodic review, and adaptation of strategies and actions based on new insights and changing framework conditions (e.g., technological developments, market shifts, climate impacts, potential crises).
- **Technology:**
  - Fostering innovation leadership in advanced bio-based technologies, including multi-product biorefineries and potentially e-fuels, depending on economic viability.
  - Encouraging the adoption of advanced biofuels derived from non-food feedstocks and high-performance bio-based materials on a large scale.
  - Achieving the full implementation of near-zero waste biorefineries through the use of advanced separation and waste valorisation technologies.

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  - Leveraging breakthroughs in synthetic biology and metabolic engineering for the design of novel products and sustainable production.
  - Strengthening continued innovation in advanced materials (e.g., nano-enabled bio-based materials).
  - Priority technologies focused on circularity and advanced solutions: driving the fully, standardised implementation of synthetic biology, metabolic engineering, advanced biofuels and SAFs from non-food feedstocks, high-performance bio-based materials, advanced waste valorisation technologies and fully integrated digital systems for optimising value chain and ensuring traceability.
- **Infrastructure:**
  - Defining and fully establishing robust and resilient biomass supply chains.
  - Standardised optimised biorefinery operations and practices.
- **Resource allocation:**
  - Harmonising the sustained investment in breakthrough R&D, particularly in synthetic biology and advanced materials.
  - Providing robust resources for workforce development and public engagement.
  - Funding for widespread adoption of circular technologies and digital integration.
- **Collaboration:**
  - Encouraging global partnerships and international collaborations to speed up the move towards a sustainable global bioeconomy.
- **Digitalisation:**
  - Achieving the full integration of digital technologies for monitoring, traceability, optimisation, and sustainability reporting across the entire value chain.
  - Expanding the use of digital twins for biomanufacturing.
- **Sustainability:**
  - Achieving a fully circular bioeconomy in Europe, contributing significantly to decarbonisation objectives and sustainable growth.
  - Ensuring sustainable and reliable supply of diverse biomass feedstocks without competing with food production.
  - Ensuring all bioeconomy activities operate strictly within safe ecological limits, with a focus on ecosystem resilience and biodiversity protection.
  - Implementing successfully the continuous monitoring and progress assessment of environmental, social, and economic impact.

7.6.4 Recommendations for cross-cutting success factors.

Firstly, it is imperative to properly **define the coordination amongst countries through enhancing the coordination of R&D efforts**. To this end, it is essential to **avoid fragmentation and to create synergies**. The establishment of pan-European value chains is to be achieved through collaborative projects and initiatives. Additionally, it will be necessary to **facilitate knowledge transfer and best practice sharing between countries and regions**. Moreover, **the importance of harmoniously incorporating regional variations into the implementation of bioeconomy strategies cannot**

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be overstated, given the importance of aligning such strategies with the specific resources and requirements of each region.

Secondly, **standardisation is pivotal to propelling the bio-based industry towards higher levels of production**. It is vital to develop and harmonise regulatory frameworks and standards across the EU and with third countries. It is essential to establish standardised sustainability certification schemes and metrics for waste reduction, resource efficiency, environmental impact (including LCA frameworks), and circularity. **The issue of standardised methodologies for conducting technical due diligence in the bio-based sector is crucial and must be addressed**.

Thirdly, a **robust financial system** is required to achieve these ambitious goals. It is essential to ensure that adequate and strategic funding mechanisms (e.g., Horizon Europe, CBE JU) are utilised to drive innovation and expand technologies. **It is recommended that financial incentives for bio-based industries, product development and the adoption of green/digital technologies be increased**. **Implementing de-risking strategies will be key to successfully attracting investment in high-risk projects and efforts aimed at achieving scale**. It is recommended that **specific financing models be established in order to support start-ups and spin-offs from R&D institutions**.

Finally, it is vital to improve **technical capabilities to ensure this step forward**. **Investing in research and development is key to improving process efficiency, developing cost-effective technologies and exploring new feedstocks and products**. Address the issue of a lack of suitably skilled workers by implementing **targeted training programmes** (e.g. digital skills training). It is vital to **strengthen innovation ecosystems and research group coordination**. The development and strengthening of technology transfer mechanisms should be given high priority. In order to **facilitate the implementation of emerging technologies**, it is essential to establish dedicated support structures. These structures should include **training and network-building programmes**.

The European bioeconomy is a dynamic sector, influenced by global trends and international competition. It is therefore essential to carry out continuous monitoring and assessment, allowing for adjustments in strategy and implementation based on evolving circumstances and potential future crises.

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8 CONCLUSIONS

The bio-based industry in Europe is a vital component of the continent's strategy for a sustainable and circular economy. As demonstrated in this report, the sector possesses the potential to reduce greenhouse gas emissions, foster economic growth, enhance energy security, and contribute to regional development. In order to ensure that the European Union maintains its position as a global leader in the bio-based economy, it is essential to strategically focus on technology development, prioritise research and innovation, implement supportive policies, and foster collaboration across the value chain.

The realisation of this potential is predicated on a concerted effort from all stakeholders. Continued investment in cutting-edge research and the scaling up of promising technologies is essential to overcome existing challenges and unlock new opportunities. It is vital for policymakers to establish a stable and supportive regulatory framework that encourages the production and consumption of bio-based products while ensuring their sustainability. Furthermore, industry players must embrace innovation, collaborate and invest in the infrastructure necessary for large-scale bio-based production.

The European bio-based industry is of pivotal importance to the sustainable, resilient, and competitive future of the continent. By embracing innovation, fostering collaboration, and implementing strategic policies, Europe can pave the way for a thriving bioeconomy that benefits both people and the planet. A comprehensive exploration of the strategic, environmental, economic, and technological dimensions of the European bioeconomy is therefore essential. The bioeconomy is a broad-ranging concept encompassing diverse sectors, including agriculture, forestry, fisheries, food production, bio-based chemicals, materials, and energy. This diversity presents both opportunities and complexities. To harness synergies and prevent fragmentation, there is a clear necessity for coordinated governance and cross-sectoral strategies.

From a strategic standpoint, the development of the EU bioeconomy is closely aligned with broader geopolitical and economic objectives. The strategic autonomy of Europe, particularly with respect to reducing its reliance on fossil-based imports, is of increasing importance in the face of volatile global markets and geopolitical uncertainties. The bio-based industries that are the focus of this analysis offer the means to localise production, enhance regional resilience, and secure essential supply chains. By leveraging domestic biomass resources and reinforcing innovation ecosystems, the EU can strengthen its internal markets and mitigate vulnerabilities to external shocks.

The EU Bioeconomy Strategy, revised in 2018, has been identified as the overarching policy framework for the realisation of these strategic ambitions. It prioritises the scaling up and deployment of sustainable bio-based solutions, reinforces bio-based sectors, and integrates circular economy principles. Horizon Europe, the EU's flagship research and innovation programme, supports bioeconomy objectives by funding research and technological development. The establishment of public-private partnerships, including the CBE JU, is pivotal in the aggregation of resources and

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expertise from diverse stakeholders, thereby facilitating accelerated innovation and market readiness.

The bioeconomy concept is predicated on environmental sustainability. A key benefit of the bioeconomy is the potential to substitute fossil-based raw materials with renewable biological resources, thereby contributing to the EU's climate objectives. Bio-based products have been shown to exhibit a considerably reduced carbon footprint, particularly when their entire life cycle is managed in a sustainable manner. The incorporation of bio-based products into sectors such as construction, transport, packaging and textiles has been demonstrated to contribute to a reduction in overall greenhouse gas emissions. For instance, bio-based construction materials such as cross-laminated timber, hempcrete, and mycelium-based composites offer alternatives to carbon-intensive materials like concrete and steel. These materials are not only renewable but also serve to sequester carbon during their lifecycle. In a similar manner, bio-based plastics and textiles derived from algae, starch, or cellulose provide an avenue for reducing the environmental burden of conventional materials. The biodegradability and recycling potential of these materials further enhance their environmental appeal.

Nevertheless, in order to ensure that bio-based products genuinely contribute to sustainability, it is crucial to conduct comprehensive LCAs. These assessments facilitate the identification of the environmental impacts associated with each stage of a product's life, from raw material extraction through to disposal. The utilisation of sustainability criteria, certification schemes and eco-labelling is instrumental in promoting responsible consumption and production patterns. The cascading use of biomass, where materials are prioritised for higher-value applications before being used for energy, is another guiding principle that maximises resource efficiency.

The bioeconomy is capable of addressing climate resilience as a further aspect of environmental sustainability. Through the sustainable management of forests, agricultural lands, and marine ecosystems, the bioeconomy supports biodiversity, soil health, and water conservation. Practices such as agroforestry, regenerative agriculture, and sustainable aquaculture enhance ecosystem services while supplying biomass for industrial use. These practices also contribute to carbon sequestration, thereby playing a role in climate mitigation.

From an economic perspective, the bioeconomy represents a significant growth opportunity for Europe. It has the capacity to generate employment, stimulate investment, and foster regional development. The EU bioeconomy is estimated to be worth over €2 trillion and provides more than 18 million jobs, spanning sectors from agriculture and forestry to bio-based chemicals and manufacturing. Of note is the tendency for this growth to be localised, thus offering a means to revitalise rural and peripheral regions by developing local biomass value chains. The establishment of localised value chains has been demonstrated to have a number of economic benefits, including a reduction in transportation costs and emissions, as well as an enhancement in the resilience of regional economies. Furthermore, these chains can generate prospects for SMEs, which possess the capacity to innovate and adapt to the availability of local resources. The emergence of clusters of bio-based industries in areas with abundant biomass has been shown to foster synergies,

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knowledge sharing, and economic spillovers. By aligning economic growth with environmental objectives, the bioeconomy presents a pathway to a sustainable industrial policy.

Investment in bio-based infrastructure is a key driver of economic impact. This encompasses biorefineries, logistics systems, and production facilities customised to bio-based inputs. The scaling up of such facilities requires substantial capital investment, often necessitating a mix of public and private funding. Public investment fulfils a catalytic role in de-risking early-stage technologies and attracting private sector participation. Financial instruments such as green bonds, innovation grants, and loan guarantees can facilitate additional investment. Furthermore, the advent of novel business models within the bioeconomy is precipitating a paradigm shift in conventional industrial dynamics. Subscription-based models, product-as-a-service concepts, and circular supply chains are reshaping the way value is created and captured. These models enhance resource efficiency and offer competitive advantages in a market that is increasingly focused on sustainability.

Technological innovation is of pivotal significance to the bioeconomy. Advancements in biotechnology, synthetic biology, process engineering and materials science are continuously broadening the scope of bio-based production. A notable example of this is the capacity of genetically engineered microorganisms to convert biomass into high-value products, including biofuels, bioplastics, and specialty chemicals. Enzyme technologies facilitate the efficient breakdown of lignocellulosic materials, rendering previously unusable biomass sources viable. The central role of biorefineries, analogous to conventional petrochemical refineries, lies in the conversion of biomass into a diverse range of bio-based products. Integrated biorefineries that produce fuels, chemicals, and materials simultaneously are particularly promising, as they maximise feedstock utilisation and improve economic viability. The development of modular and mobile biorefinery designs is a key focus area, with the objective being to process biomass at the source. This approach is intended to reduce transportation requirements and enable distributed production systems.

Digital technologies are increasingly being integrated into bio-based systems to enhance performance, traceability, and efficiency. Precision agriculture utilises satellite imagery, sensors, and machine learning algorithms to optimise resource input and enhance crop yield, while concomitantly reducing environmental impact. A similar approach is seen in smart forestry, where data analytics and remote sensing are used to manage forest resources sustainably. The application of blockchain technology ensures transparent tracking of bio-based products throughout their lifecycle, thereby reinforcing sustainability claims and enabling regulatory compliance. The fields of AI and big data analytics are also experiencing a period of rapid innovation that is having a significant impact on research related to the bioeconomy. These technologies facilitate the discovery of new bio-based compounds, the optimisation of fermentation processes, and the modelling of environmental impacts. Digital twins, defined as virtual replicas of physical processes, have emerged as a pivotal tool for simulating and optimising biorefinery operations, thereby enhancing productivity and reducing waste.

These innovations are in alignment with the objectives of the European Green Deal, thus paving the way for scalable and sustainable solutions in the bio-based industry. By leveraging modular unit

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operations and cutting-edge R&D in pilot plants, Europe is strategically positioned to spearhead the global effort towards a competitive and environmentally responsible bioeconomy.

In conclusion, it is asserted that the European bio-based industry is poised to play a transformative role in advancing strategic autonomy, environmental sustainability, economic resilience, and technological leadership. By prioritising these fundamental aspects, the EU can capitalise on the full potential of the bioeconomy as a cornerstone of its green and digital transition. The future of the European bioeconomy is therefore dependent on continued innovation, strategic investment, and a commitment to integrating sustainability at the heart of industrial development.

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10 TOBEREAL QUESTIONNAIRE

10.1 ToBeReaL Questionnaire

The ToBeReaL project aims to promote and support the development of bioeconomy projects across Europe, with a particular focus on underdeveloped regions. Its goal is to overcome obstacles and create flagship projects that represent innovative and sustainable biological solutions.

This survey, led by AINIA and PNO ES, aims to gather insights for key stakeholders in the bioeconomy sector, especially in view of the rich diversity of EU regions. This questionnaire takes approximately 20 minutes. Your responses will help identify challenges, opportunities, and areas for policy support.

Based on your answers and stakeholder type, specific sections of the questionnaire have been tailored to provide a more valuable and relevant experience while gathering accurate information about participants' involvement in the bioeconomy sector.

By participating in this survey, you will gain free access to the ToBeReaL Community Platform, which includes exclusive features such as access to patents, academic papers, funded projects, and online webinars.

This questionnaire has been designed in accordance with the General Data Protection Regulation (GDPR) (EU) 2016/679 and follows the Horizon Europe framework's ethical and data protection guidelines. All personal data collected through this survey will be processed lawfully, fairly, and transparently. Data will be used solely for research and analytical purposes related to the ToBeReaL project and will not be shared with unauthorized third parties. Responses will be anonymized where applicable, and appropriate technical and organizational measures have been implemented to safeguard the confidentiality and integrity of the collected data. Participants have the right to access, rectify, or erase their data and may withdraw their consent at any time.

For further details on data protection measures, please contact the data controller of this study (francisco.julia@pnoconsultants.com).

The figure below illustrates the initial page of the questionnaire, which was completed by various participants (completed by 87 respondents on 10 May 2025) and subsequently the scheme of the questionnaire's first version, which has been endorsed by all partners of the EU-funded ToBeReaL project. During the development of the questionnaire, efforts were made to enhance its agility, dynamism and ease of understanding. This was achieved through a reduction in the number of open questions and a reconfiguration of the interconnexion routes between sections, with the objective of facilitating the completion of the questionnaire by the participant.

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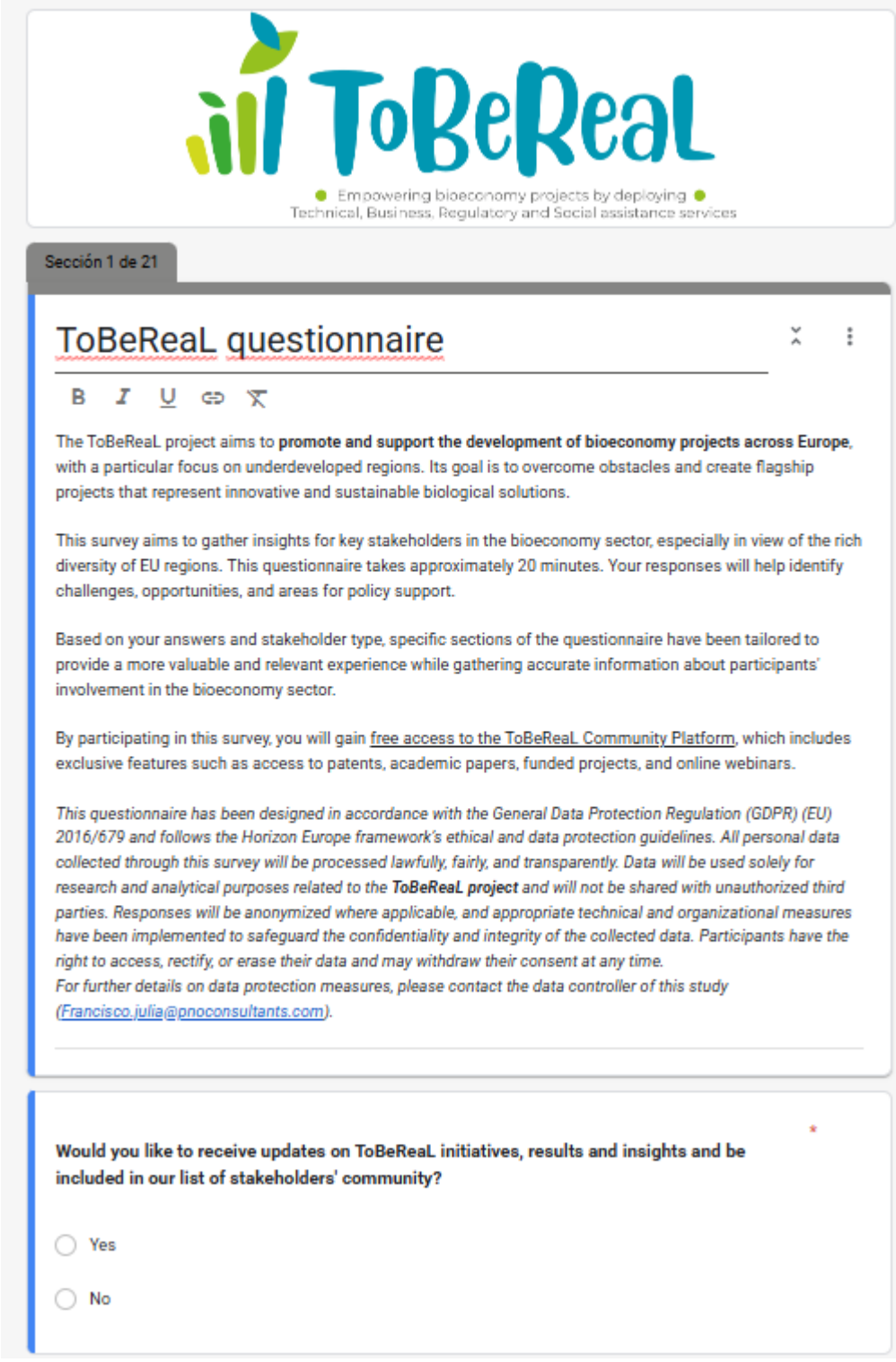


Figure 15. - First page of the ToBeReal questionnaire.

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1. GENERAL INFORMATION

Name of your organisation:
Type of organisation:

- [ ] SME (e.g., bio-based product manufacturers, agri-tech start-ups, or local bioeconomy service providers).
- [ ] Large enterprise (e.g., multinational companies in biofuels, bioplastics, or biotechnology).
- [ ] Technological/research center (e.g., RTOs, innovation hubs, R&D institutions, or labs specialising in bio-based technologies).
- [ ] University (e.g., academic institutions conducting bioeconomy research or training the future workforce).
- [ ] Cluster/network organisation (e.g., regional bioeconomy clusters, industry alliances, or multi-actor partnerships).
- [ ] Governmental body (e.g., ministries of agriculture, energy, or environment, or regional policy development agencies).
- [ ] Non-governmental organisations or NGO (e.g., sustainability advocacy groups or organisations promoting circular bioeconomy practices).
- [ ] Farmers' cooperative or association (e.g., collectives producing bio-based feedstocks or engaging in sustainable agricultural practices).
- [ ] Logistics and supply chain company (e.g., companies involved in transporting or storing bio-based materials or products).
- [ ] Certification or standard body (e.g., organisations providing eco-certifications, bio-based product labelling, or compliance assessments).
- [ ] Venture capital or private investment firm (e.g., investors specialising in green innovation or bio-based start-ups).
- [ ] Other (please specify):

Open question: Country of origin of your organisation
Rate the current technological readiness of your R&D project:

- [ ] TRL 4
- [ ] TRL 5
- [ ] TRL 6
- [ ] TRL 7
- [ ] TRL 8

Open question: What do you consider to be the top three technological challenges/barriers to developing flagship bioeconomy projects in your region? (According to the **Circular Bio-Based Europe Strategic Research Agenda**, a flagship project is a first-of-a-kind innovation action project ending at TRL 8 that includes all sections of a sustainable circular bio-based system: from feedstock through to market application and end of life).
Which of the following areas present the most significant barriers to your project? (Select all that apply)

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- [ ] Process efficiency.
- [ ] Bioconversion process.
- [ ] Technology integration.
- [ ] Process automation.
- [ ] Social Acceptance.
- Market/consumer demand
- [ ] Regulatory barriers.
- [ ] Energy consumption.
- [ ] Energy-intensive production systems.
- [ ] Production costs.
- [ ] Scalability.
- [ ] Feedstock supply, logistics and variability.
- [ ] Economic feasibility.

Open question: Describe any innovative technologies or approaches you have implemented to overcome these challenges? Please add a brief description of them.

Which stage of the bioeconomy value chain does your organisation primarily focus on?

- [ ] Feedstock supply (e.g., cultivation and harvesting of crops for bio-based materials, forestry management, forestry industry by-products, marine biomass collection such as algae, or waste material sourcing).
- [ ] Bioconversion and processing (e.g., biorefineries, fermentation, enzymatic processes, biomass pretreatment, or integrating biotechnologies to convert raw materials into bio-based intermediates or products).
- [ ] Product development and market launch (e.g., developing biodegradable plastics, bio-based chemicals, biofuels, or launching sustainable consumer products to market).
- [ ] Circular solutions (e.g., waste valorisation, recycling or upcycling agricultural or industrial waste, composting, biochar production, or closed-loop production models).
- [ ] Distributors and marketers (wholesale and retail companies that bring bioproducts to market).
- [ ] Consumers or End-Users (who determine the final value of products by choosing what to buy in regional, national, and international markets).
- [ ] Local communities (that participate in the implementation and benefit from bioeconomy projects, especially in rural areas).
- [ ] Entrepreneurs (who develop new business models and products based on the bioeconomy).
- [ ] Other (please specify):

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2. FEEDSTOCK SUPPLY (if Feedstock supply option is selected).

How would you rate the current availability of sustainable feedstocks for bioeconomy projects in your region?

- [ ] Very low
- [ ] Low
- [ ] Moderate
- [ ] High
- [ ] Very high

On a scale of 1 to 5, being 1 the least optimistic and 5 the most optimistic, how optimistic are you about increasing feedstock availability for bioeconomy projects by 2030?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What are the main challenges in securing a stable supply of feedstock for bioeconomy projects? (Select all that apply)

- [ ] Seasonal variability.
- [ ] Competition with food crops.
- [ ] Competition with existing biomass consuming industries.
- [ ] Logistical issues.
- [ ] Quality inconsistencies.
- [ ] Regulatory barriers.
- Price volatility
- [ ] Other (please specify):

Open question: What specific technological innovations have you identified as necessary to maximise the valorisation of your feedstock?

What are the primary sustainable feedstock sources available in your region? (check all that apply and specify where applicable)

- Agricultural surplus production (edible food that is not sold due to market demand or aesthetic properties)
- [ ] Agricultural residues (e.g., straw, corn stover, wheat, sugarcane, oilseeds, husks, or bagasse).
- [ ] Forestry residues (e.g., wood chips, sawdust, bark, or thinning residues).
- [ ] Dedicated energy crops (e.g., miscanthus, switchgrass, or short-rotation coppice like willow or poplar).
- [ ] Municipal waste (e.g., organic household waste, municipal solid waste, or garden waste, amongst others).
- [ ] Aquatic biomass (e.g., aquatic plants, algae, microalgae, macroalgae/seaweed, fish processing by-products).

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- [ ] Industrial waste and side-streams (e.g., food processing waste, pulp and paper industry by-products, animal manure, fats, glycerol, spent grain, bagasse, or fermentation and/or manufacturing residues).
- Other (please specifiy):

3. FARMING (if Agricultural Residues and Other Plant-based biomass options are selected).

Which types of crops or agricultural products do you primarily produce?

- [ ] Cereals
- [ ] Oilseeds
- [ ] Sugar crops
- [ ] Lignocellulosic crops
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 the least efficient and 5 the most efficient, how would you rate current harvesting technologies for bioeconomy-specific crops?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What are the main challenges in producing biomass for bioeconomy projects?

- [ ] Soil degradation.
- [ ] Water management.
- [ ] Pest control.
- [ ] Climate change impacts.
- [ ] Competition with food crops.
- [ ] Economic feasibility
- [ ] Other (please specify):

Open question: How do you think agricultural practices need to evolve to better support bioeconomy projects?

What type of technological support would most benefit your biomass production for bioeconomy?

- [ ] Precision agriculture tools.
- [ ] Crop monitoring systems.
- [ ] Improved irrigation technologies.
- [ ] Sustainable pest management solutions.
- [ ] Other (please specify):

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4. AQUATIC BIOMASS (if Aquatic Biomass option is selected).

What type of aquatic biomass do you primarily harvest for bioeconomy projects?

- [ ] Algae.
- [ ] Fish by-products.
- [ ] Shellfish.
- [ ] Aquatic plants.
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 the least developed and 5 the most developed, how would you rate current technologies for sustainable aquatic biomass harvesting?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What is your biggest challenge in providing aquatic biomass for bioeconomy projects?

- [ ] Overfishing concerns.
- [ ] Water pollution.
- [ ] Climate change impacts.
- [ ] Regulatory restrictions.
- Feedstock availability.
- [ ] Other (please specify):

Open question: How do you think fishing and aquaculture practices need to change to better support bioeconomy projects?

What technological innovation would most benefit your aquatic biomass production for bioeconomy?

- [ ] Advanced fish finding technology.
- [ ] Sustainable aquaculture systems.
- [ ] Improved processing and preservation methods.
- [ ] Waste reduction technologies.
- [ ] Improved economic feasibility.
- [ ] Improved sustainability.
- [ ] Other (please specify):

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5. FORESTRY (if Forestry Residues option is selected):

What type of forest biomass is of most interest in bioeconomy projects?

- [ ] Forest residues.
- [ ] Sawdust
- [ ] Wood chips
- [ ] Short rotation coppice.
- [ ] Bark.
- [ ] Leaves and needles.
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 the least sustainable and 5 the most sustainable, how would you rate current forest management practices for bioeconomy purposes?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What are the main challenges in contracting or securing forest biomass for bioeconomy projects?

- [ ] Sustainable forest management.
- [ ] Efficient harvesting techniques.
- [ ] Transportation and logistics.
- [ ] Balancing ecosystem services.
- [ ] Competition with existing biomass consuming industries.
- [ ] Unwillingness/Reluctance to incorporate new innovative business in existing bio-based industries.
- [ ] Cost-effectiveness of biomass, collection and processing.
- [ ] Seasonal variations in biomass availability.
- [ ] Quality and consistency of biomass supply.
- [ ] Regulatory barriers and policy uncertainties.
- [ ] Lack of established markets for biomass products.
- [ ] Environmental concerns and sustainability requirements.
- [ ] Other (please specify):

What technological innovation would most benefit your forest biomass production for bioeconomy?

- [ ] Advanced and reliable forest monitoring.
- [ ] Precision forestry tools.
- [ ] Improved biomass conversion technologies.
- [ ] Sustainable harvesting equipment.
- [ ] Cost-effective harvesting.
- [ ] Logistic solutions for different assortments.
- [ ] Other (please specify):

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6. DEDICATED ENERGY CROPS (if Dedicated Energy Crops option is selected):

What type of dedicated energy crops do you primarily produce?

- [ ] Switchgrass (e.g., for biofuels, biopower, or as a feedstock for bioplastics).
- [ ] Miscanthus (e.g., for bioenergy, bio-based materials, or biogas production).
- [ ] Short-rotation woody crops (e.g., poplar, willow, eucalyptus, or other fast-growing trees for bioenergy or bio-based products).
- [ ] Energy sorghum (e.g., for ethanol production, biogas, or livestock feed integration in bioeconomy).
- [ ] Perennial grasses (e.g., reed canary grass, giant reed, or other grasses cultivated for bio-based applications).
- [ ] Oilseed crops (e.g., camelina, jatropha, or other crops for biodiesel or biolubricants).
- [ ] Industrial hemp (e.g., for bio-based textiles, biocomposites, or bioenergy).
- [ ] Other (please specify):

How long have you been involved in dedicated energy crop production?

- [ ] Less than 2 years.
- [ ] 2-5 years.
- [ ] 6-10 years.
- [ ] More than 10 years.

What is the primary end-use for your energy crops?

- [ ] Biofuel production.
- [ ] Biopower production.
- [ ] Bio-based materials.
- [ ] Other (please specify):

What are the main challenges in maintaining consistent feedstock availability?

- [ ] Weather variability.
- [ ] Pest and disease management.
- [ ] Soil quality issues.
- [ ] Harvesting and storage logistics.
- [ ] Market demand fluctuations.
- [ ] Price volatility.
- [ ] Other (please specify):

Open question: How do you manage the seasonal variability of feedstock production to ensure a stable supply throughout the year?

What percentage of your energy crops are grown on marginal or underutilised land?

- [ ] 0-25%.
- [ ] 26-50%.
- [ ] 51-75%.
- [ ] 76-100%.

Which sustainability practices have you implemented in your energy crop production? (select all that apply)

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- [ ] Reduced tillage.
- [ ] Precision agriculture techniques.
- [ ] Integrated pest management.
- [ ] Water conservation measures.
- [ ] Other (please specify):

Open question: How has the production of dedicated energy crops affected soil health and biodiversity on your land?

How would you describe the current market demand for energy crops?

- [ ] Rapidly growing.
- [ ] Steadily growing.
- [ ] Stable.
- [ ] Declining.
- [ ] Uncertain.

What is your primary motivation for producing dedicated energy crops?

- [ ] Economic returns.
- [ ] Environmental benefits.
- [ ] Diversification of farm income.
- [ ] Government incentives.
- [ ] Other (please specify):

Open question: What policy measures or market conditions would encourage you to expand your dedicated energy crop production?

Which emerging technologies have you adopted or plan to adopt in your energy crop production (select all that apply)

- [ ] Precision agriculture and remote sensing.
- [ ] Genetic modification & NBTs for improved yields.
- [ ] Advanced harvesting equipment.
- [ ] Artificial intelligence for crop management.
- [ ] None.
- [ ] Other (please specify):

How important do you think emerging technologies will be in improving feedstock availability and quality by 2030?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

What do you see as the biggest challenge for expanding dedicated energy crop production? (select top 2)

- [ ] Competition with food crops.
- [ ] Lack of established markets.

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- [ ] High initial investment costs.
- [ ] Limited processing infrastructure.
- [ ] Regulatory uncertainty.
- Feedstock availability.
- [ ] Other (please specify):

What do you believe is the most critical step to improve feedstock availability from dedicated energy crops?

- [ ] Increased research and development.
- [ ] Better market incentives.
- [ ] Improved logistics and transportation.
- [ ] Enhanced policy support.
- [ ] Development of more efficient conversion technologies.
- [ ] Other (please specify):

Open question: Based on current trends and emerging technologies, how do you think dedicated energy crop production and feedstock availability will evolve by 2030?

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7. ORGANIC WASTE (if Organic Waste option is selected):

What type of municipal waste do you primarily manage?

- [ ] Organic household waste (e.g., kitchen scraps, expired food, or biodegradable packaging).
- [ ] Municipal solid waste (e.g., mixed organic fractions, compostable materials separated from general waste).
- [ ] Garden and landscaping waste (e.g., grass clippings, leaves, tree trimmings, or other green waste).
- [ ] Food waste from commercial establishments (e.g., restaurants, supermarkets, food processing facilities, or catering services).
- [ ] Agricultural residues collected in urban or peri-urban areas (e.g., crop leftovers, manure from urban livestock).
- [ ] Sewage sludge (e.g., from wastewater treatment plants, used for biogas or compost production).
- [ ] Biodegradable packaging waste (e.g., compostable plastics, paper, or cardboard waste).
- [ ] Other (please specify):

How long has your organisation been involved in managing organic or municipal waste?

- [ ] Less than 2 years.
- [ ] 2-5 years.
- [ ] 6-10 years.
- [ ] More than 10 years.

What is the primary end-use for your collected organic waste?

- [ ] Composting.
- [ ] Anaerobic digestion for biogas production.
- [ ] Feedstock for biorefineries.
- [ ] Landfilling.
- [ ] Other (please specify):

What are the main challenges in maintaining consistent organic waste collection?

- [ ] Public participation in waste sorting.
- [ ] Contamination with non-organic materials.
- [ ] Seasonal variations in waste generation.
- [ ] Collection logistics.
- [ ] Storage and preservation issues.
- [ ] Other (please specify):

Open question: How do you manage seasonal variations in organic waste generation to ensure a stable supply for bioeconomy applications?

What percentage of your collected organic waste is currently diverted from landfills?

- [ ] 0-25%.
- [ ] 26-50%.

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- [ ] 51-75%.
- [ ] 76-100%.

Which circular economy practices have you implemented in your waste management system? (select all that apply)

- [ ] Separate collection of organic waste.
- [ ] On-site composting programs.
- [ ] Anaerobic digestion for energy recovery.
- [ ] Nutrient recovery from waste.
- [ ] Other (please specify):

Open question: How has the implementation of circular economy principles affected the overall sustainability of your waste management system?

How would you describe the current market demand for products derived from organic waste in your region?

- [ ] Rapidly growing.
- [ ] Steadily growing.
- [ ] Stable.
- [ ] Declining.
- [ ] Uncertain.

What is your primary motivation for exploring bioeconomy applications for organic waste?

- [ ] Reducing landfill usage.
- [ ] Generating revenue from waste.
- [ ] Meeting regulatory requirements.
- [ ] Environmental benefits.
- [ ] Other (please specify):

Open question: What policy measures or market conditions would encourage you to expand the use of organic waste in bioeconomy applications?

Which emerging technologies have you adopted or plan to adopt in your organic waste management? (select all that apply)

- [ ] Advanced sorting and contamination removal systems.
- [ ] Hydrothermal carbonisation.
- [ ] Microbial fuel cells.
- [ ] AI-driven waste collection optimisation.
- [ ] Other (please specify):

How important do you think emerging technologies will be in improving the utilisation of organic waste in the bioeconomy by 2030?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

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What do you see as the biggest challenge for expanding the use of organic waste in the bioeconomy? (select top 2)

- [ ] Inconsistent waste quality and availability
- [ ] Lack of processing infrastructure.
- [ ] Public/consumer perception and participation.
- [ ] Competition with other waste management methods.
- [ ] Regulatory barriers.
- [ ] Logistic challenges.
- [ ] Other (please specify):

What do you believe is the most critical step to improve the utilisation of organic waste in the bioeconomy?

- [ ] Improved waste sorting technologies.
- [ ] Development of more efficient conversion processes.
- [ ] Enhanced public education and engagement.
- [ ] Supportive policy frameworks.
- [ ] Access to subsidies for technology development.
- [ ] Increased investment in processing facilities.
- [ ] Other (please specify):

Open question: Based on current trends and emerging technologies, how do you think the role of organic waste in the bioeconomy will evolve by 2030?

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8. AQUATIC BIOMASS (if Aquatic Biomass option is selected):

What type of aquatic biomass do you primarily work with?

- [ ] Aquatic plants (e.g., water hyacinth, duckweed, or other freshwater plants used for bioenergy or bioproducts).
- [ ] Microalgae (e.g., Chlorella, Spirulina, Nannochloropsis, or other species used for biofuels, bioplastics, or nutraceuticals).
- [ ] Macroalgae/seaweed (e.g., kelp, red algae, brown algae, or green algae for biogas, biofertilisers, or food ingredients).
- [ ] Fish processing by-products (e.g., fish oil, fish meal, scales, or other residues used for bio-based materials or fertilisers).
- [ ] Crustacean shell waste (e.g., shrimp shells, crab shells, or lobster shells for chitosan extraction or other bio-based applications).
- [ ] Aquaculture residues (e.g., waste biomass from aquaculture systems, including uneaten feed or feces, for biogas or biofertilisers).
- [ ] Freshwater algae (e.g., blue-green algae for bioproducts or bioenergy).
- [ ] Other (please specify):

How long has your organisation been involved in aquatic biomass production or processing?

- [ ] Less than 2 years.
- [ ] 2-5 years.
- [ ] 6-10 years.
- [ ] More than 10 years.

What is the primary end-use for your aquatic biomass?

- [ ] Food and nutrition.
- [ ] Biofuels.
- [ ] Cosmetics and pharmaceuticals.
- [ ] Bio-based materials.
- [ ] Other (please specify):

What are the main challenges in maintaining consistent aquatic biomass production? (Select all that apply)

- [ ] Environmental factors (temperature, pH, etc.).
- [ ] Nutrient availability.
- [ ] Contamination issues.
- [ ] Harvesting and processing logistics.
- [ ] Market demand fluctuations.
- [ ] Other (please specify):

Open question: How do you manage seasonal variations in aquatic biomass production to ensure a stable supply throughout the year?

What percentage of your aquatic biomass is produced through sustainable cultivation methods?

- [ ] 0-25%.
- [ ] 26-50%.

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- [ ] 51-75%.
- [ ] 76-100%.

Which sustainability practices have you implemented in your aquatic biomass production? (select all that apply)

- [ ] Integrated multi-trophic aquaculture.
- [ ] Closed-loop production systems.
- [ ] Use of renewable energy in operations.
- [ ] Waste reduction and recycling.
- [ ] Other (please specify):

Open question: How has your aquatic biomass production affected local marine or freshwater ecosystems?

How would you describe the current market demand for your aquatic biomass products?

- [ ] Rapidly growing.
- [ ] Steadily growing.
- [ ] Stable.
- [ ] Declining.
- [ ] Uncertain.

What is your primary motivation for producing or processing aquatic biomass?

- [ ] Economic returns.
- [ ] Environmental benefits.
- [ ] Food security.
- [ ] Bioremediation potential.
- [ ] Other (please specify):

Open question: What policy measures or market conditions would encourage you to expand your aquatic biomass production or processing?

Which emerging technologies have you adopted or plan to adopt in your aquatic biomass production or processing? (select all that apply)

- [ ] Advanced cultivation systems (e.g., photobioreactors).
- [ ] Genetic modification for improved yields.
- [ ] AI-driven monitoring and control systems.
- [ ] Novel extraction and processing technologies.
- [ ] Other (please specify):

How important do you think emerging technologies will be in improving aquatic biomass production and utilisation by 2030?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

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What do you see as the biggest challenge for expanding aquatic biomass production and utilisation? (select top 2)

- [ ] Scaling up production.
- [ ] Regulatory barriers.
- [ ] Feedstock availability.
- [ ] Competition with traditional biomass sources (price).
- [ ] Limited processing infrastructure.
- [ ] Public perception and acceptance.
- [ ] Other (please specify):

What do you believe is the most critical step to improve the utilisation of aquatic biomass in the bioeconomy?

- [ ] Increased research and development.
- [ ] Improved cultivation and harvesting technologies.
- [ ] Enhanced public awareness and education.
- [ ] Supportive policy and financial frameworks
- [ ] Development of new bio-based products.
- [ ] Other (please specify):

Open question: Based on current trends and emerging technologies, how do you think the role of aquatic biomass in the bioeconomy will evolve by 2030?

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9. INDUSTRIAL WASTE (if Industrial Waste and Side-Streams option is selected):

What type of industrial waste or side-streams do you primarily manage?

- [ ] Food and beverage industry waste (e.g., brewery spent grains, fruit and vegetable peels, whey, coffee grounds, or used cooking oil).
- [ ] Pulp and paper industry residues (e.g., lignin, black liquor, bark, or other wood-processing by-products).
- [ ] Textile industry waste (e.g., cotton scraps, wool trimmings, or polyester fibres).
- [ ] Agricultural processing residues (e.g., husks, shells, or meal from oilseed processing like soy or sunflower).
- [ ] Bioethanol or biodiesel production residues (e.g., glycerol, distillers' grains, or press cakes).
- [ ] Chemical industry by-products (e.g., organic acids, solvents, or waste streams from biorefining processes).
- [ ] Construction and demolition waste (e.g., residues and bio-based materials used in construction).
- [ ] Pharmaceutical or cosmetic industry residues (e.g., plant extracts, by-products from essential oil production).
- [ ] Bioplastics production side-streams (e.g., off-spec polymer batches or scraps from manufacturing processes).
- [ ] Animal processing waste (e.g., fats, bones, or hides from slaughterhouses for bioenergy or bioproducts).
- [ ] Other (please specify):

How long has your organisation been involved in managing these industrial wastes or side-streams?

- [ ] Less than 2 years.
- [ ] 2-5 years.
- [ ] 6-10 years.
- [ ] More than 10 years.

What is the primary end-use for your collected industrial waste or side-streams?

- [ ] Bioenergy production.
- [ ] Biochemicals.
- [ ] Soil amendments.
- [ ] Bio-based materials.
- [ ] Other (please specify):

What are the main challenges in maintaining consistent waste collection? (Select all that apply)

- [ ] Seasonal variations in production.
- [ ] Quality inconsistencies.
- [ ] Storage and preservation issues.
- [ ] Transportation logistics.
- [ ] Regulatory compliance.
- [ ] Other (please specify):

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Open question: How do you manage variations in waste or side-stream generation to ensure a stable supply for bioeconomy applications?

What percentage of your collected industrial waste or side-stream is currently diverted from landfills?

- [ ] 0-25%.
- [ ] 26-50%.
- [ ] 51-75%.
- [ ] 76-100%.

Which circular economy practices have you implemented in your waste or side-stream management system? (select all that apply)

- [ ] Industrial symbiosis.
- [ ] Waste-to-energy conversion.
- [ ] Upcycling to higher-value products.
- [ ] Nutrient recovery.
- [ ] Other (please specify):

Open question: How has the implementation of circular economy principles affected the overall sustainability of your waste management system?

How would you describe the current market demand for products derived from your industrial waste or side-streams?

- [ ] Rapidly growing.
- [ ] Steadily growing.
- [ ] Stable.
- [ ] Declining.
- [ ] Uncertain.

What is your primary motivation for exploring bioeconomy applications for industrial waste or side-streams?

- [ ] Cost reduction.
- [ ] Revenue generation.
- [ ] Regulatory compliance.
- [ ] Environmental benefits.
- [ ] Other (please specify):

Open question: What policy measures or market conditions would encourage you to expand the use of industrial waste or side-streams in bioeconomy applications?

Which emerging technologies have you adopted or plan to adopt in your waste management? (select all that apply)

- [ ] Advanced sorting and purification systems.
- [ ] Biotechnology for waste conversion.
- [ ] AI-driven process optimisation.
- [ ] Novel extraction and processing technologies.
- [ ] Other (please specify):

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How important do you think emerging technologies will be in improving the utilisation of industrial waste and side-streams in the bioeconomy by 2030?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

What do you see as the biggest challenge for expanding the use of industrial waste and side-streams in bioeconomy applications? (select top 2)

- [ ] Inconsistent waste quality.
- [ ] Regulatory barriers.
- [ ] Competition with traditional disposal methods.
- [ ] Lack of processing infrastructure.
- [ ] Limited market acceptance.
- [ ] Lack of technologies at industrial scale.
- [ ] Lack of supportive mechanisms.
- [ ] Other (please specify):

What do you believe is the most critical step to improve the utilisation of industrial waste and side-streams in the bioeconomy?

- [ ] Improved waste valorisation technologies.
- [ ] Increased investment in processing facilities.
- [ ] Enhanced cross-sector collaboration.
- [ ] Supportive policy frameworks.
- [ ] Development of new bio-based products.
- [ ] Other (please specify):

Open question: Based on current trends and emerging technologies, how do you think the role of industrial waste and side-streams in the bioeconomy will evolve by 2030?

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10. TECHNOLOGY AND INNOVATION (if Bioconversion and processing option is selected):

Is your organisation currently integrating multiple technologies to enhance bio-based processes?

- [ ] Yes
- [ ] No
- If yes, which technologies are being integrated?

What type of biotech-related products does your company/institution primarily produce?

- [ ] Biofuels and other advanced fuels.
- [ ] Bulk chemicals.
- [ ] Bioplastics.
- [ ] Bioactive compounds.
- [ ] Enzymes.
- [ ] Food.
- [ ] Feed.
- [ ] Proteins
- [ ] Personal care products and cosmetics.
- [ ] Packaging and biomaterials
- [ ] Specialty chemicals
- [ ] Other (please specify):

How long has your company/institution been involved in biotech-related production?

- [ ] Less than 2 years.
- [ ] 2-5 years.
- [ ] 6-10 years.
- [ ] More than 10 years.

What is your company/institution's primary focus in the bioeconomy value chain?

- [ ] Raw material processing.
- [ ] Intermediate product manufacturing.
- [ ] End-product development.
- [ ] Technology provider.
- [ ] Scale-up/Piloting[ ] Other (please specify):

What role will gas feedstocks play in the future of the bioeconomy? (check all that apply and specify where applicable)

- [ ] Carbon Dioxide (CO2) (e.g., utilisation for microbial fermentation, chemical synthesis like fuels or bioplastics, or algal growth).
- [ ] Methane (CH4) (e.g., biogas from anaerobic digestion, landfill gas, or renewable natural gas for energy or conversion to biochemicals).
- [ ] Hydrogen (H2) (e.g., as a clean energy input for bio-based processes or synthetic fuel production).
- [ ] Carbon Monoxide (CO) (e.g., use in syngas fermentation for bio-based chemical production).

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- [ ] Syngas (CO + H2) (e.g., derived from gasification of biomass for biofuel or chemical synthesis).
- [ ] Nitrogen-based Gases (e.g., ammonia, N2O) (e.g., for agricultural applications or industrial processes).
- [ ] Other Gas Feedstocks (e.g., oxygen, volatile organic compounds or specialty gases, please specify):

In your opinion, what are the most pressing technological gaps that need to be addressed to align bioeconomy projects with EU and UN goals?

- [ ] High production costs.
- [ ] Low process efficiency.
- [ ] Lack of scalability.
- [ ] High energy consumption.
- [ ] Limited access to advanced technologies.
- [ ] Technology integration.
- [ ] Feedstock variability or quality issues.
- [ ] Feedstock cost.
- [ ] Insufficient automation or process control.
- [ ] Other (please specify):

On a scale of 1 to 5 (being 1 highest priority, 5 lowest priority), which of the following technology areas require the most improvement to advance bio-based processes?

- [ ] Biotechnologies (e.g. synthetic biology, metabolic engineering, fermentation technology, CRISPR and genome editing, enzyme engineering, bioprocess engineering, omics technologies).
- [ ] Process automation and control.
- [ ] Digital technologies (e.g. AI, IoT, predictive analytics).
- [ ] Feedstock pretreatment and valorisation.
- [ ] Implementation of Circular economy technologies.

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11. CHALLENGES AND OPPORTUNITIES:

Open question: What specific technologies do you believe are critical for overcoming current bioeconomy roadblocks?
Open question: What specific technological innovations have you identified as necessary to maximise the valorisation of your feedstock?
According to your experience in bioeconomy projects, are there technological solutions that you consider underutilized in bioeconomy projects? Please answer this question based on your specific role and experience in the bioeconomy sector, considering your unique insights and the constraints or opportunities within your regional ecosystem or organisational activities. We recognise that responses may vary depending on your perspective (e.g., cluster organisation, company, research institution, distributor, end-user, etc.)?

- [ ] Yes
- [ ] No
- If yes, please specify:

According to your experience in bioeconomy projects or collaborations, are there specific policies or funding gaps that hinder technological development and innovation in bioeconomy projects? Please consider the following aspects in your response: policy barriers (e.g., regulatory inconsistencies or complex administrative procedures), funding gaps (e.g., difficulties in accessing finance for specific project groups or limitations in available financial instruments), innovation challenges (e.g., gaps in support for transitioning from research to commercial markets or obstacles in accessing appropriate skills or expertise), market access (e.g., barriers to entering the market with bio-based products or the need for policies to stimulate demand for bioeconomy products), and regional disparities (e.g., the presence of significant differences in bioeconomy support across EU regions or the impact of national and regional bioeconomy strategies in your activities).

- [ ] Yes
- [ ] No
- If yes, please specify:

Open question: Based on your experience in previous and ongoing bioeconomy projects, what technological advancements do you consider most critical for the bioeconomy sector in your region over the next 5 years?
Indicate any collaborations or partnerships that have been crucial in overcoming technological barriers in your organisation.

- [ ] Industry Partnerships (e.g., collaborations with companies for technology transfer, scaling, or commercialisation).
- [ ] Academic Collaborations (e.g., research partnerships with universities or research institutions).
- [ ] Government or Policy Support (e.g., funding, regulatory advice, or public-private partnerships).
- [ ] Cluster or Network Organisations (e.g., bioeconomy clusters, innovation hubs, or trade associations).

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- [ ] Technological Centers (e.g., specialised R&D facilities or innovation accelerators).
- [ ] Cross-Sector Partnerships (e.g., partnerships with non-bioeconomy sectors like IT, energy, or materials science).
- [ ] International Collaborations (e.g., partnerships across EU regions or with non-EU countries).
- Other collaborations (please specify:).

How would you rate the collaboration between stakeholders (e.g. industry, academia, policymakers) in addressing technological barriers in bioeconomy projects?

- [ ] Poor.
- [ ] Fair.
- [ ] Good.
- [ ] Excellent.

What key outcomes would you like to see from efforts to address technological roadblocks in the bioeconomy sector? (check all that apply and elaborate where necessary).

- [ ] Increased Process Efficiency (e.g., improved yields, reduced energy consumption, or shorter production cycles).
- [ ] Lower Production Costs (e.g., affordable bio-based products or cost-competitive alternatives to fossil-based products).
- [ ] Scalability of Technologies (e.g., successful scale-up from pilot to commercial levels).
- [ ] Enhanced Sustainability (e.g., reduced environmental impact, better resource efficiency, or circularity in processes).
- [ ] Broader Technology Adoption (e.g., widespread integration of advanced technologies across regions and industries).
- [ ] Diversification of Feedstocks (e.g., more efficient utilisation of underexploited or regional feedstocks).
- [ ] Market Expansion (e.g., creation of new markets for bio-based products or increased market share of bioeconomy products).
- [ ] Improved Collaboration (e.g., stronger partnerships between stakeholders such as industry, academia, and policymakers).
- [ ] Policy and Regulatory Support (e.g., clearer regulatory frameworks, better funding mechanisms, or incentives for innovation).
- [ ] Increased Public Awareness (e.g., greater consumer acceptance of bio-based products and their benefits).
- [ ] Other Outcomes (please specify:).

What are the main challenges technological stakeholders and companies face in implementing new technologies in bioeconomy processes? (Select all that apply)

- [ ] High initial investment costs.
- [ ] Lack of skilled workforce.
- [ ] Regulatory barriers.
- [ ] Scaling up opportunities.

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- [ ] Technological complexity.
- [ ] Market uncertainty.
- High-risk of investment
- [ ] Other (please specify):

What emerging technologies do you believe will have the most significant impact on the bioeconomy sector? (Select top 3)

- [ ] Biotechnologies (e.g., advanced microbial engineering, CRISPR, synthetic biology, bioprinting, or precision fermentation).
- [ ] Digital technologies (e.g., artificial intelligence, big data analytics, machine learning, IoT for precision agriculture and bioeconomy, or digital twins).
- [ ] Nanotechnologies (e.g., nanomaterials for bioproducts or nanosensors for process monitoring).
- [ ] Renewable Energy Technologies (e.g., advanced biofuels, biogas upgrading, or integration with renewable energy systems).
- [ ] Advanced Bioconversion Systems (e.g., enzyme development, or anaerobic digestion technologies).
- [ ] Circular Economy Innovations (e.g., technologies for recycling bio-based products, waste valorisation, or closed-loop systems).
- [ ] Process Automation and Robotics (e.g., automated systems for bio-based production or smart factories).
- [ ] Carbon Capture and Utilisation (CCU) (e.g., CO2-to-chemicals, single cell proteins SCP for food or feed, fuels, or bioplastics).
- [ ] Feedstock-Specific Technologies (e.g., advanced pretreatment methods for lignocellulosic biomass or algae cultivation systems).
- [ ] Other Emerging Technologies (please specify):

Open question: What challenges do you foresee in adopting these emerging technologies?

Open question: What are the most promising bio-based technological strategies for your specific region or country?

Open question: What do you see as the most promising technological breakthrough for your sector of the bioeconomy in the next 5 years?

On a scale of 1 to 5, being 1 least significant and 5 the most significant, how would you rate the potential impact of AI-driven processes in optimising bioeconomy supply chains?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

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12. SUSTAINABILITY AND CIRCULAR ECONOMY:

How important is the implementation of circular economy principles in bioeconomy processes?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

Which sustainable practices do you think companies have adopted in bioeconomy operations? (Select all that apply)

- [ ] Waste reduction and recycling.
- [ ] Use of renewable energy.
- [ ] Waste conservation.
- [ ] Carbon capture and utilisation.
- [ ] Other (please specify):

Which policy measures do you believe would most effectively support technological innovation in the bioeconomy sector? (Select top 3)

- [ ] Increased R&D funding.
- [ ] Tax incentives for bio-based products.
- [ ] Streamlined regulatory processes.
- [ ] Support for technology transfer and scale up processes
- [ ] Enhanced public-private partnerships.
- [ ] Other (please specify):

What do you think is the biggest opportunity for technological companies in the bioeconomy sector?

- [ ] Developing novel bio-based materials.
- [ ] Improving process efficiency through AI and automation.
- [ ] Creating circular economy solutions.
- [ ] Advancing synthetic biology applications.
- [ ] Scaling up sustainable production methods.
- [ ] Other (please specify):

Open question: What innovations or trends do you foresee shaping the bio-based product market in the coming years?

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13. COLLABORATIVE AND PARTNERSHIP ENVIRONMENT:

How important is cross-sector collaboration in driving innovation in your bioeconomy processes?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

With which stakeholders do companies primarily collaborate on bioeconomy innovation? (Select all that apply)

- [ ] Research institutions.
- [ ] Biotech companies.
- [ ] Government agencies.
- [ ] Raw material suppliers.
- [ ] End-product manufacturers.
- [ ] Other (please specify):

Open question: Describe a successful collaboration that has significantly advanced your company's bioeconomy innovation efforts. If you don't represent a company, write N/A.

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14. DISTRIBUTORS AND MARKETERS (if Product development and market launch option is selected):

What type of company do you represent?

- [ ] Wholesole distributor.
- [ ] Retail company.
- [ ] E-commerce platform.
- [ ] Other (please specify):

Which bio-based product categories does your company distribute or market? (Select all that apply and specify examples if applicable)

- [ ] Bio-based chemicals (e.g., solvents, adhesives, lubricants, or specialty chemicals like biosurfactants).
- [ ] Biofuels [e.g., bioetanol, biodiesel, biogas, or advanced biofuels such as jet biofuel).
- [ ] Bio-based plastics (e.g., polylactic acid (PLA), bio-based polyethylene, or biodegradable packaging materials).
- [ ] Bio-based textiles (e.g., fabrics made from bio-based fibers like hemp, organic cotton, or lyocell).
- [ ] Bio-based food and beverages (e.g., plant-based proteins, fermented foods, or bio-based functional ingredients).
- [ ] Bio-based materials (e.g., insulation materials from agricultural waste and fungi, wood-based batteries, biocontrol agents, mycelium-based products, bio-based glitter, or bio-based alternatives to concrete and steel).
- [ ] Other (please specify):

How long has your company been involved in distributing or marketing bio-based products?

- [ ] Less than 2 years.
- [ ] 2-5 years.
- [ ] 6-10 years.
- [ ] More than 10 years.

On a scale of 1 to 5, being 1 very low and 5 very high, how would you rate the current demand for bio-based products in your market?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What factors do you believe are driving the demand for bio-based products? (Select all that apply)

- [ ] Environmental concerns.
- [ ] Government regulations.
- [ ] Consumer preferences.
- [ ] Price competitiveness.
- [ ] Product performance.

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- [ ] Other (please specify):

Open question: What do you see as the main challenges in marketing bio-based products compared to their conventional counterparts?

What are the main supply chain challenges you face in distributing bio-based products? (Select all that apply)

- [ ] Inconsistent product quality.
- [ ] Limited product availability.
- [ ] Higher costs.
- [ ] Lack of established logistics networks.
- [ ] Regulatory compliance issues.
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 least significant and 5 most significant, how would you rate the impact of these supply chain challenges on your business?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

Open question: How do you think the bio-based product supply chain could be improved to better meet market demands?

How would you rate consumer awareness of bio-based products in your market?

- [ ] Very low.
- [ ] Low.
- [ ] Moderate.
- [ ] High.
- [ ] Very High.

What do you perceive as the main barriers to consumer adoption of bio-based products? (Select all that apply)

- [ ] Lack of awareness.
- [ ] Higher prices.
- [ ] Scepticism about product claims.
- [ ] Limited product range.
- [ ] Perceived inferior quality.
- [ ] Other (please specify):

Open question: What strategies have you found effective in educating consumers about the benefits of bio-based products?

How would you rate the current regulatory environment for bio-based products in your region?

- [ ] Very unfavourable.
- [ ] Somewhat unfavourable.
- [ ] Neutral.

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- [ ] Somewhat favourable.
- [ ] Very favourable.

Open question: Are there specific funding schemes or incentives available for bio-based businesses to support investment in your country?

Which regulatory measures do you believe would most benefit the bio-based product market? (Select all that apply)

- [ ] Tax incentives for bio-based products.
- [ ] Stricter regulations on conventional products.
- [ ] Mandatory labelling of bio-based content.
- [ ] Green public procurement policies.
- [ ] Other (please specify):

Open question: How has the recent EU law to ban greenwashing and misleading product information affected your marketing strategies for bio-based products?

On a scale of 1 to 5, being 1 least optimistic and 5 most optimistic, how optimistic are you about the growth of the bio-based product market in the next 5 years?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

Which bio-based product categories do you believe have the highest growth potential in your market? (Select top 3)

- [ ] Bio-based chemicals (e.g., solvents, adhesives, lubricants, or specialty chemicals like biosurfactants).
- [ ] Biofuels [e.g., bioetanol, biodiesel, biogas, or advanced biofuels such as jet biofuel).
- [ ] Bio-based plastics (e.g., polylactic acid (PLA), bio-based polyethylene, or biodegradable packaging materials).
- [ ] Bio-based textiles (e.g., fabrics made from bio-based fibers like hemp, organic cotton, or lyocell).
- [ ] Bio-based food and beverages (e.g., plant-based proteins, fermented foods, or bio-based functional ingredients).
- [ ] Other (please specify):

What do you think is the most critical step to accelerate the adoption of bio-based products in the market?

- [ ] Increased consumer education.
- [ ] More competitive pricing.
- [ ] Improved product performance.
- [ ] Stronger regulatory support.
- Regional/state support for market creation.
- [ ] Enhanced distribution networks.

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- [ ] Other (please specify):

Open question: What innovations or trends do you foresee shaping the bio-based product market in the coming years?

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15. CONSUMERS or END-USERS

Gender

- Female
- Male
- Other
- Prefer not to say

Age:

- 18-24
- 25-34
- 35-44
- 45 -54
- 55-64
- 65 +

Country:

- Belgium
- Bulgaria
- Croatia
- Cyprus
- Czechia
- Estonia
- France
- Greece
- Hungary
- Italy
- Latvia
- Lithuania
- Malta
- Poland
- Portugal
- Romania
- Slovakia
- Slovenia
- Spain
- Sweden
- UK

Open question: What is your job position?

How familiar are you with the bioeconomy?

- Not familiar
- Somewhat familiar

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- Very familiar

Which of the following sectors do you understand to be part of the bioeconomy?

- Agriculture
- Forestry
- Textiles (fashion)
- Biotechnology and pharma
- Fisheries and aquaculture
- Waste management
- Chemistry
- Construction
- Energy
- Tourism and recreation
- Machine industry
- Food and gastronomy
- Health and wellbeing
- Other (please specify)

How familiar are you with bio-based products?

- [ ] Not at all familiar.
- [ ] Slightly familiar.
- [ ] Moderately familiar.
- [ ] Very familiar.
- [ ] Extremely familiar.

If you are familiar, where did you get information about bioeconomy and bio-based products?

- Social networks
- Media
- Workshops
- Newspapers
- Professional articles
- Campaigns in informing citizens

Have you ever consciously purchased a bio-based product?

- [ ] Yes.
- [ ] No.
- [ ] Unsure.

Which bio-based product categories have you purchased? (Select all that apply)

- [ ] Biofuels and other advanced fuels.
- [ ] Bulk chemicals.
- [ ] Bioplastics.
- [ ] Bioactive compounds.
- [ ] Enzymes.
- [ ] Food.

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- [ ] Feed.
- [ ] Proteins.
- [ ] Personal care products and cosmetics.
- [ ] Bio-based textiles.
- [ ] Packaging and biomaterials.
- [ ] Specialty chemicals.
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 very low and 5 very high, how would you rate your understanding of the environmental benefits of bio-based products?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What factors influence your decision to purchase bio-based products? (Select all that apply)

- [ ] Environmental concerns.
- [ ] Health benefits.
- [ ] Product performance.
- [ ] Price.
- [ ] Brand reputation.
- [ ] Cultural norms
- [ ] Peer opinions
- [ ] Other (please specify):

Do you think that bio-based products are more trustworthy, of higher quality or more sustainable?

- Yes
- No
- Other

Open question: What concerns, if any, do you have about bio-based products?

Open question: What barriers do consumers face in adopting bio-based products, according to your organisation's research or experience?

How often do you actively look for bio-based alternatives when shopping?

- [ ] Never.
- [ ] Rarely.
- [ ] Sometimes.
- [ ] Often.
- [ ] Always.

Are you willing to pay a premium for bio-based products?

- [ ] Not willing to pay extra.
- [ ] Willing to pay up to 5% more.
- [ ] Willing to pay 6-10% more.

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- [ ] Willing to pay 11-20% more.
- [ ] Willing to pay more than 20% extra.

Open question: What would motivate you to purchase more bio-based products in the future?
How important is clear labelling of bio-based content in your purchasing decisions?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

Which type of information about bio-based products would you find most valuable? (Select top 3)

- [ ] Percentage of bio-based content.
- [ ] Environmental impact.
- [ ] Origin of bio-based materials.
- [ ] End-of-life disposal instructions.
- [ ] Third-party certifications.
- [ ] Other (please specify):

Open question: How do you verify the environmental claims of bio-based products?
To what extent do you trust sustainability claims on bio-based products? (1=not at all; 5=completely)
How satisfied are you with the availability of bio-based products in your local market?

- [ ] Very dissatisfied.
- [ ] Somewhat dissatisfied.
- [ ] Neutral.
- [ ] Somewhat satisfied.
- [ ] Very satisfied.

Where do you typically purchase bio-based products? (Select all that apply)

- [ ] Supermarkets.
- [ ] Specialty eco-stores.
- [ ] Online marketplaces.
- [ ] Directly from manufacturers.
- [ ] Other (please specify):

Open question: What challenges do you face in finding and purchasing bio-based products?
On a scale of 1 to 5, being 1 least likely and 5 most likely, how likely are you to increase your consumption of bio-based products in the next 5 years?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

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Which bio-based product categories are you most interested in seeing more options for? (Select top 3)

- [ ] Food packaging (e.g., biodegradable or compostable containers, bio-based films, or edible packaging materials).
- [ ] Clothing and textiles (e.g., fabrics made from bio-based fibers like bamboo, hemp, or bio-polyester).
- [ ] Personal care products (e.g., bio-based shampoos, lotions, biodegradable wipes, or cosmetics).
- [ ] Household items (e.g., bio-based detergents, cleaning products, or biodegradable utensils and tableware).
- [ ] Transportation fuels (e.g., bioethanol, biodiesel, or advanced bio-jet fuels).
- [ ] Other (please specify):

What do you think is the most critical step to encourage wider adoption of bio-based products amongst consumers?

- [ ] More affordable pricing.
- [ ] Improved product performance.
- [ ] Better education about benefits (environmental, health)
- [ ] Wider availability in stores.
- [ ] Stricter regulations on conventional products.
- [ ] Other (please specify):

Open question: How do you think consumer behaviour towards bio-based products will change in the coming years and what will influence it the most?

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15. ACADEMIC AND RESEARCH INSTITUTIONS (if Circular Solutions option is selected).

What type of institution do you represent?

- [ ] University.
- [ ] Public research center.
- [ ] Private research institute.
- [ ] Incubator.
- [ ] Other (please specify):

How long has your institution been involved in bioeconomy-related research?

- [ ] Less than 5 years.
- [ ] 5-10 years.
- [ ] 11-20 years.
- [ ] More than 20 years.

Which bioeconomy-related research areas does your institution focus on? (Select all that apply)

- [ ] Agriculture and food sciences.
- [ ] Biotechnology.
- [ ] Environmental sciences.
- [ ] Materials science.
- [ ] Social sciences and economics.
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 very low and 5 very high, how would you rate your institution's current level of bioeconomy-related research output?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What are the main challenges in conducting bioeconomy research at your institution? (Select all that apply)

- [ ] Lack of interdisciplinary collaboration.
- [ ] Funding limitations.
- [ ] Limited access to necessary equipment or facilities.
- [ ] Regulatory barriers.
- [ ] Other (please specify):

Open question: What do you consider to be your institution's most significant contribution to bioeconomy research in the past five years?

With which sectors do your institution primarily collaborate on bioeconomy projects? (Select all that apply)

- [ ] Other academic institutions (e.g., universities or research centers specialising in biotechnology, agriculture, or environmental science).

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- [ ] Industry partners (e.g., companies in bio-based manufacturing, renewable energy, chemical production, or food processing).
- [ ] Government agencies (e.g., ministries of agriculture, energy, or environment, or regional development bodies).
- [ ] Non-governmental organisations (e.g., environmental advocacy groups, sustainability organisations, or development-focused NGOs).
- [ ] International organisations (e.g., EU-funded consortia, UN agencies, or international research networks).
- [ ] Other (please specify):

How satisfied are you with the current level of knowledge transfer between your institution and industry partners in bioeconomy projects?

- [ ] Very dissatisfied.
- [ ] Somewhat dissatisfied.
- [ ] Neutral.
- [ ] Somewhat satisfied.
- [ ] Very satisfied.

Open question: What strategies has your institution found effective in fostering collaboration between academia and industry in bioeconomy projects?

Does your institution offer specific bioeconomy-related degree programs or courses?

- [ ] Yes, degree and/or PhD programs.
- [ ] Yes, individual courses.
- [ ] No, but planning to introduce them.
- [ ] No, and no current plans.

What skills do you believe are most crucial for students entering the bioeconomy sector? (select top 3)

- [ ] Interdisciplinary thinking (e.g., the ability to integrate knowledge from biology, chemistry, engineering and economics to solve complex problems).
- [ ] Data analysis and interpretation (e.g., proficiency in bioinformatics, statistical modelling, or big data analysis for bio-based approaches).
- [ ] Sustainability assessment (e.g., conducting life cycle assessments, carbon footprint analysis, or resource efficiency evaluations).
- [ ] Biotechnology expertise (e.g., skills in genetic engineering, fermentation technology, enzyme development, or bio-based process optimisation).
- [ ] Business and entrepreneurship skills (e.g., market analysis, business model development, or commercialisation strategies for bio-based innovations).
- [ ] Other (please specify):

Open question: How is your institution adapting its curriculum to meet the evolving needs of the bioeconomy sector?

How has your institution's funding for bioeconomy research changed in the past 5 years?

- [ ] Significantly decreased.

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- [ ] Slightly decreased.
- [ ] Remained the same.
- [ ] Slightly increased.
- [ ] Significantly increased.

What are your institution's primary sources of funding for bioeconomy research? (Select all that apply)

- [ ] Government grants (e.g., national funding from ministries of agriculture, environment, or energy, or regional development programs).
- [ ] European Union funding (e.g., Horizon Europe, European Regional Development Fund (ERDF), or Bio-Based Industries Joint Undertaking (BBI JU)).
- [ ] Industry partnerships (e.g., collaborations with bio-based manufacturing companies, agribusinesses, or energy firms providing research funding).
- [ ] Private foundations (e.g., philanthropic organisations or foundations funding sustainability or innovation projects).
- [ ] Institutional funds (e.g., internal research budgets or seed funding provided by your university or research institute).
- [ ] Other (please specify):

Open question: What strategies is your institution employing to secure sustainable funding for bioeconomy research?

On a scale of 1 to 5, being 1 least optimistic and 5 most optimistic, how optimistic are you about the growth of bioeconomy research at your institution in the next 5 years?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

Which policy measures do you believe would most effectively support bioeconomy research in academic institutions? (Select top 3)

- [ ] Increased public funding for research.
- [ ] Tax incentives for industry-academia collaborations.
- [ ] Streamlined regulatory processes for bio-based innovations.
- [ ] Enhanced support for international research collaborations.
- [ ] Improved mechanisms for technology transfer.
- [ ] Other (please specify):

What role do you see for academic institutions in shaping the future of the bioeconomy?

- [ ] Conducting fundamental research.
- [ ] Developing applied technologies.
- [ ] Training the future workforce.
- [ ] Informing policy decisions.
- [ ] Fostering public engagement and awareness.

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- [ ] Other (please specify):

Open question: What recommendations would your institution make to policymakers to strengthen the role of academic research in advancing the bioeconomy?

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16. LOCAL COMMUNITIES (if Local Communities option is selected):

How would you describe your community?

- [ ] Rural village.
- [ ] Small town.
- [ ] Agricultural area.
- [ ] Coastal community.
- [ ] Forest-dependent community.
- [ ] Other (please specify):

How long has your community been involved in bioeconomy projects?

- [ ] Less than 1 year.
- [ ] 1-3 years.
- [ ] 4-5 years.
- [ ] More than 5 years.

What type of bioeconomy projects are present in your community? (Select all that apply)

- [ ] Sustainable agriculture.
- [ ] Forestry and wood products.
- [ ] Bioenergy production.
- [ ] Bio-based materials manufacturing.
- [ ] Waste management and recycling.
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 least involved and 5 most involved, how would you rate your community's involvement in local bioeconomy projects?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What are the main benefits your community has experienced from bioeconomy projects? (Select all that apply)

- [ ] Job creation.
- [ ] Increased income.
- [ ] New skills and knowledge.
- [ ] Enhanced community cohesion.
- [ ] Environmental improvements.
- [ ] Other (please specify):

Open question: Describe briefly a specific bioeconomy project that has positively impacted your community.

What challenges has your community faced in implementing bioeconomy projects? (Select all that apply)

- [ ] Lack of technical knowledge.

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- [ ] Limited access to funding.
- [ ] Regulatory barriers.
- [ ] Resistance to change.
- [ ] Environmental concerns.
- [ ] Other (please specify):

How well do you feel your community's concerns are addressed in bioeconomy project planning?

- [ ] Not at all addressed.
- [ ] Slightly addressed.
- [ ] Moderately addressed.
- [ ] Well addressed.
- [ ] Very well addressed.

Open question: What steps could be taken to better involve your community in bioeconomy projects?
What skills do you believe are most crucial for community members to participate in bioeconomy projects? (select top 3)

- [ ] Technical skills (e.g., operating bio-based production machinery, conducting basic maintenance, or understanding bioprocesses).
- [ ] Business and entrepreneurship skills (e.g., developing business plans, marketing bio-based products, or managing small-scale enterprises).
- [ ] Environmental management skills (e.g., conducting waste audits, implementing sustainable farming practices, or restoring ecosystems).
- [ ] Digital literacy (e.g., using digital tools for data collection, managing logistics, or leveraging e-commerce platforms for bio-based products).
- [ ] Project management skills (e.g., coordinating resources, timelines, and stakeholders in bioeconomy projects).
- [ ] Communication and community engagement skills (e.g., raising awareness, promoting bio-based solutions, or facilitating stakeholder collaboration).
- [ ] Education and training skills (e.g., teaching others about bioeconomy concepts or leading workshops on sustainable practices).
- [ ] Policy and regulatory awareness (e.g., understanding local environmental laws, certifications, or funding opportunities for bioeconomy initiatives).
- [ ] Other (please specify):

Has your community received training related to bioeconomy projects?

- [ ] Yes, extensive training.
- [ ] Yes, some training.
- [ ] No, but training is planned.
- [ ] No, and no training is planned.

Open question: How has participation in bioeconomy projects affected skill development in your community?
How satisfied are you with the level of collaboration between your community and other stakeholders in bioeconomy projects?

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- [ ] Very dissatisfied.
- [ ] Somewhat dissatisfied.
- [ ] Neutral.
- [ ] Somewhat satisfied.
- [ ] Very satisfied.

With which stakeholders do your community collaborate on bioeconomy projects? (Select all that apply)

- [ ] Local government.
- [ ] Private companies.
- [ ] Research institutions.
- [ ] Non-governmental organisations.
- [ ] Other communities.
- [ ] Other (please specify):

Open question: Describe a successful partnership that has benefited your community's involvement in bioeconomy projects.

On a scale of 1 to 5, being 1 least optimistic and 5 most optimistic, how optimistic is your organisation about the growth of consumer demand for bio-based products in the next 5 years?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What support do you believe would most effectively help your community benefit from bioeconomy projects? (Select top 3)

- [ ] Increased funding opportunities.
- [ ] More training and education programs.
- [ ] Better infrastructure development.
- [ ] Stronger partnerships with external stakeholders.
- [ ] Tailored policies for rural bioeconomy development.
- [ ] Other (please specify):

What do you see as the biggest opportunity for your community in the bioeconomy sector?

- [ ] Sustainable job creation.
- [ ] Environmental conservation.
- [ ] Increased local economic resilience.
- [ ] Innovation and technological advancement.
- [ ] Improved quality of life.
- [ ] Other (please specify):

Open question: What recommendations would you give to policymakers to ensure bioeconomy projects better serve rural communities like yours?

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17. ENTREPRENEURS (if Entrepreneurs option is selected):

What type of company are you?

- [ ] Start-up (e.g., newly established company focused on innovation or niche markets).
- [ ] Spin-off from academic institution (e.g., company created to commercialise research from a university or research center).
- [ ] Spin-off from established company (e.g., division or innovation arm launched as an independent entity).
- [ ] Small or Medium Enterprise, SME (e.g., an independent company with fewer than 250 employees).
- [ ] Social enterprise (e.g., a company focused on sustainability and societal impact as core goals).
- [ ] Family-owned business (e.g., a bio-based business with generational involvement in the bioeconomy or agriculture sectors).
- [ ] Cooperative (e.g., organization jointly owned and operated by its members, such as farmers or bio-based product producers).
- [ ] Non-profit organisation (e.g., mission-driven entity involved in bioeconomy development without profit motives).
- [ ] Other (please specify):

How long has your company been operating?

- [ ] Less than 1 year.
- [ ] 1-3 years.
- [ ] 4-5 years.
- [ ] More than 5 years.

Which bioeconomy sector does your company primarily operate in?

- [ ] Agriculture and food (e.g., sustainable farming, plant-based food production, or precision agriculture technologies).
- [ ] Forestry and wood products (e.g., sustainable forestry management, bio-based construction materials, or wood-derived chemicals.
- [ ] Marine and aquaculture (e.g., algae-based products, sustainable fisheries, or bio-based marine resources).
- [ ] Bioenergy (e.g., biofuels, biogas, advanced-jet biofuels, or renewable energy derived from biomass).
- [ ] Bio-based materials (e.g., biodegradable plastics, biocomposites, biochemicals, or textiles from renewable resources).
- [ ] Engineering and technology development (e.g., companies developing bioprocess engineering, bio-based production systems, or bioreactor technologies).
- [ ] Biotechnology and life sciences (e.g., synthetic biology, enzyme production, or genetic engineering for bio-based innovation).
- [ ] Waste management and valorisation (e.g., recycling, composting, or transforming waste into bio-based products).

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- [ ] Pharmaceuticals and healthcare (e.g., bio-based drug development, nutraceuticals, or bio-medical materials).
- [ ] Circular economy solutions (e.g., systems for upcycling residues, closed-loop production models, or circular bio-based products).
- [ ] Other (please specify):

On a scale of 1 to 5, being 1 least innovative and 5 most innovative, how would you rate your company's business model in terms of innovation within the bioeconomy sector?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

What are the main challenges in developing and implementing your bioeconomy-based business model? (Select all that apply)

- [ ] Access to funding.
- [ ] Feedstock availability
- [ ] Regulatory barriers.
- [ ] Market acceptance.
- [ ] Technology scalability.
- [ ] Supply chain complexity (logistics, infrastructure).
- [ ] Other (please specify):

Open question: Briefly describe your company's most innovative bioeconomy-related product or service.

What are your primary sources of funding? (Select all that apply)

- [ ] Venture capital.
- [ ] Angel investors / Business angels / Private investors / Seed investors.
- [ ] Government grants.
- [ ] Crowdfunding.
- [ ] Personal savings.
- [ ] Other (please specify):

How challenging has it been to secure funding for your bioeconomy venture?

- [ ] Very challenging.
- [ ] Somewhat challenging.
- [ ] Neutral.
- [ ] Somewhat easy.
- [ ] Very easy.

Open question: What strategies have you found most effective in attracting investors to your bioeconomy-based business?

What do you consider to be your company's main competitive advantage? (select top 3)

- [ ] Unique technology.

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- [ ] Sustainable practices.
- [ ] Cost-effectiveness.
- [ ] Strong partnerships.
- [ ] Innovative business model.
- [ ] Other (please specify):

How would you describe the current market demand for your bioeconomy products or services?

- [ ] Rapidly growing.
- [ ] Steadily growing.
- [ ] Stable.
- [ ] Declining.
- [ ] Uncertain.

Open question: How does your company differentiate itself from competitors in the bioeconomy sector?

How important are partnerships and collaborations for your company's success?

- [ ] Not at all important.
- [ ] Slightly important.
- [ ] Moderately important.
- [ ] Very important.
- [ ] Extremely important.

With what types of organisations do you primarily collaborate? (Select all that apply)

- [ ] Academic institutions.
- [ ] Established companies.
- [ ] Other start-ups.
- [ ] Government agencies.
- [ ] Non-governmental organisations.
- [ ] Other (please specify):

Open question: Describe briefly a successful collaboration that has significantly benefited your bioeconomy venture.

On a scale of 1 to 5, being 1 least optimistic and 5 most optimistic, how optimistic are you about the growth potential of your company in the bioeconomy sector over the next 5 years?

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5

Which policy measures do you believe would most effectively support bioeconomy entrepreneurs and start-ups? (Select top 3)

- [ ] Increased access to funding.
- [ ] Tax incentives for bioeconomy ventures.
- [ ] Streamlined regulatory processes.

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- [ ] Support for technology transfer and scale-up.
- [ ] Enhanced public procurement of bio-based products.
- [ ] Other (please specify):

Which policy gaps prevent the development of bioeconomy businesses?

What do you see as the biggest opportunity for bioeconomy entrepreneurs in the coming years?

- [ ] Developing new bio-based materials.
- [ ] Validation of their biotech technology on pilot and demo level.
- [ ] Creating circular economy solutions.
- [ ] Innovating in sustainable feed & food production.
- [ ] Advancing bioenergy technologies.
- [ ] Improving waste valorisation processes.
- [ ] Other (please specify):

Open question: What advice would you give to policymakers to better support bioeconomy entrepreneurs and start-ups in driving innovation and economic growth?

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11 ANALYSIS OF THE QUESTIONNAIRE

This annex presents a comprehensive report based on the expert questionnaire conducted within the framework of the ToBeReaL project. The project explores current perspectives on the EU circular bioeconomy, with a particular focus on the profile of participating entities and the key challenges they face. The findings presented herein are derived from a sample of 88 responses, thus offering a solid and representative overview of the European bioeconomy landscape.

11.1 General Results of the Survey Sample

The ToBeReaL survey garnered 88 responses, providing a broad geographical and organisational spectrum for analysis.

Geographical coverage: the participants and their organisations present a broad European (and partially international) scope. While participant nationality reflects the personal origin of survey respondents (shown in Figure 16), the geographical coverage of their organisations indicates where these companies are actively operating – often in multiple countries (depicted in Figure 17). Slovakia notably accounts for the largest proportion, representing 18% of participants while 17% of organisations are active there. Other significant contributions include Spain (14% of participants are based in Spain, 24% of all organisations reported operating in Spain), Czechia (10% of participants, 18% of organisations), Sweden (9% of participants, 15% of organisations), Belgium (8% of participants, 15% of organisations), Italy (7% of participants, 17% of organisations), Slovenia (7% of participants, 13% of organisations), the UK (6% of participants, 14% of organisations) and Greece (6% of participants, 15% of participants). The remaining percentage is distributed amongst various countries, including France, Switzerland, Croatia, Estonia, the Netherlands, Poland, Portugal, North Macedonia, Austria, and even USA.

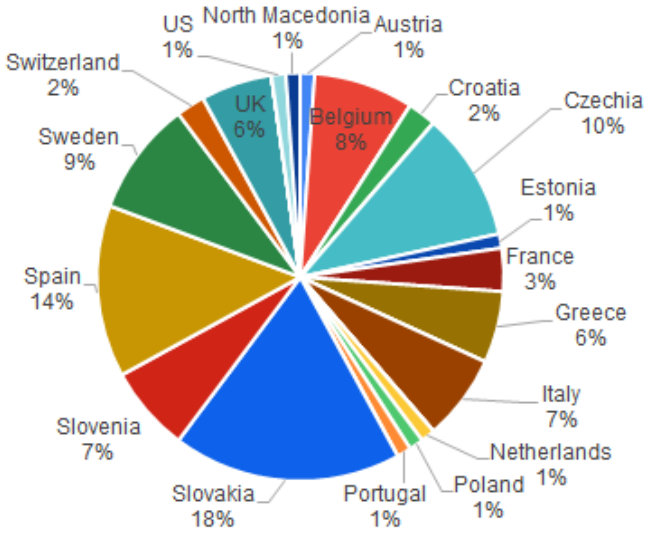


Figure 16. - Countries represented by participants in the ToBeReaL questionnaire.

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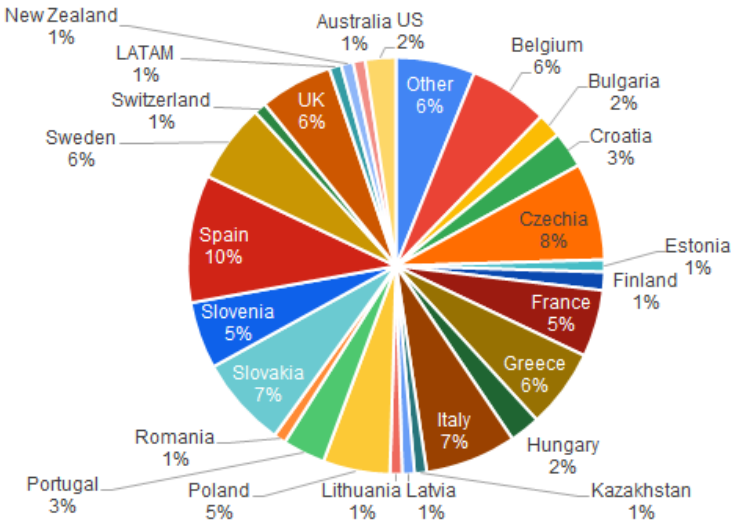


Figure 17. - Countries in which participant's organisations operate.

Organisational typology: the respondent pool is made up of a wide range of entity types (depicted in Figure 18), which is an indication of the multifaceted nature of the circular bioeconomy ecosystem. Universities constitute the largest segment at 24% of the sample, closely followed by SMEs and start-ups at 23%. Subsequently, Clusters and Network organisations together represent 20%. Following this, technological centres and R&D institutions account for 15%, representing a combined total of 82% of the overall participation. The remaining 18% includes other entities such as Non-Governmental Organisations (NGOs), large enterprises, consultancies and advisories, and public administrations. This distribution demonstrates a notable presence of research and development entities, as well as private sector organisations of both nascent and established stages.

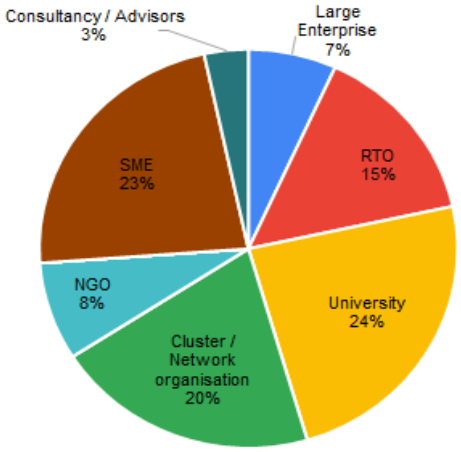


Figure 18. - Types of organization participating in the ToBeReaL questionnaire.

Value Chain Engagement: the surveyed organisations operate across the entire bioeconomy value chain, from the production of raw materials and their transformation to product development, waste management, and consultancy services. The highest rate of participation was observed amongst

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entrepreneurs, who represented 21% of the total and focused their activity on developing new business models and innovative services and products based on the bioeconomy. A similar level of participation was observed amongst technological partners related to bioconversion and processing (e.g. biorefineries, fermentation, enzymatic processes, biomass pretreatment, or integrating biotechnologies to convert raw materials into bio-based intermediates or products) and those devoted to circular solutions (e.g. waste valorisation, recycling or upcycling agricultural or industrial waste, composting, biochar production, or closed-loop production models). These two categories accounted for 19% of the sample each. Lower participation was observed for those stakeholders who work on product development and market launch (e.g., developing biodegradable plastics, bio-based chemicals, biofuels, or launching sustainable consumer products to market), representing 17% of the total participation, and feedstock supply (e.g., cultivation and harvesting of crops for bio-based materials, forestry management, forestry industry by-products; marine biomass collection such as algae, or waste material sourcing), identified by 13%.

TRL distribution: an assessment of the TRL of participants' responses indicates a notable interest in the potential benefits offered by the services provided by partners in the ToBeReaL project (as shown in Figure 19). However, it should be noted that there was no explicit indication of the participants' TRL in relation to the projects they are developing. This group constitutes 46% of the total respondents. Conversely, the predominant proportion of responses with a defined TRL is TRL 5, accounting for 16%. The subsequent category is TRL 4, representing 14%, which demonstrates the interest of potential collaborators and partners with technologies in early-to-mid-stage development.

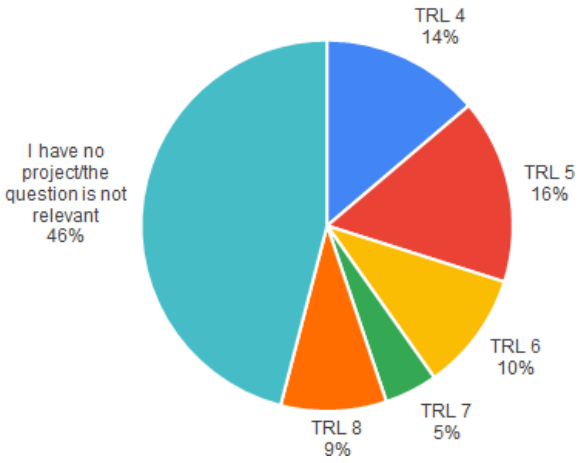


Figure 19. - Current technological readiness (TRL) of the R&D project ideas developed by the participants who express interest in the ToBeReaL project.

Collectively, TRLs from 4 to 6 account for 40% of participants, predominantly involving universities, R&D centres and institutions, and start-ups. Higher TRLs are less prevalent and are typically led by large enterprises and both clusters and network organisations engaged in commercialisation phases. The findings of this study indicate that a considerable proportion of the surveyed population appear to be placing a substantial emphasis on research and pilot-scale development.

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The Nordic and Central European regions demonstrate a higher proportion of projects at higher TRLs (7-8). This finding suggests a greater maturity in specific bioeconomy sectors, particularly in the domains of biogas, biofuels, and forest management technologies. It is reasonable to hypothesise that these regions have invested more in infrastructure and policies that support the scaling and commercialisation of bio-based solutions. Despite this advanced maturity, these regions still face challenges, notably logistical complexities and scalability issues. This indicates that even established bioeconomy sectors encounter hurdles in expanding their operations.

In contrast, Mediterranean regions predominantly feature projects at lower to mid-TRLs (4-6). The primary focus of these enterprises is frequently oriented towards the valorisation of agricultural waste and the integration of digitalisation. This regional specialisation is likely driven by the abundance of agricultural residues in these areas. However, these regions face greater regulatory and financing barriers, which may impede their ability to advance projects to higher TRLs and achieve widespread commercialisation. This underscores the necessity for bespoke policy measures and financial instruments that address the specific challenges and opportunities inherent in the agricultural bioeconomy of Southern Europe.

This geographical disparity in TRLs emphasises the necessity for region-specific strategies and support mechanisms. While certain regions are demonstrating innovation in the field of commercialisation, others are still encountering challenges related to the validation of technology and the initiation of developmental processes at the early stage. It is imperative that effective European bioeconomy policy acknowledges and addresses regional differences if equitable growth across the continent is to be fostered.

11.2 Principal Barriers to Technological and Implementation Progress

The ToBeReaL questionnaire identified a range of significant challenges impeding the advancement and implementation of the circular bioeconomy. This section delves into the critical obstacles hindering the progress of bioeconomy projects, differentiating between technological and non-technological challenges.

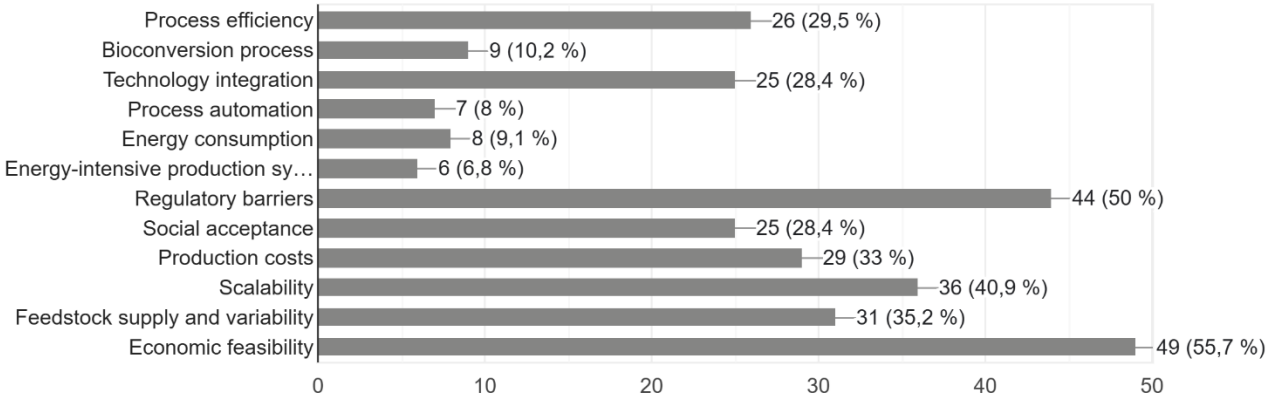


Figure 20. - Technological and non-technological barriers identified by the participants in the ToBeReaL questionnaire.

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Participants identified several key technological barriers that hinder the development and scaling of bioeconomy projects, which are depicted in Figure 20. These findings emphasise that while the scientific principles for bio-based solutions are clear, their practical and economic implementation on a large scale remains a significant challenge. The interlinked nature of costs, scalability and process efficiency is evident.

Recurrent technological barriers: these pertain to the intrinsic difficulties in developing and deploying bioeconomy technologies.

- **Low economic feasibility** and **lack of scalability** are the most frequently cited, with 56% and 41% of mentions, respectively. This indicates a critical need for cost reduction strategies and improved upscaling methodologies. Even with mature lab-scale processes, translating them into cost-effective commercial models remains extremely challenging due to high capital costs and uncertain returns.
- The **variability and consistent supply of raw materials (feedstock)** are concerns for 35% of participants, underscoring logistical and quality control issues. Feedstock quality and availability – especially from agricultural or waste sources – are logistical and process stability challenges. These issues affect scaling, product uniformity, and system optimisation, and were noted as critical in studies on lignocellulosic and food/agri-waste biorefineries. Survey data from stakeholders in Sweden, North Macedonia, and Slovakia reinforce these findings. Forestry residues emerged as the dominant feedstock, revealing a strong reliance on conventional biomass sources and limited engagement with alternatives such as aquatic biomass or organic waste. While several respondents reported high TRL-level projects (TRL 8), others indicated no active R&D, suggesting uneven technological maturity. Stakeholders also expressed only moderate optimism about feedstock availability by 2030, with regulatory hurdles and logistical constraints cited as key obstacles. Notably, technological innovation in feedstock valorisation was seldom mentioned, signalling a potential gap in adoption or awareness of advanced tools. This highlights the need for policy support, infrastructure investment, and strategic diversification of raw material sources to ensure long-term supply security.
- **High production costs** and **low process efficiency** are subsequently identified as significant technological barriers, cited by 33% and 30% of respondents, respectively. Bioconversion processes often have low yields, high energy inputs, and require costly enzymes or pretreatment methods. These inefficiencies are usually cited as key reasons biorefineries remain economically unviable on a large scale.
- **Insufficient technological integration** across processes is a significant barrier, cited by 28% of respondents, pointing to challenges in harmonising disparate biotechnological processes. Fragmented bioprocess chains and lack of system integration (e.g., between fermentation, separation, and valorisation steps) remain major challenges. Process intensification and integrated biorefinery models are being researched to bridge these gaps.

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- **Bioconversion processes** are also mentioned by the 10% of the respondents, surfacing the need for improvement these unit operations. The enzymatic breakdown of biomass is still a bottleneck in many biorefinery systems improvements in microbial strain development and biocatalyst design are essential for process optimisation.
- **High energy consumption** and **insufficient process automation** are also mentioned by 9% and 8% of respondents, respectively. Several studies have highlighted that a significant proportion of bio-based processes are characterised by high energy efficiency. This attribute renders them unsustainable, or uncompetitive, in the absence of subsidies. Whilst automation has the potential to reduce energy consumption and enhance consistency, its implementation remains constrained in the majority of settings. Furthermore, the limited access to advanced technologies and digitalisation is strongly associated with these two terms, suggesting disparities in technological infrastructure and adoption.
- **Energy-intensive processes** remain a hurdle for 7%, highlighting the need for more energy-efficient bioprocesses.

Non-technological barriers are equally, if not more, prevalent than their technological counterparts and profoundly influence the advancement of the bioeconomy. These findings indicate that progress is not solely a matter of scientific or engineering expertise; it is deeply affected by the policy environment, economic incentives, public perception, and human capital development.

Non-technological barriers: these are extrinsic factors that impede market entry, adoption, and overall sector growth.

- **Regulatory barriers** are the most prominent, cited by 50% of respondents, indicating a critical need for clear, stable, and supportive policy frameworks.
- **Social acceptance** is noted by 28%, highlighting the importance of public engagement and awareness campaigns.

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11.3 Relevant Interrelationships and Segmentations

From the 35% of the total participants in this survey (34 respondents), a significant proportion of respondents from universities, technological centres and R&D institutions have been engaged in bioeconomy-related research for more than 11 years, constituting 62% of the total participation. In contrast, junior researchers in the field account for only 12% of participants. This indicates that the results obtained through the following questionnaire primarily reflect the perspectives of **highly experienced professionals in the bioeconomy sector**.

According to the multiple-choice responses provided by participants from universities, technological centres, and R&D institutions, the main areas of expertise of their organisations are agriculture and food sciences, and environmental sciences, followed by biotechnology. **These responses indicate a robust institutional commitment to bioeconomy-related research**. In fact, 59% of participants rated their institution's current research output in the bioeconomy as high or very high. In contrast, only 6% of respondents felt that their institution needed to make significant improvements to its research output in this area.

Furthermore, the key challenges to conducting bioeconomy research at their respective institutions were identified by researchers as follows: **limited funding**, **insufficient interdisciplinary collaboration**, and **restricted access to essential equipment and facilities**. As outlined in previous sections of this deliverable, these are consistently referenced and cited as significant barriers to advancing bioeconomy research and development. These barriers underscore the necessity for coordinated funding strategies, institutional reform to support interdisciplinary work, and investments in research infrastructure. For instance, public policies and inconsistent research funding can be found to hinder bioeconomy development, especially for SMEs and applied innovation projects. It has been noted that comparable issues have been reported in other country-specific bioeconomy frameworks, in which regulatory and funding challenges have been identified as key factors limiting technological advancement. In a similar vein, the implementation of interdisciplinary research continues to present challenges. These challenges can be attributed to the presence of disciplinary silos, a lack of institutional support, and inadequate incentives.

Collaboration is a pivotal catalyst for innovation and the successful overcoming of complex challenges in a multidisciplinary field such as the bioeconomy. The high rate of collaboration amongst surveyed organisations is indicative of the recognition of shared challenges and the necessity of collective action. In response to the question regarding the sectors with which their institutions primarily engage in bioeconomy projects, the predominant response from the participants in this study was the **collaboration with academic and research institutions, including universities or research centres specialising in biotechnology, agriculture, or environmental science**, having established relevant collaboration and demonstrating a strong inclination towards partnership. This accounts for an overwhelming 91% of the total participation, indicating that accessing research expertise, new technologies, and talent from the academic sector is a primary driver for partnerships. Subsequently, the respondents proceeded to select **industry partners from a range of sectors, including but not limited to bio-based manufacturing, renewable energy, chemical production and food processing**. This process was undertaken by a representative

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sample of 74% of the respondents, suggesting a focus on business-to-business partnerships for market expansion or supply chain optimisation. The remaining categories, namely government agencies, non-governmental organisations, and international organisations, were unable to attain the 50% mark, with percentages of approximately 38% and 41% being recorded in each instance.

Regarding satisfaction with the current level of knowledge transfer between institutions and industry partners, approximately half of the participants expressed a neutral opinion (44%), followed by somewhat dissatisfied (21%) and very dissatisfied (12%). **While the transfer of knowledge between academia and industry is recognised as vital, many stakeholders in the bioeconomy sector still perceive it as inadequate or underdeveloped**. This concept, which is evident throughout the entire composition of this deliverable, highlights an underlying need for systemic improvement in this area, better incentives, and facilitation tools.

In this regard, the responses to the questionnaire presented in Figure 21 offer valuable insights, **44% of respondents indicated that their respective institutions offer specific bioeconomy-related degree programmes or courses**. Furthermore, participants emphasised the significance of **interdisciplinary thinking** (e.g., the ability to integrate knowledge from biology, chemistry, engineering and economics to solve complex problems). and **sustainability assessment** (e.g., conducting life cycle assessments, carbon footprint analysis, or resource efficiency evaluations) as pivotal competencies for students entering the bioeconomy sector - with 77% and 65% of respondents highlighting their importance, respectively. Consequently, educational and training programmes must be meticulously designed to instruct new students and junior researchers in the complexities of the bioeconomy value chain. It should **incorporate subjects related to the bioeconomy, interdisciplinary curricula, education focused on innovation and sustainability, and lectures complemented by current information**, amongst other features. Such learning initiatives must be **designed to facilitate the acquisition of new competencies in business, problem-solving, engineering, biotechnology, artificial intelligence, biorefining, scale-up, entrepreneurship, carbon accounting, circular system thinking and other subjects pertinent to the bioeconomy**. The necessity for these initiatives to undergo regular review is **twofold**: firstly, **to ensure that they align with the evolving needs of the bioeconomy**; and secondly, **to update study materials and prepare students for emerging societal, economic, and environmental challenges**.

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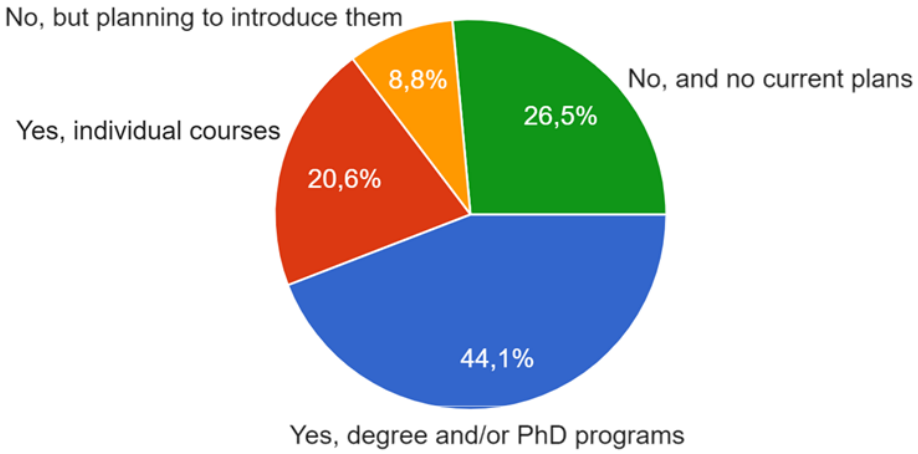


Figure 21. - Percentage of surveyed institutions offering specific bioeconomy-related degree programs or courses.

The respondents identified **government grants and EU funding as their primary sources for bioeconomy research (with a strong 74% of the participants)**. In contrast, alternative funding sources such as industrial partnerships, institutional funds and private foundations were cited only very infrequently.

For all the above-mentioned reasons, surveyed participants identified that the most effective way to support bioeconomy research in these institutions is **to increase public funding for research and enhance support for international research collaborations**. Similarly, they identified the role of academic and research institutions in shaping the future of the bioeconomy as **to develop applied technologies** that address real-world challenges and support sustainable industrial transformation.

11.4 Entrepreneurship in Bioeconomy

Amongst the survey respondents, a subset of 11 participants identified themselves as entrepreneurs who develop new business models and innovative products based on bioeconomy principles. Results are presented in Figure 22. These entrepreneurs often aim to create sustainable value chains, promote circular resource use, and address environmental and societal challenges through market-driven solutions. The survey revealed that **55% of respondents primarily affiliated with non-profit organisations** (i.e., mission-driven entity involved in bioeconomy development without profit motives). The remaining respondents were affiliated with a variety of other types of organisations, including **SMEs** (i.e. independent companies with fewer than 250 employees), **R&D funding advisory/consultancy, clusters, and start-ups** (i.e. newly established companies with a focus on innovation or niche markets).

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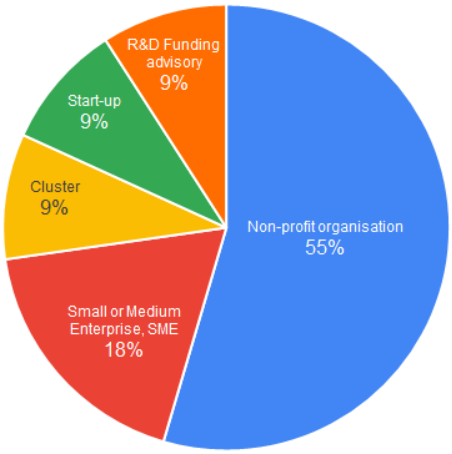


Figure 22. Percentage of surveyed institutions who develop entrepreneurship initiatives within the bioeconomy framework.

Non-profit and social entrepreneurship models are especially prevalent in bioeconomy innovation ecosystems. These entities frequently prioritise long-term impact over immediate financial returns, thereby playing a crucial role in early-stage development and community-driven sustainability transitions. **The majority of surveyed companies have been operating in bioeconomy-related innovation for a period exceeding five years** (64% of the respondents), **reflecting a combination of established expertise and emerging initiatives in the field**. The findings demonstrate that SMEs and non-profit organisations are correctly recognised as key players in bridging innovation and implementation in bioeconomy. Despite the barriers to market entry that have been previously outlined, **a growing number of these entities are not new entrants to this economic sector and have embedded bio-based strategies into their operations for several years**, especially in sectors such as agriculture, food, biotechnology, and materials.

These surveyed companies are mainly focused on defining and developing **circular economy solutions** (e.g., systems for upcycling residues, closed-loop production models, or circular bio-based products). **as well as engaging in agricultural biotechnology** (agribiotech or agritech). These two sectors each account for 27,5% of the entrepreneurial participation, **representing a combined total of 55%**. Both areas are driving technological development and supporting systemic sustainability transitions across Europe and beyond. In the first case, businesses operating with circular economy solutions are crucial for strengthening the bioeconomy sector, as they **facilitate the closure of resources loops**. This leads to reduced dependence on raw materials and external inputs, while simultaneously extending the lifespan of existing materials. This strategic focus is closely aligned with objectives related to sustainability, community resilience, and cross-sectorial circularity. In the latter case, the **bioeconomy sector is intrinsically linked to agriculture and food systems, which serve as primary sectors for circular bioeconomy transitions**. Biotechnology innovation, particularly those involving microbial and algal applications, are being developed to valorise waste, regenerate soils, and produce sustainable agricultural inputs, making agribiotech a key frontier for innovation.

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Respondent companies reported several critical barriers to the successful business model development in bioeconomy:

- **Limited funding and difficulties in accessing and securing financing** (e.g., insufficient subsidies, grants, or tax credits), particularly for early-stage ventures. Despite having participated in matchmaking and brokerage events for connecting with investors, **all respondents (100% of the 11 participants) found this very challenging**.
- **Regulatory barriers**, including inconsistent regulatory frameworks and complex approval pathways for bio-based innovations.
- **Insufficient market support and acceptance**, showing the lack of public awareness and consumer trust in new bio-based products. However, they also observed that the current market demand for bio-based products and bioeconomy-related services is steadily growing.
- **Technology scalability**, implying that scaling from pilot to industrial scale is difficult due to technical complexity, lack of demonstration infrastructure, and capital intensity.
- **Supply chain complexity**, highlighting the need for coordination and integration across feedstock suppliers, processors, and end-users, which is often lacking.
- **Limited support for feedstock supply** (availability, cost, seasonality, and quality), which is limited by logistical and legal challenges.

Conversely, **82% of the respondents identified their ability to build strong partnerships as their main competitive advantage**. As **91% of respondents clearly identified**, **these partnerships and collaborations are crucial** for ensuring the success of bioeconomy projects. In a similar vein, open collaboration should be promoted **through joint research facilities, the formation of interregional groups with shared interests, and the exchange of opportunities to support joint initiatives and strategic alliances**. These efforts aim to establish bioeconomy hubs that connect key actors across the bioeconomy ecosystem, integrating the circular bioeconomy into strategic frameworks and facilitate the development of bioeconomy projects at various TRLs. Furthermore, the study identified **established companies and academic institutions as the ideal partners to work with, representing 91 and 82% respectively**. **Government agencies** are mentioned in 64% of respondents, representing a significant presence in the field.

For all these reasons, almost all the participants (73%) found **an increased and improved access to funding** to be the most effectively support for entrepreneurs and start-ups.

Regarding the perspective of these respondents about the growth potential of their companies in the bioeconomy sector over the next 5 years, **all the respondents are very optimistic with its evolution and the prospectives of new development, projects and services linked to the bioeconomy initiatives**. A range of **opportunities to encourage the growth of entrepreneurship** in the bioeconomy sector over the next few years was identified. These include the **creation of circular economy solutions**, the **advancement of bioenergy technologies**, the **improvement of waste valorisation processes and** the **validation of biotech technology at higher scales**. Entrepreneurial innovation in the circular bioeconomy is increasingly focused on the upcycling of

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residues and circular production loops. This highlights the significance of waste valorisation technologies, including bioenergy technologies such as sustainable anaerobic digestion and co-substrate optimisation, as well as the transformation of biomass into bioproducts, biofuels or biomaterials. The concept of a zero-waste biorefinery is also crucial, along with structured frameworks such as stage-gated readiness levels. These integrate sustainable scale-up strategies with life cycle thinking, and supportive business models are essential for enabling this transition.

11.5 TECHNOLOGY INNOVATION

In the context of the bioeconomy, technological and innovative developments have been identified as key drivers of sustainable growth and enhanced resource efficiency. This involves the development and application of cutting-edge technologies, including biotechnology, nanotechnology and digital solutions, with the objective of optimising the use of renewable biological resources. Innovation in the bioeconomy sector is centred on the creation of novel processes, products and services that maximise the value extracted from biomass while minimising environmental impact.

A significant proportion of respondents (**38% of the total participation**) have been **involved for more than 10 years in biotech-related production, followed by companies and institutions which are starting to work in bioeconomy with an experience of less than 2 years (25%)**. Participation levels were similar between (37% of the total). It is evident that the results obtained through the following questionnaire reflect the perspectives of a well-balanced mix of experienced and emerging actors within the bioeconomy sector. The presence of long-established participants (38%) ensures that the insights are grounded in practical, real-world experience with biotech production and innovation. Meanwhile, the substantial involvement of newcomers (25%) and mid-stage actors (37%) brings fresh perspectives, current challenges, and evolving needs into the discussion. The findings are strengthened by the diversity of the research, which captures both the maturity of existing bio-based practices and the emerging trends and expectations of a rapidly growing innovation landscape.

The survey revealed that over half (55%) of respondents are currently integrating multiple technologies into biotechnology to enhance the productivity and quality of bio-based processes. These approaches are diverse, including control engineering, optimised biomass pretreatment, single-step valorisation with renewable energy, membranes for concentration and purification, reductive catalytic fractionation, integration of LCSA to ensure sustainability, safe and sustainable by-design approaches, digitalisation and precision agriculture, AI-driven bioprocesses, bioinformatics, microencapsulation or spray drying to obtain a stable bio-based product, and many more.

Regarding the type of biotech-related product primarily produced by the surveyed companies, the above-mentioned improvements are developed to generate a wide diversity of bio-based products spanning multiple value chains, including food, feed, biofuels and other advanced fuels, bioactive compounds, bioplastics, chemical platforms and biomaterials, indicating the potential richness of the bioeconomy sector. According to 32% of respondents, food ingredients represent the most commonly developed innovative products. The increasing use of bio-based ingredients in functional

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and future foods (e.g. mycoproteins, algae, cultured meat) is driving strong demand and innovation activity in this segment. Following them, biofuels are still a central pillar of the bioeconomy, developed by 29% of respondents. However, their current role is increasingly framed within integrated biorefineries producing multiple co-products, featuring bioplastics (23% of respondents), biochar (23% of respondents), and biomaterials (18% of respondents) in sustainable energy, reflecting ongoing efforts in the renewable energy and materials sectors. Another key bioproduct identified by respondents is bioactive compounds (26% of respondents), showcasing innovation in high-valued biochemicals.

The presence of a wide range of bio-based products is indicative of a healthy diversification of bio-based product development. This multi-product approach aligns with biorefinery concepts, which aim to extract multiple high-value products from a single feedstock, thereby improving economic viability. This diversification could also indicate a future market growth (and evolution) for bio-based products, enhancing the overall resilience and economic potential of the bioeconomy sector by reducing reliance on a single market or product type and demonstrating an increasing level of sophistication in the utilisation of biomass. Apart from market acceptance, challenges related to high production costs (identified by 60% of respondents as the most pressing technological gap that needs to be addressed to align bioeconomy projects with the European Green Deal and Sustainable Development Goals of the United Nations), feedstock supply (in terms of variability and quality, 40% of respondents), lack of scalability (39%), and technology integration (37%) will need to be addressed for the bioeconomy sector to truly flourish. It should be noted that all of these challenges were identified in the previous questionnaire.

In terms of emerging technologies, respondents identified circular economy innovations and implementation (e.g. technologies for recycling bio-based products, waste valorisation, or closed-loop systems) and biotechnologies (e.g. advanced microbial engineering, CRISPR and genome editing, enzyme engineering, synthetic biology, bioprinting, omics technology, bioprocess engineering or fermentation technology) as having the most significant technological and industrial impact on the bioeconomy sector, representing 36% and 35% of the total participation (as can be observed in Figure 23).

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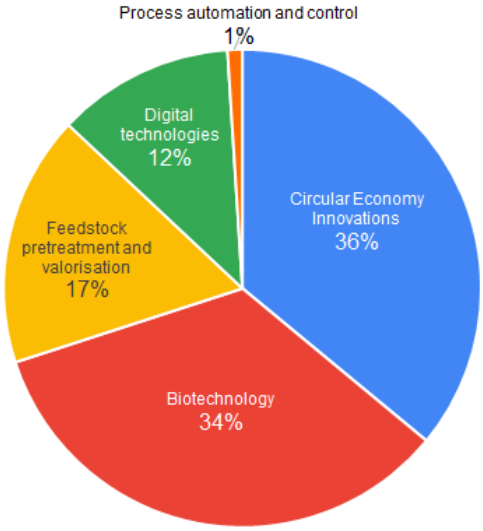


Figure 23. - Technology areas that require the most improvement to advance bio-based processes according to the participants in the ToBeReaL questionnaire.

11.6 Driving Innovation through Circular Practices and Collaboration

This section highlights the proactive measures and innovative approaches being adopted by participants within the bioeconomy to foster sustainability and drive growth. The nature of challenges and opportunities shifts significantly across different TRLs, reflecting the evolving needs of projects as they mature. Participants were invited to share their insights on the key outcomes required to address the technological challenges hindering the bioeconomy sector's current state, shown in Figure 24. In their responses, the participants identified the **scalability of technologies** (representing 63% of the total participation), **policy and regulatory support** (mentioned by 57% of the total sample), **improved collaboration** (noted by 53% of the total respondents) **and lower production costs** (remarked by 53% of the respondents) as the main efforts.

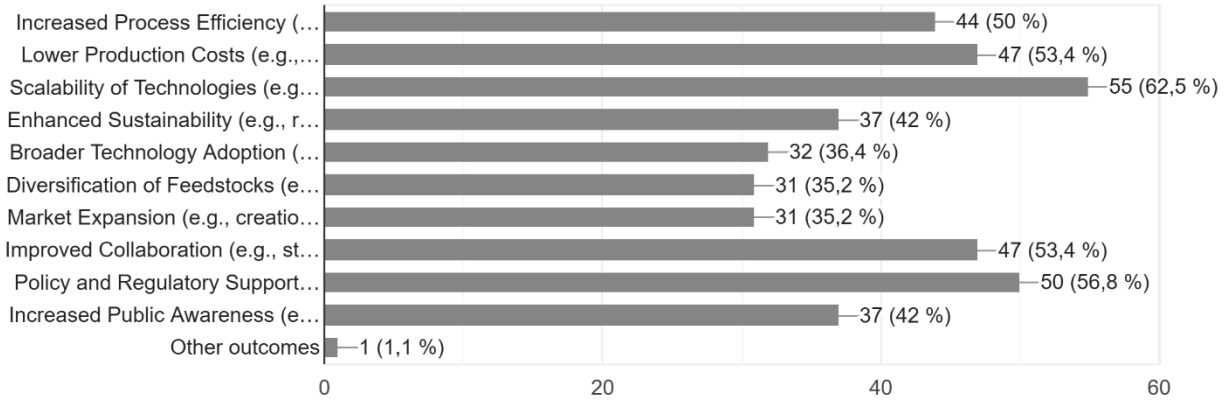


Figure 24. - Key outcomes to overcome technological roadblocks in bioeconomy identified by the participants in the ToBeReaL questionnaire.

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It has been frequently identified that challenges in scaling from pilot to successfully commercial production are a major and critical bottleneck to commercialisation in the bioeconomy. This is due to high capital costs, technological limitations, and performance uncertainty.

In a similar vein, policy and regulatory support (e.g., clearer regulatory frameworks, better funding mechanisms, or incentives for innovation) is a central concern, with research demonstrating that incoherent or slow-moving policy environments hinder innovation and investment. Furthermore, respondents identified the existence of specific policies or funding gaps that hinder technological development and innovation in bioeconomy projects. The following were amongst the most prevalent:

- Non-existence of a common strategic frameworks for developing bioeconomy and non-action plan adopted at national level.
- Lack of know-how on accessing various funding sources.
- Weak technology transfer from research to practice.
- Lack of trust amongst different actors in the bioeconomy value chain.
- Barriers to entering the market due to policy and regulatory restrictions.
- Funding gaps and regulatory inconsistencies regarding market access for bio-based products.
- Funding gaps in support for transitioning from research to commercial markets or obstacles in accessing appropriate sills or expertise.
- Difficulties in securing long-term biomass supply and financing.
- Complex and novel regulations that do not take into account the stakeholders.
- Complex administrative procedures.
- Differences in bioeconomy support across regions, regional disparities.
- Lack of harmonisation in waste regulation.
- Mutual recognition of end of waste.

Improved collaboration amongst stakeholders (e.g., stronger partnerships between stakeholders such as industry, academia, and policymakers) can be also regarded as a vital strategy for overcoming innovation roadblocks and accelerating market entry of bio-based products and technologies. In this instance, **50% of respondents considered the current collaboration between stakeholders in addressing technological barriers to be fair**, identifying the **industrial partnerships** (with a representative 59%) and the **academic and research collaborations** (57%) as crucial collaboration or partnership to overcome such barriers (see Figure 25). A comparable percentage of respondents in both categories rated it as either poor (26%) or good (22%). A mere 2% of respondents expressed confidence in the current level of communication amongst stakeholders.

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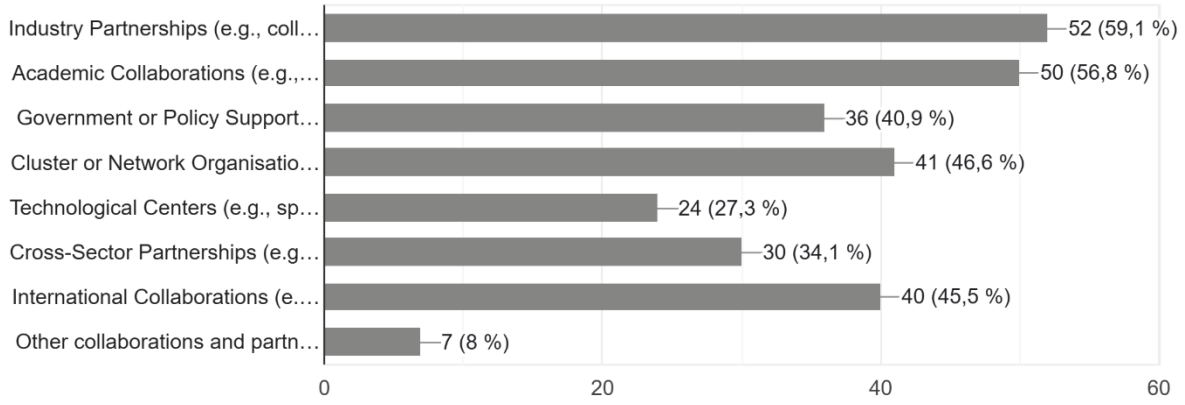


Figure 25. - Key collaborations or partnerships identified to overcome technological barriers.

Additionally, a vast 89% of the respondents indicated the importance of cross-sector collaboration in driving innovation in the bioeconomy sector. Cross-sector collaboration facilitates the generation of novel innovations and business models, particularly within traditional industries such as forestry, by establishing connections with other sectors, including textiles and plastics. The potential benefits of such collaborations include enhanced learning, the generation of intellectual property and an increase in adaptive capacity, even in cases where commercialisation is not immediately successful. Collaborative strategies are essential to the successful mainstreaming of bio-based innovations. Alignment with global value chains and the establishment of firm partnerships will be key factors in this process.

Finally, lower production costs (e.g., affordable bio-based products or cost-competitive alternatives to fossil-based products) are repeatedly mentioned, with solutions including research and development for cost-efficient bioprocesses, better funding mechanisms, and improved access to affordable inputs.

In detail, respondents identified the primary challenges encountered by stakeholders and companies in implementing new technologies in bioeconomy processes. The most commonly cited challenges were **high initial investment costs** (59%) **and regulatory barriers and market uncertainty** (both 50%).

Amongst the surveyed respondents, the most promising bio-based technological strategy identified for their specific region or country was **waste valorisation**, a strategy which was selected by **63% of participants**. This strategy is pivotal to the circular bioeconomy, which involves the transformation of waste streams into valuable resources. The elevated rate of adoption indicates a pronounced organisational dedication to the principles of circularity. As can be seen in Figure 26, these results perfectly matched with the sustainable practices adopted in bioeconomy operations by their companies, which are related to **waste reduction, recycling, and valorisation (76% of the total participation) and the use of renewable energy (63%)**.

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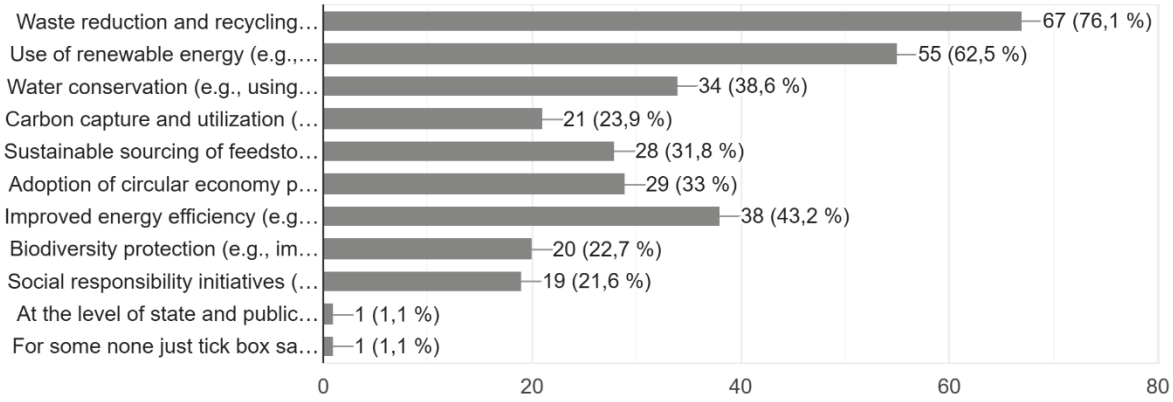


Figure 26. - Key sustainable practices actually adopted in bioeconomy operations.

The analysis revealed that **composting** emerged as the most commonly implemented practice, with **32% of organisations adopting this approach**. This can be attributed to the fact that composting does not require advanced technology and is a practice with which many organisations are already familiar. **Anaerobic digestion, or the production of biogas**, is a closely related process, **accounting for 28% of the total**. This method is a well-established technique for the recovery of energy. The **production of bioplastics and biochar** was reported by **22%**, indicating a growing interest in high-value material outputs. However, it should be noted that these approaches often require more advanced technologies. The implementation of **industrial recycling and upcycling**, as strategies to reintroduce waste into industrial value chains, was observed in **18% of the surveyed respondents**. The prioritisation of composting and anaerobic digestion suggests that organisations currently focus on well-established, economically viable biological processes. In contrast, the comparatively lower adoption rates of bioplastics, biochar production and industrial upcycling may be indicative of higher technological complexity, greater capital requirements or limited market readiness. These factors are consistent with the "high production costs" and "lack of scalability" previously identified as key technological barriers. To bridge this gap and accelerate the adoption of more advanced valorisation strategies, targeted support for R&D, pilot-scale infrastructure, and market development is essential. **These findings emphasise a significant challenge: the discrepancy between current practices and the full potential of an integrated, circular bioeconomy**.

About the implementation of circular economy principles in bioeconomy processes, **more than 88% of the respondents** considered it to be of great importance to ensure the successful application of these principles. This harmonised view is in alignment with the European Union's strategic prioritisation of a circular bioeconomy as a key element in achieving sustainable development and climate neutrality objectives. The implementation of circular principles within bio-based sectors, such as agriculture and forestry, is essential for enhancing sustainability and resource efficiency. Specifically, respondents also identified **the upscaling of sustainable production methods (36% of the total participation) and the creation of circular economy solutions (62% of the total participation) as the primary opportunities for technological companies in the bioeconomy sector**. Furthermore, an effective circular bioeconomy transition clearly requires new business

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models and depends on public policy support. The respondents identified effective tools to support technological innovation in the bioeconomy sector, particularly **increased R&D funding and innovation needs, tax incentives for bio-based products and support for technology transfer** as an enabler.

11.7 Conclusions of this Analysis

The ToBeReaL project's questionnaire provides a robust snapshot of the European circular bioeconomy landscape, based on 88 expert responses. The findings emphasise the multifaceted character of the bioeconomy ecosystem, identifying significant impediments to progress, the necessity for robust collaboration and education, and the pivotal role of entrepreneurship and circular innovation. Nevertheless, the industry is confronted by persistent structural and technological challenges.

The bioeconomy ecosystem is diverse and constantly developing. The survey captured a **broad geographical and organisational spectrum** of participants across Europe, with notable contributions from Slovakia, Spain, Czechia, and Sweden. This complex ecosystem is composed of universities (24%), SMEs/start-ups (23%), clusters/networks (20%), and R&D centres (15%), demonstrating a strong foundation in both research and commercial application. Additionally, organisations **actively cover the entire value chain, from feedstock to product development and waste valorisation**, with the largest engagement in **developing new business models and innovative services (21%)**, bioconversion and processing (19%), and circular solutions (19%). A significant proportion of projects are in **mid-stage TRLs (4-6), accounting for 40% of participants**, primarily involving universities and R&D centres. There is a discernible **regional disparity in TRLs**: Nordic and Central European regions exhibit higher TRLs (7-8), particularly in biogas, biofuels and forest management, suggesting greater maturity despite facing logistical and scalability issues. Conversely, Mediterranean regions predominantly feature projects at lower to mid-TRLs (4-6), focusing on agricultural waste valorisation, but encountering significant regulatory and financing hurdles. This disparity highlights the need for **region-specific strategies and support mechanisms** to foster equitable growth.

Persistent barriers to progress. Both technological and non-technological challenges significantly impede the bioeconomy's advancement. **Technological barriers** are dominated by **low economic feasibility (56%) and lack of scalability (41%)**, highlighting the critical need for cost reduction and improved upscaling methodologies. Other key technological challenges include the variability and inconsistent supply of raw materials (35%), high production costs (33%), and low process efficiency (30%). Insufficient technological integration across processes (28%) and the need for improvements in bioconversion processes (10%) also present substantial hurdles. **Non-technological barriers** are equally prevalent, with **regulatory barriers cited by 50%** of respondents, stressing the urgent need for clear, stable, and supportive policy frameworks. Social acceptance (28%) is also a notable impediment.

The crucial role of research, collaboration, and education is also demonstrated. The survey revealed that insights primarily reflect the perspectives of **highly experienced professionals** (62%

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with over 11 years of experience) from universities and R&D institutions. Key challenges for bioeconomy research include **limited funding, insufficient interdisciplinary collaboration, and restricted access to equipment/facilities**. Public policies and inconsistent research funding are particularly detrimental to SMEs and applied innovation projects. **Collaboration with academic and research institutions is paramount (91%)** for accessing expertise and new technologies. However, the **transfer of knowledge between academia and industry is widely perceived as inadequate**, with 44% expressing neutral opinion and 33% dissatisfied or very dissatisfied. Educational programmes must prioritise **interdisciplinary thinking (77%) and sustainability assessment (65%)** to equip future professionals with necessary competencies. Increased public funding for research and enhanced support for international research collaborations are identified as the most effective ways to support bioeconomy research.

Entrepreneurship is identified as a driver for innovation. SMEs and non-profit organisations are identified as key players in bridging innovation and implementation within the bioeconomy sector. Entrepreneurs primarily focus on circular economy solutions and agricultural biotechnology (27.5% each), driving both technological development and systemic sustainability transitions. The main barriers for entrepreneurs in business model development are **limited funding and difficulties in securing financing**, regulatory hurdles, insufficient market support, technology scalability, and supply chain complexity. Despite these challenges, **building strong partnerships (82%)** is considered their main competitive advantage. Entrepreneurs are highly optimistic about the **growth potential** in the bioeconomy, driven by circular economy solutions, bioenergy technologies, and waste valorisation processes.

Innovation is centred on circularity and diversification. Over half of the respondents (55%) are integrating multiple technologies to enhance the productivity and quality of bio-based processes. **A wide diversity of bio-based products** is being developed, including food ingredients (32%), biofuels (29%), bioplastics (23%), and bioactive compounds (26%). **Circular innovations (36%) and biotechnologies (35%)** are considered to have the most significant technological and industrial impact. Waste valorisation (63%) is identified as the most promising bio-based technological strategy, reflecting a strong commitment to circularity. While sustainable practices like waste reduction, recycling, and valorisation (76%) are widely adopted, the high adoption of composting (32%) and anaerobic digestion (28%) contrast with lower rates for bioplastics and industrial upcycling (22% and 18% respectively). This suggests a gap between current, established practices and the full potential of an integrated, circular bioeconomy, often due to higher technological complexity and capital requirements.

The call for integrated strategic support is loud and clear. Overcoming technological obstacles requires focus on the **scalability of technologies (63%), robust policy and regulatory support (57%), improved collaboration (53%), and lower production costs (53%)**. Significant policy and funding gaps include the **non-existence of common strategic frameworks** and national action plans for the bioeconomy, lack of know-how on accessing funding, weak technology transfer, and a lack of trust amongst actors. **Cross-sector collaboration (89%) is deemed essential** for driving innovation, particularly by connecting traditional industries with emerging sectors. To truly foster

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innovation and transition, key enabling tools identified are **increased R&D funding, tax incentives for bio-based products, and robust support for technology transfer**. The successful application of circular economy principles is seen as vital by over 88% of respondents, aligning with EU strategic priorities.

In essence, the advancement of the EU circular bioeconomy demands a **holistic and coordinated approach**. This involves addressing persistent economic, regulatory, and scalability barriers, fostering deeper collaboration between academia and industry, ensuring consistent financial and political support for research and market deployment, and designing educational programmes that cultivate interdisciplinary and sustainability-focused competencies. The transition to a fully integrated circular bioeconomy necessitates overcoming technological and market complexities through strategic innovation, sustainability integration, and strong value chain cooperation.

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