BIOWISE

Advancing Applied Biotechnology for Sustainable Innovation in Wood, Textile, and Furniture in Higher Education

Grant Agreement number: 2025-1-PL01-KA220-HED-000353539

D2.2 REPORT ON EMERGING KNOWLEDGE OPPORTUNITIES IN BIOTECH

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Glossary

Term	Definition
Artificial Intelligence (AI)	Computational methods that enable machines to analyse data, recognise patterns, optimise processes and support decision-making.
Bio-based Material	A material wholly or partially derived from renewable biological resources rather than fossil-based feedstocks.
Biodegradable Material	A material capable of being decomposed by microorganisms into natural substances such as water, carbon dioxide, methane and biomass.
Bioeconomy	An economic system based on the sustainable production and utilisation of renewable biological resources to produce food, materials, chemicals and energy.
Biofabrication	The production of materials and products using biological organisms, cells or biological processes.
Biofuel	Fuel produced from renewable biological materials including plant biomass and organic residues.
Biomass	Organic material originating from plants, animals or microorganisms used as a renewable raw material.
Biomaterial	A material produced from biological sources or biological processes for industrial or medical applications.
Biomanufacturing	Industrial production using biological systems such as microorganisms, enzymes or cultured cells.
Biopolymer	A naturally occurring or biologically produced polymer derived from renewable resources.
Bioprocess	An industrial process employing living organisms, enzymes or biological systems to manufacture products.
Biorefinery	An integrated processing facility that converts biomass into fuels, chemicals, materials and energy while maximising resource efficiency.
Bioremediation	The use of microorganisms or plants to remove, degrade or neutralise environmental pollutants.
Biosynthetic Material	A material produced through biological or engineered biological processes.

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Bacterial Cellulose	High-purity cellulose synthesised by bacteria and used for advanced materials, textiles and biomedical applications.
Carbon Footprint	The total greenhouse gas emissions associated with a product, process or organisation.
Carbon Neutrality	Achieving net-zero greenhouse gas emissions through emission reduction and carbon removal.
Cascading Use of Biomass	Sequential utilisation of biomass for progressively higher-value applications before final energy recovery.
Cellulose Nanofibrils (CNF)	Nanostructured cellulose fibres with high mechanical strength used in advanced biomaterials.
Cellulose Nanocrystals (CNC)	Highly crystalline cellulose nanoparticles used to reinforce composites and functional materials.
Circular Bioeconomy	Integration of bioeconomy and circular economy principles to maximise the sustainable use of biological resources.
Circular Economy	An economic model focused on reducing waste through reuse, repair, remanufacturing and recycling.
Circular Bio-based Europe Joint Undertaking (CBE JU)	European partnership supporting research and innovation in the circular bio-based economy.
CRISPR	Genome-editing technology enabling precise modification of DNA sequences.
Digital Product Passport (DPP)	Digital record containing information about a product's composition, origin, environmental performance and end-of-life management.
Digital Twin	A virtual representation of a physical process or system used for simulation and optimisation.
Enzyme	A biological catalyst that accelerates chemical reactions under mild conditions.
Enzymatic Processing	Industrial processing using enzymes instead of conventional chemical treatments.
Environmental, Social and Governance (ESG)	Framework used to evaluate organisational sustainability performance.
Ecodesign for Sustainable Products Regulation (ESPR)	EU regulation introducing sustainability requirements for products placed on the European market.
European Green Deal	European Union strategy to achieve climate neutrality by 2050 while promoting sustainable economic growth.
Extended Producer Responsibility (EPR)	Policy requiring producers to take responsibility for products throughout their life cycle, including end-of-life management.
Fermentation	Biological process in which microorganisms convert organic substrates into valuable products.
Forest Stewardship Council (FSC)	International certification system promoting responsible forest management.
Fungal Biotechnology	Application of fungi and fungal enzymes for industrial production, waste valorisation and biomaterial development.
Genetically Modified Organism (GMO)	Organism whose genetic material has been deliberately altered using biotechnology.

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Green Chemistry	Design of chemical products and processes that minimise hazardous substances and environmental impacts.
Horizon Europe	The European Union's flagship programme for research and innovation (2021–2027).
Industrial Biotechnology (White Biotechnology)	Application of biological systems, microorganisms and enzymes for industrial manufacturing.
Industry 4.0	Integration of automation, digitalisation, artificial intelligence and smart manufacturing technologies.
Integrated Biorefinery	Biorefinery producing multiple products simultaneously from the same biomass feedstock.
Intellectual Property (IP)	Legal rights protecting inventions, patents, trademarks and innovations.
Internet of Things (IoT)	Network of connected sensors and devices exchanging data in real time.
Life Cycle Assessment (LCA)	Method for evaluating environmental impacts throughout the entire life cycle of a product or process.
Lignin	Complex aromatic polymer found in wood that can be converted into bio-based chemicals and advanced materials.
Lignocellulosic Biomass	Plant biomass composed primarily of cellulose, hemicellulose and lignin.
Living Materials	Materials incorporating living organisms or cells capable of responding to environmental stimuli.
Metabolic Engineering	Modification of cellular metabolic pathways to improve production of desired compounds.
Microbial Fermentation	Production of industrial products using microorganisms cultivated under controlled conditions.
Microbial Pigments	Natural colourants produced by microorganisms for textile, coating and food applications.
Mycelium	Vegetative network of fungal hyphae used to produce biodegradable biomaterials.
Mycelium Composite	Composite material produced by growing fungal mycelium on lignocellulosic substrates.
Nanocellulose	Cellulose at the nanoscale possessing exceptional mechanical and barrier properties.
New European Bauhaus (NEB)	EU initiative connecting sustainability, aesthetics and inclusion in the built environment.
Patent	Exclusive legal right protecting an invention for a defined period.
PEFC	Programme for the Endorsement of Forest Certification, promoting sustainable forest management.
Precision Fermentation	Controlled production of specific molecules using genetically optimised microorganisms.
Renewable Feedstock	Raw material originating from renewable biological resources.
Resource Efficiency	Efficient use of natural resources while minimising waste and environmental impacts.
Scale-up	Transition of a process from laboratory or pilot scale to industrial production.

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Small and Medium-sized Enterprise (SME)	Company employing fewer than 250 people according to the European Commission definition.
Smart Biomaterial	Material capable of responding to environmental changes such as temperature, moisture or pH.
Smart Textile	Textile incorporating sensing, electronic or responsive functionalities.
Synthetic Biology	Engineering discipline applying biological design principles to create new biological systems or modify existing ones.
Technology Readiness Level (TRL)	Scale describing the maturity of a technology from basic research (TRL 1) to commercial deployment (TRL 9).
Technology Transfer	Process of translating research results into commercial products and industrial applications.
Valorisation	Conversion of waste or low-value materials into products with higher economic value.
Volatile Organic Compounds (VOC)	Organic chemicals that readily evaporate and may contribute to indoor and outdoor air pollution.
Waste Valorisation	Recovery of valuable products, chemicals or energy from industrial or agricultural waste streams.
White Biotechnology	Alternative term for industrial biotechnology.

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Acronym	Full Name
AI	Artificial Intelligence
ATP	Adenosine Triphosphate
BC	Bacterial Cellulose
Bt	Bacillus thuringiensis
CBE JU	Circular Bio-based Europe Joint Undertaking
CEAP	Circular Economy Action Plan
CLT	Cross-Laminated Timber
CNC	Cellulose Nanocrystals
CNF	Cellulose Nanofibrils
CRISPR	Clustered Regularly Interspaced Short Palindromic Repeats
DPP	Digital Product Passport
EEA	European Environment Agency
EIC	European Innovation Council
EPR	Extended Producer Responsibility
ESG	Environmental, Social and Governance
ESPR	Ecodesign for Sustainable Products Regulation
EU	European Union
FPUF	Flexible Polyurethane Foam
FSC	Forest Stewardship Council
GHG	Greenhouse Gas
GMO	Genetically Modified Organism
IP	Intellectual Property
IoT	Internet of Things
JRC	Joint Research Centre (European Commission)
LCA	Life Cycle Assessment
LIFE	Programme for the Environment and Climate Action
LNP	Lignin Nanoparticles
LVL	Laminated Veneer Lumber
MDF	Medium-Density Fibreboard
NEB	New European Bauhaus
OSB	Oriented Strand Board
PBS	Polybutylene Succinate
PEFC	Programme for the Endorsement of Forest Certification
PHA	Polyhydroxyalkanoates
PLA	Polylactic Acid
PU	Polyurethane
R&D	Research and Development
REACH	Registration, Evaluation, Authorisation and Restriction of Chemicals
RNA	Ribonucleic Acid
SME	Small and Medium-sized Enterprise
TRL	Technology Readiness Level
UNEP	United Nations Environment Programme
VOC	Volatile Organic Compounds
VET	Vocational Education and Training
WP	Work Package

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1. Introduction

1.1 Purpose of the Report

The present report, developed within the framework of Work Package 2 – Activity 2 (WP2-A2) of the BIOWISE project, aims to provide a comprehensive and forward-looking analysis of emerging knowledge opportunities in biotechnology applied to the wood, textile, and furniture sectors. As industries across Europe face increasing pressure to transition towards more sustainable, circular, and resource-efficient production models, biotechnology is becoming a key enabling field capable of transforming traditional manufacturing processes, materials, and value chains. In this context, the report seeks to identify and analyse the most relevant technological, industrial, and knowledge developments that are shaping the future of these sectors.

The main objective of WP2-A2 is to gather, organise, and interpret the information and insights collected during previous project activities, particularly the outcomes of stakeholder discussions and sectoral analyses, and complement them with an extensive research phase jointly carried out by all project partners. This combined approach allows the report to provide not only a theoretical overview of current biotechnology trends but also a practical understanding of industry needs, innovation dynamics, and future opportunities. Through this process, the report contributes to creating a shared knowledge base that can support companies, educational institutions, researchers, policymakers, and other relevant stakeholders in anticipating and responding to the next wave of biotechnological innovation.

Building upon the thematic areas validated during WP2-A1 through stakeholder consultation sessions, this report explores the current state of the art, emerging trends, technological developments, and future-oriented knowledge opportunities associated with these domains. The objective is not only to analyse existing biotechnology applications within the wood, textile, and furniture sectors, but also to identify the future skills, competences, and innovation pathways that should inform the development of the BIOWISE elective course.

More specifically, the report aims to identify current and emerging biotechnology trends and innovations with potential applications in the wood, textile, and furniture industries. It explores recent technological advances, implemented industrial solutions, successful case studies, and best practices that demonstrate how biotechnology can contribute to improving sustainability, reducing environmental impact, optimising resource use, and creating new bio-based products and processes. In addition, the report examines broader economic, business, and regulatory dimensions associated with the adoption of biotechnology, including market opportunities, innovation barriers, standards, patents, and policy frameworks relevant at the European and international levels.

Another key purpose of the report is to analyse the skills challenges and knowledge gaps associated with the integration of biotechnology into traditional industrial sectors. As biotechnology increasingly intersects with digitalisation, circular economy strategies, advanced manufacturing, and green innovation, companies and workers require new interdisciplinary competences that combine technical, scientific, environmental, and digital skills. Therefore, the report also seeks to identify emerging training needs and opportunities for Vocational Education and Training (VET), higher education, and lifelong learning systems in order to better prepare the workforce for future industrial transformations.

The scope of the study focuses specifically on biotechnology applications and opportunities

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within the wood, textile, and furniture sectors, which represent important industries for the European economy but also sectors facing significant sustainability and competitiveness challenges. The analysis includes both established and emerging biotechnology solutions, ranging from bio-based materials and enzymatic processing technologies to waste valorisation, biomaterials, fungal applications, and circular production systems. The report adopts a cross-sectoral perspective, recognising that many innovations and knowledge opportunities can be transferred and adapted across industries.

Finally, this report is intended to serve as a strategic reference document that supports informed decision-making and future collaboration between industry, academia, training providers, and policymakers. By identifying key trends, innovation pathways, and knowledge opportunities, the report contributes to fostering a more resilient, sustainable, and innovation-driven industrial ecosystem aligned with European green and digital transition priorities.

1.2 Methodology

Research approach

This report adopts a mixed-method and evidence-based research approach combining desk research, scientific literature review, stakeholder consultation, and comparative sector analysis. The methodology was designed to identify current developments, emerging technological trends, future knowledge opportunities, and skills requirements related to biotechnology within the wood, textile, and furniture sectors. The report builds upon the outcomes generated during Activity 2.1 of the BIOWISE project, where thematic priorities were identified and validated through stakeholder consultation. These results were subsequently complemented by an extensive review of scientific, industrial, and policy-related information undertaken jointly by all project partners.

The adopted methodology integrates qualitative and descriptive analysis with comparative assessment across the three target sectors. Particular attention was given to identifying technologies with high innovation potential, industrial relevance, and applicability within the European bioeconomy and circular economy framework.

Literature review and desk research

A comprehensive literature review was conducted to establish the current state of knowledge concerning industrial biotechnology and its applications in the target sectors. The review covered peer-reviewed scientific publications, review articles, technical reports, industrial white papers, European policy documents, market analyses, and publicly available patent information.

The desk research focused on:

- current biotechnology applications in the wood, textile, and furniture industries;
- emerging biomaterials and bio-based manufacturing technologies;
- industrial biotechnology processes, including enzymatic processing, microbial fermentation, fungal biotechnology, and biorefineries;
- circular economy and waste valorisation strategies;
- regulatory developments, sustainability standards, and European policy initiatives;
- industrial case studies and successful implementation examples;
- future research directions, innovation opportunities, and workforce skills requirements.

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Information collected from multiple sources was critically analysed and synthesised to identify common trends, technological gaps, and future-oriented knowledge opportunities relevant to higher education and industrial innovation.

Discussion groups and stakeholder feedback

The report incorporates the results of stakeholder consultation activities organised during Work Package 2-Activity 1. Representatives from industry, higher education institutions, research organisations, vocational education and training providers, and innovation support organisations participated in online focus groups and consultation meetings.

The objective of these discussions was to validate the thematic areas proposed for the BIOWISE curriculum, identify current industrial challenges, explore future biotechnology applications, and determine the knowledge and competences most needed by employers. Stakeholder feedback helped prioritise topics with the greatest relevance for future educational programmes and ensured that the report reflects real industrial needs alongside scientific developments.

The validated thematic areas formed the basis for the subsequent literature review and the structure of this report.

Sources consulted (papers, reports, patents, articles, sector studies)

The report is based on information collected from a broad range of more than 169 sources, including:

- peer-reviewed scientific journals in biotechnology, materials science, forestry, textile engineering, furniture technology, and sustainability;
- review papers and meta-analyses;
- European Commission reports and policy documents;
- reports from organisations such as the European Environment Agency (EEA), Joint Research Centre (JRC), Textile Exchange, and other international organisations;
- industrial reports, market analyses, and technology roadmaps;
- patent databases and innovation monitoring resources;
- company case studies, technical documentation, and best practice examples;
- stakeholder contributions collected during BIOWISE consultation activities.

The combination of scientific evidence and stakeholder knowledge provides a comprehensive overview of the current situation while highlighting future opportunities for biotechnology-driven innovation.

Scope and Target Sectors

The BIOWISE project focuses on three strategic manufacturing sectors that play an important role in the European economy while simultaneously facing significant sustainability, competitiveness, and digital transition challenges. Although each sector has its own specific characteristics, they share common opportunities for applying industrial biotechnology to improve resource efficiency, develop innovative bio-based products, and support circular production systems.

Wood Sector

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The wood sector encompasses forestry, primary wood processing, engineered wood products, pulp and paper production, bio-based chemicals, and emerging wood biorefineries. Biotechnology contributes to this sector through sustainable forest management, enzymatic processing, fungal biotechnology, biomass valorisation, bio-based adhesives, advanced wood modification, mycelium materials, and circular utilisation of lignocellulosic biomass. These technologies support climate-neutral construction, improved resource efficiency, and higher-value utilisation of forest resources.

Textile Sector

The textile sector is undergoing a major transformation towards sustainable manufacturing. Biotechnology enables the development of bio-based fibres, enzymatic processing technologies, microbial dyes, biodegradable polymers, biofabricated materials, biological recycling systems, and functional textiles. These innovations contribute to reducing water consumption, chemical use, greenhouse gas emissions, and textile waste while supporting circular production models and sustainable fashion.

Furniture Sector

The furniture sector increasingly incorporates biotechnology through sustainable materials, bio-based adhesives, natural coatings, fungal pigments, mycelium composites, biodegradable foams, polyurethane recycling, and biological waste treatment technologies. These developments contribute to reducing dependence on fossil-based materials, improving indoor environmental quality, extending product life cycles, and facilitating circular manufacturing systems.

Although analysed separately, the three sectors demonstrate considerable technological convergence. Many biotechnology solutions (including enzymatic processing, biomass valorisation, industrial fermentation, fungal biotechnology, and circular resource management) can be transferred across sectors, creating opportunities for interdisciplinary innovation and knowledge exchange.

1.3 Biotechnology and Industrial Transition

Definition of Industrial Biotechnology

Industrial biotechnology, often referred to as white biotechnology, is the application of biological systems, living organisms, cells, enzymes, and microorganisms to develop industrial products, manufacturing processes, and services. By replacing conventional chemical and energy-intensive production methods with biological alternatives, industrial biotechnology enables more efficient, environmentally friendly, and resource-efficient manufacturing.

Applications include enzyme-based processing, microbial fermentation, biomass conversion, bio-based chemicals, advanced biomaterials, waste valorisation, biofuels, biodegradable polymers, and biologically derived functional materials. Industrial biotechnology increasingly integrates with digital technologies, advanced manufacturing, synthetic biology, and artificial intelligence to optimise production processes and accelerate innovation.

Bioeconomy and Circular Economy Context

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Industrial biotechnology is one of the main enabling technologies supporting the European bioeconomy and circular economy strategies. The bioeconomy promotes the sustainable use of renewable biological resources for producing food, materials, chemicals, and energy, while reducing dependence on fossil resources. The circular economy complements this approach by extending product life cycles, reducing waste generation, improving resource efficiency, and promoting reuse, repair, remanufacturing, and recycling.

Biotechnology supports these objectives by enabling the conversion of renewable biomass into high-value products, transforming industrial residues into valuable secondary resources, developing biodegradable materials, and facilitating biological recycling processes. Integrated biorefineries, enzymatic recycling technologies, fungal biotechnology, and waste valorisation systems represent important examples of biotechnology supporting circular industrial ecosystems.

Relevance for European Industries and the Green Transition

The European Green Deal, the Circular Economy Action Plan, the EU Bioeconomy Strategy, and the updated Industrial Strategy identify biotechnology as a strategic technology for strengthening Europe's competitiveness while achieving climate neutrality and sustainable economic growth.

For the wood, textile, and furniture sectors, biotechnology offers opportunities to reduce greenhouse gas emissions, minimise hazardous chemical use, improve material efficiency, replace fossil-based raw materials with renewable alternatives, and create innovative bio-based products with higher added value. At the same time, biotechnology supports industrial resilience by diversifying raw material sources, promoting local value chains, and stimulating innovation.

The transition towards biotechnology-based production systems also creates significant demand for new knowledge, interdisciplinary competences, and lifelong learning. Future professionals will require expertise combining biotechnology, materials science, engineering, sustainability, digital technologies, circular economy principles, and innovation management. Consequently, higher education institutions play a crucial role in preparing graduates capable of supporting Europe's green and digital industrial transition through biotechnology-driven innovation.

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2. Current State of Biotechnology in the Target Sectors

2.1 Biotechnology in the Wood Sector

Current Applications

Biotechnology is increasingly transforming the wood sector by enabling more sustainable, resource-efficient, and high-value industrial processes (Ek et al., 2009; D. Lu et al., 2024; Stange & Wagenführ, 2022). One of the most important applications is the development of integrated wood biorefineries, where lignocellulosic biomass is fractionated into its main components (cellulose, hemicellulose and lignin) and each fraction is converted into valuable products (Chong et al., 2020; Sun et al., 2025). Cellulose is used for the production of bioethanol, nanocellulose and fibres; hemicellulose can be transformed into xylitol and organic acids; while lignin is increasingly valorised for products such as vanillin, phenolic resins and carbon materials. This approach supports circular economy strategies by maximising the use of forest biomass and reducing industrial waste (Grimm & Wösten, 2018).

Biotechnology also plays a significant role in modern forestry and tree breeding. Techniques such as tissue culture, somatic embryogenesis, marker-assisted selection and genomic selection allow the rapid propagation of tree species with desirable characteristics, including faster growth, improved wood quality, and enhanced tolerance to environmental stress. These technologies are widely applied in commercially important species such as eucalyptus, poplar and pine, contributing to more productive and climate-resilient forestry systems (Asiegbu, 2025; Sedjo, 2001; Singh et al., 2024).

Another important application concerns pest and disease management in forests. Biological control strategies and genetically modified trees are increasingly explored to improve resistance against insects and pathogens while reducing the use of chemical pesticides. For example, transgenic poplar trees expressing *Bacillus thuringiensis* (Bt) genes have been commercially planted in China to enhance resistance against insect pests and improve forest productivity (Alvarez & Ordás, 2023; Cao et al., 2024; Kumar et al., 2015).

Biotechnological pretreatment of wood biomass is also gaining relevance in industrial wood processing and bioenergy production. Biological pretreatments using fungi and enzymes can selectively degrade lignin and improve fibre separation, thereby reducing the energy required for milling, pulping, and refining operations. White-rot fungi such as *Trametes versicolor*, *Pleurotus ostreatus*, and *Ceriporiopsis subvermispora* are among the most studied species for these applications. These processes are particularly important in pulp and paper manufacturing, particleboard production, and bioethanol generation, where improved enzymatic hydrolysis and biomass digestibility can significantly increase process efficiency.

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Figure 1. Fruiting bodies of Trametes versicolor one of the most prominent fungus used in wood biotechnology (Source: University of Ljubljana)

In material science, biotechnology is enabling the development of innovative wood-based mate rials and bio-based products. Emerging applications include bioincising techniques to improve wood permeability, controlled fungal spalting for decorative wood products, and the production of mycocomposites using fungal mycelium as a natural binder. Mycocomposites are increasingly investigated as biodegradable alternatives to petroleum-based materials in packaging, insulation, and interior design. Biotechnology is also contributing to the development of more sustainable wood adhesives through the use of lignin-based formulations and enzymatic bonding systems that reduce dependence on formaldehyde-based resins (Pessanha Silva et al., 2021; Réggia Gomes Pessanha et al., 2021).

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Figure 2. Examples of mycelium composites (Source: University of Ljubljana)

Table 1: Examples of fungal species applied in wood biomass pretreatment processes

Fungal species	Biomass type	Main application
Ceriporiopsis subvermispora	Beech wood	Delignification and bioethanol production
Trametes versicolor	Beech, willow, pine	Enzymatic hydrolysis enhancement
Pleurotus ostreatus	Beech wood	Lignin degradation and biomass conversion
Ganoderma sp.	Olive wood	Combined fungal pretreatment
Polyporus sp.	Olive wood	Biomass decomposition
Coriolus versicolor	Bamboo and beech	Improved saccharification
Cyathus stercoreus	Cedar wood	Wood biodegradation
Irpex lacteus	Olive wood	Lignocellulosic pretreatment

Source: Adapted from (Itoh et al., 2003; Tian et al., 2012).

Additionally, biotechnology is being applied in the valorisation of wood residues and secondary products. Fungi and microorganisms are used to convert lignocellulosic biomass into biofuels, organic acids, aromatic compounds such as vanillin, and other high-value chemicals. Wood-based substrates are also widely used in mushroom cultivation, contributing to circular production systems and waste valorisation strategies (Oleson & Schwartz, 2016; Ragauskas et al., 2006).

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Industrial Challenges

Despite its growing potential, biotechnology in the wood sector still faces several industrial and technological challenges that limit its widespread implementation. One of the main barriers is the scalability of biological processes. Compared to conventional chemical and mechanical methods, biotechnological treatments often require longer processing times and highly controlled environmental conditions, making industrial integration more complex and sometimes less economically competitive.

Another important challenge is the variability of wood biomass itself. Differences in species composition, moisture content, lignin structure, and extractive compounds can significantly affect the efficiency and reproducibility of biological processes. This variability complicates standardisation and large-scale industrial application, particularly in biorefineries and enzymatic processing systems (Ek et al., 2009).

Economic competitiveness also remains a major concern. Many biotechnology-based solutions still involve relatively high initial investment costs, specialised equipment, and advanced technical expertise. In some cases, bio-based alternatives must compete with cheaper fossil-based chemicals and conventional industrial materials that already benefit from mature supply chains and economies of scale (Chong et al., 2020).

Regulatory and social challenges are particularly relevant in relation to genetically modified trees and advanced genetic engineering technologies. Concerns regarding biodiversity, gene flow, ecosystem impacts, and long-term environmental consequences have resulted in strict regulations and cautious public acceptance in many countries. As a result, the commercial deployment of genetically modified forest species remains limited outside a few regions (Alvarez & Ordás, 2023).

The integration of biotechnology into traditional wood manufacturing systems also presents organisational and workforce-related challenges. Many companies in the wood sector, especially small and medium-sized enterprises (SMEs), lack the technical knowledge, infrastructure, and investment capacity required to adopt advanced biotechnological solutions. At the same time, there is an increasing demand for specialised skills related to industrial biotechnology, bio-based materials, bioprocess engineering, and circular production systems.

Finally, some biological treatments still face technical limitations regarding process control, reproducibility, and product consistency. Biological systems are sensitive to temperature, humidity, nutrient availability, and microbial contamination, which can affect process stability and industrial reliability.

Adoption Level

The adoption level of biotechnology in the wood sector is currently uneven and depends on the specific application, technological maturity, and regional industrial context. Some biotechnology applications are already commercially established, while others remain in experimental or pilot phases (Atif et al., 2025).

Technologies associated with pulp and paper production, enzymatic treatments, mushroom cultivation, and biomass valorisation are among the most mature and widely adopted applications. Industrial biorefineries and lignocellulosic biofuel production are also receiving increasing investment and policy support, particularly in regions with strong bioeconomy strategies such as Northern Europe, Canada, and parts of Asia (Christov & Prior, 1998; Fackler et

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al., 2002).

Countries including Finland, Sweden, China, Brazil, and Canada are among the global leaders in the integration of biotechnology into forestry and wood-related industries. These countries benefit from large forest resources, strong research infrastructures, and public policies supporting sustainable bio-based industries. In China, for example, genetically modified poplar plantations have been commercially deployed for pest resistance purposes since the early 2000s (Gaston et al., 1995; Sedjo, 2001).

However, many advanced applications (including CRISPR-based gene editing, fungal bioincising, mycocomposites, and fully bio-based adhesive systems) are still primarily at research, pilot, or demonstration stages. Although these technologies show considerable potential, further technological optimisation, regulatory development, and market acceptance are required before large-scale commercialisation can occur (Cao et al., 2024).

In Europe, the adoption of biotechnology in the wood sector is strongly linked to sustainability objectives, circular economy policies, and the transition toward climate-neutral industries. Increasing pressure to reduce carbon emissions, minimise chemical use, and valorise industrial waste is expected to accelerate the adoption of biotechnology solutions in the coming years.

Overall, biotechnology is gradually becoming a strategic innovation area for the wood industry. While adoption remains fragmented across regions and subsectors, ongoing technological advances, growing environmental awareness, and supportive policy frameworks suggest that biotechnology will play an increasingly important role in the future competitiveness and sustainability of the wood sector.

2.2 Biotechnology in the Textile Sector

Current Applications

Biotechnology has emerged as a transformative force within the textile industry, offering innovative solutions to address the environmental, economic, and social challenges associated with conventional textile production. The integration of biological systems, living organisms, enzymes, microorganisms, and bio-derived materials into textile manufacturing and processing represents a pivotal integration of principles from biology, chemistry, materials science, and engineering, with the objective of developing sustainable solutions throughout the textile value chain, from raw material production to finishing, functionalization, and recycling. Conventional textile manufacturing is heavily reliant on synthetic fibres derived from fossil fuels and resource-intensive processes that consume substantial amounts of water, energy, and chemicals. These practices have been demonstrated to contribute significantly to greenhouse gas emissions, wastewater generation, microplastic pollution, and resource depletion. In contrast, biotechnology facilitates the development of more sustainable materials and production processes through the utilisation of renewable resources and biologically driven technologies. Applications encompass the production of bio-based fibres, dyes, and pigments, as well as enzymatic treatments that enhance processing efficiency while minimising the use of hazardous chemicals. Moreover, biotechnology facilitates the development of textiles with enhanced functionalities, including antimicrobial activity, self-cleaning properties, UV protection, controlled release of active compounds, and therapeutic effects (Khan, 2025).

Transition from Conventional to Bio-Based Textile Systems

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The textile industry is undergoing a gradual transition from conventional production systems toward bio-based and renewable alternatives. Conventional textiles, and synthetic fibres in particular, such as polyester and nylon, are heavily reliant on non-renewable petroleum resources and are a significant cause of environmental pollution. Textile processing also involves the intensive use of dyes, salts, acids, alkalis, and finishing agents, which results in the generation of wastewater containing organic pollutants, surfactants, heavy metals, and other potentially toxic compounds. In order to address these challenges, bio-based textile systems have emerged as sustainable alternatives that utilise renewable biological feedstocks, including agricultural residues, plant-derived materials, microbial fermentation products, natural polymers, proteins, and bioactive compounds. Examples of such materials include fibres produced from polylactic acid (PLA), bacterial cellulose, regenerated proteins, and other biodegradable polymers. These materials offer the potential to reduce dependence on fossil resources while lowering the environmental footprint of textile production. Enzymatic technologies have been identified as playing a pivotal role in this transition. Conventional textile treatments, including desizing, scouring, bleaching, dyeing, and finishing, are being increasingly replaced or supplemented by enzymatic alternatives. Enzymes such as amylases, cellulases, proteases, lipases, and pectinases provide highly selective catalytic activity under mild operating conditions. This reduces chemical consumption, energy requirements, and wastewater generation while improving product quality. Furthermore, advancements in synthetic biology, metabolic engineering, and industrial biotechnology are enabling the production of bespoke pigments, polymers, proteins, and functional molecules through microbial fermentation, thereby creating new opportunities for sustainable textile innovation. Notwithstanding the advances achieved thus far, the transition towards bio-based textile systems is encumbered by challenges pertaining to scalability (Catarino et al., 2025; Parnell et al., 2025; Rosenboom et al., 2022).

Role of Biotechnology in Sustainability and the Circular Economy

Biotechnology plays a crucial role in advancing sustainability and supporting the implementation of circular economy principles within the textile sector. The circular economy seeks to minimize waste generation, maximize resource efficiency, and extend material lifecycles through reuse, recycling, and regeneration. Biotechnological innovations contribute directly to these objectives by enabling cleaner production methods, waste valorization strategies, and biological recycling processes.

Several mechanisms illustrate the contribution of biotechnology to sustainability:

Reduction of water and chemical consumption: Biological processes generally operate under milder conditions and require fewer chemicals than conventional treatments. Enzymatic technologies significantly reduce water usage, energy consumption, and wastewater generation.

Waste valorization and biomass utilization: Agricultural residues and industrial by-products can serve as valuable feedstocks for the extraction of bioactive compounds, pigments, and biomaterials used in textile applications. This approach transforms waste streams into high-value products, supporting resource efficiency and circularity.

Development of biodegradable and renewable materials: Bio-based fibers and polymers derived from renewable resources can replace petroleum-based materials, reducing environmental impacts throughout the product lifecycle and facilitating end-of-life biodegradation.

Biological recycling and material recovery: Enzymes and microorganisms can be employed to degrade and depolymerize textile materials, enabling the recovery of valuable raw materials from textile waste and promoting closed-loop production systems.

In addition, biotechnology enables the development of advanced textile functionalities that

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enhance durability, performance, and product lifespan, potentially reducing consumption rates and resource demand. By replacing resource-intensive processes with biological alternatives, biotechnology contributes to reducing carbon emissions, water pollution, and waste generation, while supporting the development of a more resilient and environmentally responsible textile industry (Catarino et al., 2025; Parnell et al., 2025).

Future Perspectives

Biotechnology is transforming the textile sector by enabling the shift from conventional manufacturing approaches toward more sustainable, circular, and high-performance systems. Through the integration of renewable materials, biological processes, synthetic biology, biofabrication, and advanced recycling technologies, biotechnology offers significant opportunities to reduce environmental impacts while enhancing product functionality and value.

Although challenges remain regarding economic competitiveness, large-scale implementation, long-term performance, and regulatory acceptance, ongoing advances in biotechnology, materials science, and industrial bioprocesses are expected to accelerate commercialization and industrial adoption. As sustainability becomes a strategic priority across the global textile value chain, biotechnology will continue to play an increasingly important role in shaping the future of textile manufacturing and supporting the transition toward a circular bioeconomy.

Industrial Challenges

Environmental impact of textile processing

According to the European Commission, production and consumption of textiles generate the fourth highest environmental impact, after food, housing and mobility. Furthermore, the textile industry is among the top three sectors for water and land consumption, and one of the top five for primary resource consumption and greenhouse gas emissions (estimated around 10% of annual carbon emissions). The reasons for these significant impacts on the environment can be found in intrinsic nature of textile processing, that is traditionally characterized by a massive use of chemicals along the whole supply chain, by a large water consumption (most of the textile production processes require the use of water), and by the use of energy-intensive processes (*Textiles Strategy - Environment - European Commission*, n.d.; *What If Fashion Were Good for the Planet? | Think Tank | European Parliament*, n.d.).

Water and chemical consumption

Textile production processes are characterized by intensive inputs of water for the cultivation of natural cellulosic fibers (mainly cotton), for synthetic fibers production (mainly polyester), and for wet processing like preparation, dyeing, and finishing. According to reports from the European Parliament, fashion industry consumes 1,5 trillion liters of water per year and causes 20 % of global clean water pollution as consequence of dyeing and finishing processes (that can release chemicals in wastewater), and the use of pesticides and herbicides during the cultivation phase of natural cellulosic fibers. A study conducted by the Cotton Advisory Committee (ICAC) indicates that producing one kilogram of cotton fiber requires an average of 8900 liters of water and around 27% (2400 liters) of this amount comes from direct freshwater extraction. Considering these numbers and then the water needs for all the production steps, it is possible to estimate a water consumption of 2700 liters to produce a cotton T-shirt and up to 10000 liters for a pair of jeans. For synthetic fibers production water consumption is significantly lower than that required for cellulosic fibers. According to the Water Footprint Network, to produce one kilogram of polyester yarn, an average amount of around 60 liters are requested. Textile manufacturing processes are also characterized by the massive use of chemicals along all the

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supply chain, including raw materials production, preparation, dyeing, and finishing. Textile production chain complexity is reflected in the great variety of chemicals that are used along the manufacturing process like acids, alkalis, salts, organic compounds, halogenated compounds, and others (Chapagain et al., 2006; Periyasamy, 2023; *Water Consumption in the Textile Industry: Challenges and Solutions | Fulgar S.p.A.*, n.d.; *Water Footprint Assessment of Polyester and Viscose | GWICA*, n.d.; *WATER FOOTPRINT IN COTTON 2020-2024: A GLOBAL ANALYSIS - ICAC*, n.d.; *What If Fashion Were Good for the Planet? | Think Tank | European Parliament*, n.d.).

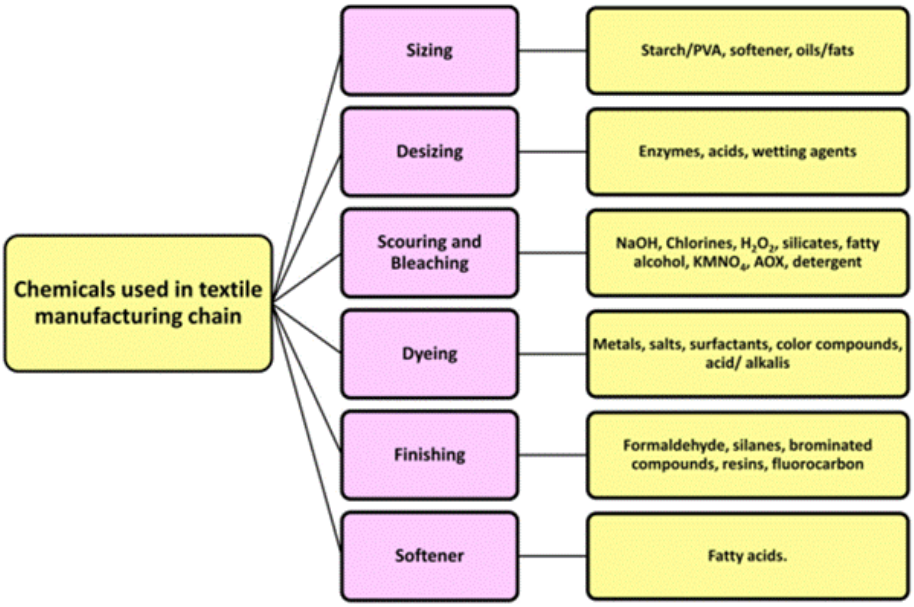


Figure 3. Chemicals used in textile manufacturing chain (Source: A.P. Periyasamy. Microfiber Emissions from Functionalized Textiles: Potential Threat for Human Health and Environmental Risks. Toxics 2023, 11, 406).

Microplastic pollution

Among the different sources of microplastics, textile is considered one of the most relevant due to the intensive use of synthetic fibers. Most of the textile products present on the market are made by polyester and its blends with other fibers, but also synthetic fibers, like polyamide (nylon), polypropylene, and polyurethanes are widely used in textile products, thus playing a role in microplastic release and then pollution. Textiles represent a source of microplastics along the whole product life, from manufacturing to end-of-life, including also use phase and maintenance (*Alleanza Italiana per Lo Sviluppo Sostenibile*, n.d.).

Waste generation and landfill accumulation

The textile industry is characterized by mass production, in particular for fashion products, that often have a short life and quickly become waste. According to the UN Environment Programme, 92 million tonnes of textile waste are produced globally every year and, while the production of textile products is constantly growing, the duration of garment use is decreasing. Due to the large volumes of synthetic fibers production, 11% of plastic waste comes from clothing and textiles and a very small fraction (around 8% in 2023) of fibers was made from recycled sources. Focusing on Europe, the European Environment Agency indicates that the EU generated around 6,95 million tonnes of textile waste in 2020 — around 16 kg per person (EEA, 2024; *Unsustainable Fashion and Textiles in Focus for International Day of Zero Waste 2025*, n.d.).

Need for sustainable and biodegradable alternatives

On the basis of what was discussed above, it is evident how fundamental it is to develop and

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implement sustainable solutions for a more environmentally friendly textile production system. To reduce non-renewable resources, a shift to bio-based material should be encouraged and integrated in the manufacturing system, thus reducing the dependency on fossil-based raw materials and also potentially reducing environmental impacts related to their production. Bio-based material could be also used in substitution of traditional chemicals widely used along the whole textile product chain, again reducing the use of fossil-based substances but also potentially reducing persistent pollution due to the use of these substances. Also and fiber level, the shift to bio-based alternatives to conventional polyester, polyamide, polyurethane, and others could represent a useful way to improve the sustainability of the product chain. Focusing on waste production and potential pollution, due to the release of chemicals, waste, and microplastics, the development and use of biodegradable materials (chemicals and fibers) could reduce the environmental pressure, since biodegradable materials don't persist in the environment for long time and can turn into less impacting substances.

Adoption Level

The degree of adoption of biotechnologies by the textile sector varies according to the specific aspect of the supply chain that is considered. The use of enzymes in wet processing of textile (from preparation to finishing) is a consolidated practice and industrial level, where partial or total substitution of conventional chemicals (acids, bases, oxidants, etc.) with enzymes can significantly reduce the environmental impacts and guarantee a high quality of the products. Moving to innovative biobased fibers, their use in textile manufacturing is growing thanks to the introduction of biobased versions of polyester and polyamide, obtained from plant-derived feedstock, but their diffusion is still low and comparable with those of traditional fossil-based fibers. The same is for bio-fabricated materials, obtained from different kind of microorganisms (also after genetic modification). These innovative materials represent a potential shift to a more environmental-friendly textile supply chain, but their adoption level is still low. This is because currently most of the solutions have higher costs that can reduce their adoptions. Moreover, in some cases the performances of the innovative products, coming from alternative solutions, are still lower than the traditional ones, another aspect that can reduce the market acceptance. Finally, biotechnologies in textile manufacturing find applications in waste management. If the use of enzymes and microorganisms for textile waste valorisation (e.g., de-polymerization of textiles into valuable building blocks) is still limited at the research level, bio-based technologies show more consolidated applications in water treatment, for example to remove or recover chemicals used during the wet processes.

2.3 Biotechnology in the Furniture Sector

Current Applications

Biotechnological approaches are increasingly being explored for the treatment and valorization of waste generated in the furniture sector. Recent research has demonstrated the potential of microorganisms, particularly filamentous fungi and bacterial consortia, to support sustainable waste management and circular economy strategies.

One promising application is the detoxification and cleaning of contaminated wood waste, particularly streams containing chemical additives such as preservatives, biocides, copper compounds, azoles, or urea-formaldehyde resins. Laboratory-scale studies have shown that fungi, either alone or combined with bacteria, can efficiently remove copper-based preservatives (Kartal et al., 2004), azole compounds (Vandekerkhove et al., 2025), and urea-formaldehyde

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resins from post-consumer or industrial wood residues (García-Vara et al., 2021).

Another interesting application is the biodegradation and valorisation of polyurethane (PU), widely used in the furniture sector, particularly as flexible polyurethane foams (FPUF) in upholstery and mattresses, as well as in coatings, adhesives, and insulation materials. Several bacteria and fungi have demonstrated the ability to metabolize polyurethane through enzymatic hydrolysis processes, breaking polymer chains into low-molecular-weight compounds that may subsequently be reused as raw materials for the synthesis of new polymers. A wide range of enzymes associated with PU depolymerization have progressively been identified, including esterases, ureases, amidases, proteases, cutinases, lipases, and oxidoreductases (Magnin et al., 2020; Schmidt et al., 2017). Several bacterial genera with polyurethane-degrading capabilities have been reported, including *Pseudomonas*, *Bacillus*, *Comamonas*, *Serratia*, *Streptomyces*, *Moraxella*, and *Corynebacterium* (Cregut et al., 2013). Among fungi, biodegradation activity has been described for species belonging to the genera *Alternaria*, *Aspergillus*, *Pestalotiopsis*, *Cladosporium*, and *Trichoderma* (Álvarez-Barragán et al., 2016; Loredo-Treviño et al., 2012). Although recent studies have reported promising microbial degradation of FPUF (Ji et al., 2024) and (Zeng et al., 2016) efficient biological recycling systems for commercial PU materials remain limited.

In addition to recycling and valorization, biotechnology can also contribute to developing new, sustainable products and materials for furniture sector, such as coatings, adhesives, and biofabricated products. These emerging applications contribute to reducing dependence on fossil-based raw materials while supporting circular economy strategies and environmentally friendly manufacturing practices.

One of the most promising applications involves the use of fungal pigments as natural alternatives to synthetic dyes for wood coatings, lacquers, and varnishes. Several fungi can produce stable pigments during growth on different waste (Gutiérrez & Robinson, 2015; Robinson et al., 2012).



Figure 4. Wood lacquers and varnishes incorporating natural pigments extracted from fungi. (Source: own elaboration.)

Biotechnology is also contributing to the development of bio-based adhesives for wood composites and furniture manufacturing. Conventional formaldehyde-based adhesives present environmental and health concerns due to volatile organic compound (VOC) emissions. As an alternative, lignin-based adhesives are being developed using lignin recovered from lignocellulosic biomass through biological or biochemical delignification processes involving white-rot fungi such as *Ceriporiopsis subvermispora, Phanerochaete chrysosporium* or *Ganoderma applanatum* (Hatakka, 1994; Yelle et al., 2014). The extracted lignin can subsequently be chemically modified and incorporated into adhesive formulations for

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particleboards, plywood, and other wood-based materials (Umemura et al., 2013; Winslott Hiselius & Svensson, 2017). Similarly, sucrose-based adhesives can be produced from sugars obtained through enzymatic hydrolysis of plant-derived. Research has demonstrated that sucrose combined with organic acids or bio-based crosslinkers can produce wood adhesives with suitable mechanical performance and reduced environmental impact compared with synthetic resins (Dimitriou et al., 2019; Umemura et al., 2013; D. Zhang et al., 2020).



Figure 5. Exmples of wood spalting (Source: University of Ljubljana)

Another rapidly developing area is the production of mycelium-based materials. Mycelium, the vegetative structure of fungi, can act as a natural binder when cultivated through controlled growth conditions on agricultural or lignocellulosic residues, generating lightweight composites with structural, insulating, and decorative properties. These biomaterials are increasingly being investigated as sustainable alternatives for furniture components, packaging, acoustic panels, insulation materials, and interior decorative elements (Attias et al., 2017; Girometta et al., 2019). The same technology is also being used to develop mycelium-based leather alternatives for upholstery applications. Mycelium leather is produced by cultivating fungal networks under controlled conditions to generate flexible sheet-like materials that can mimic some properties of animal leather (Elsacker et al., 2020).

Overall, these applications demonstrate the growing integration of biotechnology into the furniture sector, supporting the transition toward more sustainable materials, cleaner production processes, and circular manufacturing systems.

Industrial Challenges

Despite promising laboratory-scale results, the industrial implementation of most biotechnology-based processes in furniture industry remains limited. Although biotechnology offers significant opportunities for waste valorization and sustainable material development several technical, economic, and regulatory challenges still hinder large-scale adoption. In general, maintaining optimal growth conditions for fungi and bacterial consortia at industrial scale may require significant control of moisture, temperature, aeration, and contamination risks. Finally, across all biotechnology-based applications, regulatory approval, certification requirements, consumer acceptance, and the demonstration of long-term environmental and economic benefits remain essential steps for successful industrial deployment.

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In wood waste treatment, several barriers remain, including process scalability, variability in waste composition, treatment efficiency under industrial conditions, and economic feasibility. The heterogeneous nature of furniture waste represents a major challenge, as wood residues often contain mixtures of coatings, adhesives, preservatives, and composite materials that can affect microbial activity and process stability. Regulatory aspects related to the management of biologically treated waste and the removal of hazardous substances also require further validation.

In the polyurethane recycling area, an important challenge is detected particularly due to the intrinsic recalcitrance and chemical complexity of PU materials. Factors such as polymer composition, bond type, crystallinity, molar mass, and macromolecular architecture strongly influence susceptibility to microbial degradation (Magnin et al., 2020; Zeng et al., 2016). Polyester-based PU is generally more biodegradable than polyether-based PU, while foamed materials are considerably more resistant than coatings or aqueous dispersions (Liu et al., 2021; Nakajima-Kambe et al., 1995). Most microorganisms identified to date exhibit relatively low degradation efficiencies when applied to commercial PU materials under industrially relevant conditions, requiring optimization of microbial consortia, enzyme production, substrate accessibility, and process conditions. Moreover, few technologies have progressed beyond laboratory-scale demonstrations.

The development of fungal pigments for coatings and wood-finishing applications also faces important challenges: achieving consistent colour production, long-term stability, and UV resistance. Similarly, bio-based adhesives derived from lignin or sugars must overcome performance-related limitations before widespread adoption: improving water resistance, mechanical strength, durability, and compatibility with existing manufacturing processes. In both cases, industrial production must also ensure reproducibility and economic competitiveness compared with conventional products.

Mycelium-based materials and fungal leather alternatives face challenges related to standardisation, scalability, and market acceptance. Biological variability during cultivation can affect material consistency, while achieving the mechanical properties, durability, moisture resistance, and fire performance required for furniture applications remain an active area of research.

Continued research, pilot-scale validation, and collaboration between academia and industry will be necessary to facilitate broader adoption within the furniture sector.

Adoption Level

At present, biotechnological applications in furniture sector are still at an early development stage. Most activities remain within research, pilot-scale, or demonstration projects, with limited industrial deployment. Nevertheless, increasing environmental regulations, growing pressure related to plastic waste management and increasing interest in sustainable and circular economy policies are accelerating research efforts in this field.

Some applications have reached higher levels of technological maturity than others. Biotechnology is enabling the development of lignin- and sugar-based adhesives through biological delignification and enzymatic biomass conversion processes. Although these technologies have shown promising results at laboratory and pilot scale, their industrial adoption remains limited compared with conventional bio-based adhesive systems. Similarly, fungal pigments are attracting growing interest as sustainable alternatives to synthetic colorants,

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although large-scale commercial adoption remains limited.

Mycelium-based materials represent one of the fastest-growing biotechnology fields relevant to the furniture sector. Several start-ups and innovative companies have already commercialized mycelium-derived products for interior design, insulation, and decorative applications: Mogu[1] in Italy or Grown bio[2], in Netherlands.



Figure 6. Mycelium-based bench designed and produced by Grown.bio. (Source: Grown.bio)

The adoption of biotechnology for polyurethane recycling is currently less advanced. Most technologies remain at laboratory scale, although recent advances in microbial degradation, enzyme engineering, and hybrid chemical-biological recycling processes demonstrate significant future potential. Likewise, biological wood waste detoxification and valorisation technologies are still emerging, with few industrial examples currently available.

Although biotechnology is gaining prominence in the furniture industry, its actual integration remains highly fragmented. While mycelium-based composites have successfully achieved growing commercialization for interior solutions, upstream technologies (such as enzymatic polyurethane depolymerization and bio-based adhesive synthesis) remain largely restricted to laboratory or pilot-scale validation. Nevertheless, intensifying regulatory and sustainability demands within the manufacturing sector continues to drive its development, accelerating research and increasing needs for broader commercialization.

[1] https://mogu.bio/?utm

[2] https://www.grown.bio/?utm)

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3. Emerging Trends and Knowledge opportunities within the validated thematic areas

3.1 Materials Science

Materials science is emerging as one of the most strategic domains in the transition towards sustainable and bio-based industrial systems. Across the wood, textile, and furniture sectors, increasing attention is being directed towards the development of advanced biomaterials capable of combining high performance with reduced environmental impact (Asiegbu, 2025). Among the most promising innovations are nanocellulose-based materials, which offer exceptional mechanical strength, lightweight properties, and biodegradability. Nanocellulose is increasingly explored for applications ranging from packaging and coatings to composite reinforcement and smart materials (Hamed & Hassan, 2019).

Another important trend concerns the development of smart biomaterials capable of responding to environmental stimuli such as humidity, temperature, or mechanical stress. These materials are particularly relevant for advanced textiles, adaptive surfaces, and functional furniture applications. At the same time, lightweight bio-composites are gaining industrial relevance as manufacturers seek to reduce material consumption, improve energy efficiency, and replace fossil-based components with renewable alternatives (Broda, 2020; Reinprecht, 2016; Woźniak, 2022).

Engineered wood products also represent a growing innovation area within sustainable construction and furniture manufacturing. Technologies such as Cross-Laminated Timber (CLT), Laminated Veneer Lumber (LVL), and bio-based composites are expanding the use of wood in high-performance applications while supporting low-carbon building strategies. In parallel, mycelium-based materials produced through fungal biotechnology are attracting increasing interest as biodegradable alternatives for packaging, insulation, and interior design products (Gasparri et al., 2015; Humar et al., 2020).

These developments generate important knowledge opportunities related to advanced biomaterials engineering, material performance assessment, and circular material design. Future professionals will require competences not only in material selection and functionality, but also in durability testing, environmental performance evaluation, and the integration of circular economy principles into material development processes.

3.2 Industrial Biotechnology

Industrial biotechnology is rapidly evolving as a key enabling field for sustainable manufacturing and bio-based production systems. One of the most significant trends is the increasing use of enzymatic processing technologies to replace energy-intensive and chemically aggressive industrial treatments. Enzymes are being applied in textile finishing, biomass pretreatment, biofuel production, and wood processing due to their ability to operate under milder and more environmentally friendly conditions ("Biotechnology for Environmental Protection in the Pulp and Paper Industry," 2000; Christov & Prior, 1998).

Biorefineries are also emerging as central components of the circular bioeconomy. These integrated systems aim to maximise the valorisation of biomass by converting lignocellulosic materials and biological residues into multiple high-value products, including biofuels,

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biochemicals, biomaterials, and bio-based energy. This integrated approach supports resource efficiency and waste minimisation across industrial value chains (Jones et al., 2020; Mehdikhani et al., 2019).

At the frontier of innovation, synthetic biology and CRISPR-based technologies are expanding the possibilities for engineering microorganisms, enzymes, and biomaterials with enhanced properties and functionalities. These technologies are opening new pathways for the production of advanced bio-based products, improved industrial microorganisms, and more efficient biological processes. In addition, biofabrication techniques are enabling the production of engineered living materials and biologically derived structures with applications in textiles, packaging, construction, and product design (Cao et al., 2024).

These trends create growing demand for knowledge and skills related to bioprocess optimisation, industrial fermentation, and scale-up processes. Companies increasingly require professionals capable of integrating biotechnology into manufacturing environments, managing biological production systems, and translating laboratory innovations into industrial applications.

3.3 Innovation in Bio-Based Materials

Innovation in bio-based materials is becoming a strategic driver of sustainability and industrial transformation across multiple sectors. Increasing attention is being devoted to the development of carbon-negative materials capable of storing more carbon than is emitted during their production process. Such materials are particularly relevant within the construction, furniture, and packaging industries as part of broader climate-neutrality strategies (Mayank Pratap Singh Chauhan et al., 2023)..

Bio-based coatings and adhesives are also emerging as important alternatives to conventional petroleum-derived chemicals. Research and industrial development efforts are focused on replacing formaldehyde-based resins, synthetic coatings, and fossil-based additives with lignin-based, enzyme-assisted, or biodegradable solutions that reduce toxicity and environmental impact (Sukhbaatar et al., 2009).

The development of biopolymers and functional textiles further reflects the growing diversification of bio-based innovation. Bio-based polymers derived from renewable feedstocks are increasingly used in packaging, consumer products, and industrial applications, while functional textiles incorporating biological treatments, antimicrobial properties, or responsive functionalities are opening new opportunities within the textile sector.

Another emerging field involves the development of living materials, where biological organisms or living cells actively contribute to material functionality, self-repair, or environmental responsiveness. Although still at an early stage of development, these materials represent a potentially transformative area within advanced biotechnology and material science.

These innovation pathways generate important knowledge opportunities related to product development, sustainable innovation management, and bio-based product certification. Future professionals will need competences in innovation processes, sustainability integration, product validation, and compliance with emerging environmental standards and certification systems.

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3.4 Regulatory and Supply Chain Management

The transition towards bio-based industries is increasingly influenced by evolving regulatory frameworks, sustainability requirements, and supply chain transformations. One of the most important emerging trends is the growing implementation of digital traceability systems that allow companies to monitor material origin, processing stages, environmental impacts, and product life cycles across complex value chains.

At the same time, Environmental, Social, and Governance (ESG) requirements are becoming central drivers of industrial decision-making and market competitiveness. Companies operating within the wood, textile, and furniture sectors are facing increasing pressure to demonstrate sustainability performance, reduce carbon emissions, and ensure responsible sourcing practices.

Bio-based certifications and ecolabels are also gaining relevance as mechanisms for validating environmental claims and supporting market transparency. Standards related to biodegradability, recycled content, sustainable forestry, and circular production are becoming increasingly important for accessing international markets and complying with European regulations.

Another significant trend concerns the development of circular supply chains designed to minimise waste generation, optimise resource efficiency, and promote the reuse and recycling of materials. In parallel, green procurement policies are increasingly encouraging public and private organisations to prioritise sustainable and bio-based products within purchasing processes.

These developments create growing knowledge needs related to regulatory compliance, sustainability assessment, Life-Cycle Analysis (LCA), and supply chain transparency. Future professionals will require the ability to navigate complex regulatory environments, assess environmental impacts, and implement sustainability-oriented management practices across industrial value chains.

3.5 Bioeconomy and Bio-based feedstock

The bioeconomy is increasingly recognised as a central framework for supporting the transition towards more sustainable and circular industrial systems. One of the most important trends within this domain is the cascading use of biomass, which prioritises the sequential and efficient utilisation of biological resources in order to maximise their economic and environmental value before energy recovery or disposal (European Environment Agency, 2017; Grimm & Wösten, 2018; Pires & Martinho, 2019).

Agricultural and forestry residues are also gaining strategic importance as alternative feedstocks to produce bio-based materials, chemicals, fuels, and energy. Industrial sectors are increasingly exploring ways to valorise side streams, waste materials, and underutilised biomass resources to reduce dependence on fossil-based inputs and improve circularity (European Environment Agency, 2017; Grimm & Wösten, 2018). In the wood, furniture and textile sectors, examples include the extraction of lignin and fermentable sugars from lignocellulosic biomass for the development of bio-based adhesives, the production of natural dyes through the cultivation of pigment-producing fungi on agricultural by-products, and the valorisation of wood and crop residues as substrates for mycelium-based composites and other biofabricated materials.

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Waste valorisation is therefore becoming a key component of circular bioeconomy strategies. Through biotechnological and biorefinery approaches, residues from wood processing, textiles, agriculture, and food production can be transformed into valuable secondary products and new industrial resources. Circular feedstock systems are also emerging as an important innovation pathway, promoting local resource loops, industrial symbiosis, and sustainable biomass management (Pires & Martinho, 2019).

These trends generate important opportunities for knowledge development in areas such as resource management, circular economy strategies, and feedstock sustainability assessment. Future professionals will need to understand biomass availability, resource efficiency, sustainability trade-offs, and value chain integration in order to support resilient and sustainable bio-based production systems.

3.6 Biotechnological Tools and Solutions for Waste Recovery

Biotechnological solutions for waste recovery are becoming increasingly important as industries seek to reduce environmental impacts and improve resource efficiency. One of the most promising emerging trends is fungal bioremediation, where fungi are used to degrade pollutants, recover valuable materials, and detoxify contaminated biomass or industrial waste streams. These approaches are particularly relevant for wood treatment residues, wastewater treatment, and contaminated industrial materials (Samuel et al., 2003).

Enzymatic recycling technologies are also attracting increasing attention due to their ability to selectively break down polymers, fibres, and complex materials under mild processing conditions. These technologies are especially relevant within the textile sector, where enzymatic treatments can facilitate fibre recovery, material separation, and circular recycling processes (Cho et al., 2012; Janusz et al., 2017).

Waste-to-value systems are another growing innovation area. Through biotechnology, industrial side streams and organic residues can be transformed into bio-based chemicals, biomaterials, bioenergy, and secondary raw materials. This supports the development of more circular industrial ecosystems while reducing landfill disposal and resource losses.

Industrial Symbiosis (IS) models are also emerging as important strategies for connecting industries through shared resource flows, waste utilisation, and collaborative circular systems. In these models, waste generated by one industry becomes a valuable input for another production process, improving overall system efficiency and sustainability. In this field, biotechnology has emerged as one of the most innovative and promising approaches for the recycling of flexible polyurethane foams, a major waste stream generated by the furniture industry. Recent research has demonstrated the potential of microorganisms, enzymes, and insect-assisted biodegradation to depolymerise polyurethane and biologically valorise the resulting products into high-value applications, for example, in agricultural sector (biofertilisers, biostimulants) (Orts et al., 2025). These developments generate increasing demand for knowledge related to waste stream management, circular manufacturing, and recovery technologies. Future skills will need to combine technical understanding of biological recovery systems with competences in sustainability assessment, process integration, and circular production strategies.

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4. State of the Art Technologies and Industrial Applications

4.1 Advanced Biomaterials and Bio-Based Products

Wood sector

The development of advanced biomaterials and bio-based products has become one of the principal drivers of innovation within the wood sector, supporting the transition from a traditional resource-based industry towards a knowledge-intensive and circular bioeconomy. Wood is a naturally renewable material composed primarily of cellulose, hemicellulose and lignin, each representing valuable feedstocks for the production of high-performance materials, chemicals and functional products. Rather than considering wood solely as a construction material or source of energy, modern biotechnology enables its complete valorisation through integrated biorefinery concepts, where every constituent is converted into products with high added value (Cao et al., 2024; Stange & Wagenführ, 2022).

Cellulose has emerged as one of the most promising renewable raw materials for advanced biomaterials. Nanocellulose, including Cellulose NanoFibrils (CNF) and Cellulose NanoCrystals (CNC), exhibits exceptional mechanical strength, low density, high surface area and excellent biodegradability. These unique properties enable its application in lightweight composites, barrier coatings, biomedical materials, flexible electronics, packaging and structural reinforcement. Nanocellulose also serves as an environmentally friendly alternative to petroleum-based polymers (Hamed & Hassan, 2019). Lignin, previously regarded mainly as a low-value by-product of the pulp industry, is increasingly recognised as a versatile renewable aromatic polymer. Modern biotechnological processes employ enzymes and microorganisms to depolymerise lignin into valuable intermediates that can be further converted into bio-based adhesives, phenolic resins, carbon fibres, antioxidants, flavour compounds such as vanillin, and advanced carbon materials for batteries and supercapacitors (Sukhbaatar et al., 2009).

Biotechnology also enables the development of innovative fungal-based materials. Mycelium composites are produced by cultivating fungal mycelia on lignocellulosic substrates such as sawdust, wood chips and forestry residues. During growth, fungal hyphae naturally bind the particles into lightweight, biodegradable materials without synthetic adhesives. Depending on fungal species, substrate composition and cultivation conditions, mycelium composites can be engineered for applications including insulation panels, packaging, acoustic materials, furniture components and architectural elements. Their low embodied carbon and complete biodegradability position them among the most promising next-generation biomaterials (Pessanha Silva et al., 2021; Réggia Gomes Pessanha et al., 2021).

Enzyme technologies further support material innovation by improving the performance of bio-based adhesives and coatings. Oxidative enzymes, particularly laccases and peroxidases, catalyse cross-linking reactions within lignin and tannins, allowing these naturally occurring polymers to replace phenol-formaldehyde resins. Such technologies contribute to reducing volatile organic compound emissions while maintaining mechanical performance (Hellmayr et al., 2022; Shao et al., 2016). As industrial production scales up and costs decrease, advanced wood biomaterials will play an increasingly important role in sustainable construction, packaging, transport and consumer products, strengthening the competitiveness of the forest-based bioeconomy (*KEIM LIGNOSIL®-INCO*, n.d.).

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Textile sector

The transition towards sustainable manufacturing is accelerating the development of bio-based materials that reduce dependence on fossil resources while improving circularity and environmental performance. Industrial biotechnology enables the production of renewable fibres, advanced biomaterials, and innovative composites for the textile and furniture sectors through biological processing, microbial fermentation, and biofabrication. Plant-derived fibres and biopolymers remain the dominant renewable materials in the textile industry, accounting for about one-quarter of global fibre production. Cotton is the most widely used natural fibre due to its durability, comfort, and dyeability, while flax, hemp, jute, sisal, ramie, and coir provide sustainable alternatives. Wood-derived regenerated cellulose fibres, including viscose, lyocell, and cellulose acetate, combine renewable feedstocks with industrial-scale production. Bio-based polymers such as polylactic acid (PLA), bio-polyamides, and polybutylene succinate (PBS), produced from sugars, starch, lignin, and plant oils, are increasingly replacing fossil-derived plastics in textile applications (Rahaman & Moshwan, 2026).

Algae-based materials represent another promising renewable resource. Algae grow rapidly, require limited land and freshwater, capture atmospheric CO_2, and provide pigments, polysaccharides, and bioactive compounds for textile dyeing and functionalisation. Their biodegradability and low environmental footprint make them attractive for future circular textile systems (V. Rocha et al., 2025).

Among emerging biomaterials, mycelium-based materials represent one of the most promising innovations. Fungal mycelium can be cultivated on agricultural and lignocellulosic residues to produce biodegradable composites with minimal energy use and virtually no production waste. Depending on species and processing conditions, mycelium can be engineered into leather alternatives, packaging, insulation, and textile composites. These materials provide moisture regulation, thermal and acoustic insulation, fire resistance, although improvements in mechanical performance and production scalability remain necessary (Kefale et al., 2023).

Bacterial cellulose, produced through microbial fermentation, forms a nanofibrillar network with excellent strength, flexibility, and purity, making it suitable for advanced textiles and leather substitutes. Likewise, protein-based fibres, including recombinant spider silk and collagen-derived materials, offer biodegradable alternatives with exceptional mechanical properties, moisture management, UV protection, and antimicrobial performance (Cai et al., 2023).

The furniture sector is undergoing a similar transformation through biotechnology-enabled materials. Bio-based wood composites increasingly replace conventional formaldehyde-containing adhesives with lignin-, tannin-, and enzyme-based binders, reducing hazardous emissions while maintaining mechanical performance. Renewable polyols derived from vegetable oils and lignocellulosic biomass are already used commercially in polyurethane foams, coatings, and adhesives for upholstered furniture (Branković et al., 2024; Salehi et al., 2020).

Mycelium biotechnology also offers major opportunities for furniture manufacturing. Lightweight composites produced from wood-processing residues are increasingly used for packaging, insulation, decorative elements, and non-load-bearing furniture components, while dense mycelium mats provide sustainable alternatives to leather upholstery. Controlled fungal modification of wood also creates decorative spalted wood, transforming low-value timber into premium veneers and furniture surfaces. Finally, bio-based coatings are replacing petroleum-derived finishing systems by increasing renewable content while reducing volatile organic compound (VOC) emissions. Combined with eco-design, modular construction, life-cycle assessment, and circular manufacturing principles, these biotechnology-enabled materials are improving the sustainability, durability, repairability, and recyclability of textile and furniture products, supporting Europe's transition towards a competitive circular bioeconomy.

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Furniture sector

The furniture industry is undergoing a profound transformation driven by increasing environmental awareness, stricter regulations on chemical emissions, and growing consumer demand for sustainable products. Biotechnology plays an increasingly important role in this transition by enabling the development of advanced bio-based materials that reduce dependence on fossil resources while maintaining the functionality, durability and aesthetics required for modern furniture manufacturing (Sonnino, 2016). One of the most significant developments concerns bio-based wood composites. Conventional particleboards, fibreboards and plywood rely heavily on synthetic adhesives containing formaldehyde. Biotechnology offers sustainable alternatives through enzymatically activated lignin, tannins, laccases and related oxidative enzymes promote cross-linking reactions between lignin molecules, creating strong internal bonding while significantly reducing formaldehyde emissions and improving indoor air quality (Ek et al., 2009; Singh et al., 2024).

Bio-based polyols are one of the most mature approaches for reducing the environmental footprint of polyurethane products used in furniture applications, particularly flexible foams, coatings, and adhesives. These polyols can be produced from renewable feedstocks such as vegetable oils, lignocellulosic biomass, sugars, and organic residues and they have already been implemented commercially in the furniture and bedding industries (Petrovic, 2008). A well-established example is Cargill's soy-based BiOH® polyols, which can be incorporated into flexible polyurethane foams at a content ranging from 5% to 20% for use in upholstered furniture, mattresses, pillows, and carpet cushioning. Current research aims to increase bio-based content while maintaining the mechanical performance, durability, and processing characteristics required by furniture manufacturers (Li et al., 2015; Petrovic, 2008).

Mycelium-based materials represent another rapidly expanding area of furniture biotechnology. Fungal mycelium grown on wood-processing residues forms lightweight composite materials suitable for packaging, insulation, decorative components and non-load-bearing furniture elements (Jones et al., 2020; Zimele et al., 2020). Biotechnology has also enabled the emergence of mycelium leather as an environmentally friendly alternative to both natural leather and synthetic vinyl. Dense fungal mats are cultivated, compressed and finished to obtain flexible materials suitable for upholstery applications (Jones et al., 2020).

Controlled fungal modification of wood provides additional opportunities for producing high-value decorative materials. Spalted wood, created through carefully controlled fungal colonisation, generates unique colour patterns and natural artistic textures that transform low-grade timber into premium veneers, tabletops and luxury furniture surfaces (Gutiérrez & Robinson, 2015; Robinson et al., 2011; Rui et al., 2019).

Finally, bio-based coatings are emerging as sustainable alternatives to conventional petroleum-derived finishing systems for furniture and wood products. Current developments focus on increasing the proportion of renewable raw materials while reducing Volatile Organic Compound (VOC) emissions. At the industrial level, several manufacturers have already introduced bio-based coating systems for furniture applications. Examples include the Bio ICA range of water-based coatings and KEIM Lignosil-Inco, a mineral silicate coating for interior wood and wood-based materials. The integration of advanced biomaterials with digital design, life-cycle assessment and eco-design principles further enhances the sustainability profile of modern furniture products. Manufacturers increasingly combine renewable materials with modular construction, repairability and recyclability, extending product service life while reducing environmental impacts throughout the entire value chain.

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4.2 Industrial Bioprocesses and Biorefineries

Wood sector

Industrial bioprocesses and integrated biorefineries represent one of the most important technological developments supporting the transition of the wood sector towards a circular bioeconomy. Traditional forest industries have primarily utilised wood for timber, pulp, paper and energy production. Modern biotechnology substantially expands this concept by enabling the simultaneous production of fuels, chemicals, advanced materials and bio-based products from every major component of lignocellulosic biomass. Rather than generating low-value by-products, integrated biorefineries maximise resource efficiency through cascading utilisation, where each fraction of wood is converted into the highest possible value product before final energy recovery (Chong et al., 2020).

Wood consists primarily of cellulose, hemicellulose and lignin, each requiring different processing strategies. Cellulose serves as the principal feedstock for producing bioethanol, nanocellulose, dissolving pulp and various biopolymers. Hemicellulose is converted into xylitol, organic acids, biodegradable polymers and platform chemicals, while lignin increasingly serves as a renewable source of aromatic compounds, phenolic resins, carbon materials and speciality chemicals. Biotechnology enables these conversions through highly selective enzymatic hydrolysis and microbial fermentation operating under relatively mild conditions compared with conventional chemical processing (Alvarez & Ordás, 2023).

Pretreatment remains a critical stage within industrial biorefineries because the compact lignocellulosic structure limits enzyme accessibility. Biotechnology provides environmentally friendly alternatives to harsh chemical pretreatments through fungal delignification and enzyme-assisted hydrolysis. White-rot fungi selectively degrade lignin while preserving cellulose, significantly improving enzymatic saccharification efficiency and reducing energy requirements. Hybrid systems combining biological, mechanical and mild chemical pretreatments have demonstrated considerable potential for industrial implementation (Chen et al., 2017; Kamila et al., 2014; Pelaez-Samaniego et al., 2013).

Microbial fermentation technologies enable conversion of liberated sugars into a wide spectrum of products. Besides bioethanol, microorganisms produce organic acids, bioplastics, enzymes, pharmaceuticals and specialty chemicals. Lignin-derived intermediates can be transformed into natural vanillin, antioxidants and other high-value aromatic compounds, considerably increasing overall process profitability. Simultaneously, process residues may be converted into biogas, biochar or soil amendments, ensuring nearly complete biomass utilisation (Bhatia, 2019; Ek et al., 2009; Singh et al., 2024).

Digitalisation increasingly supports industrial biorefineries through advanced process control, online monitoring and predictive optimisation. Artificial intelligence and digital twins improve fermentation efficiency, enzyme dosing, biomass logistics and energy integration across the production chain. Such technologies enhance productivity while reducing resource consumption and operating costs.

Future industrial biorefineries will likely function as integrated bio-based manufacturing platforms supplying renewable materials, chemicals and energy to multiple industrial sectors. Their successful implementation will strengthen regional bioeconomies, reduce greenhouse gas

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emissions and improve the competitiveness of forest-based industries by replacing fossil-derived raw materials with renewable biomass.

Textile sector

Synthetic biology is an interdisciplinary field that combines molecular biology, genetic engineering, systems biology, metabolic engineering, computational modeling, and engineering principles to design and construct biological systems with novel or enhanced functionalities. By enabling the rational modification of genetic circuits, metabolic pathways, and cellular processes, synthetic biology provides powerful tools for programming living organisms to produce specific molecules, materials, and biological functions with industrial relevance. Recent advances in genome editing technologies, particularly CRISPR-Cas systems, DNA synthesis, high-throughput screening, artificial intelligence-assisted design, and automated bioengineering platforms, have accelerated the development and implementation of synthetic biology solutions across multiple industrial sectors, including healthcare, agriculture, food production, environmental remediation, and advanced materials manufacturing.

Among its many industrial applications, synthetic biology is increasingly recognized as a key enabling technology for the transition towards more sustainable production systems. By engineering microorganisms with customized biosynthetic capabilities, it is possible to replace conventional petrochemical-based manufacturing routes with biological processes based on renewable feedstocks. This approach supports the development of bio-based materials while reducing energy consumption, greenhouse gas emissions, and environmental pollution associated with traditional industrial processes.

One of the most promising applications of synthetic biology is precision fermentation, a biotechnology platform that employs genetically engineered microorganisms as microbial cell factories for the efficient, scalable, and reproducible production of target compounds. By combining advances in synthetic biology, metabolic engineering, systems biology, and bioprocess optimization, precision fermentation enables the precise control of cellular metabolism, allowing microorganisms to synthesize high-value biomolecules that are difficult, inefficient, or unsustainable to obtain through conventional production methods. These biomolecules include structural proteins, biopolymers, enzymes, pigments, bioactive compounds, and specialty chemicals with applications across multiple industrial sectors.

Unlike traditional fermentation processes, which largely depend on the natural metabolic capabilities of microorganisms, precision fermentation relies on the rational design and optimization of biosynthetic pathways to maximize productivity, product quality, and process consistency. This approach not only improves manufacturing efficiency but also enables the production of novel materials with tailored properties. As advances in strain engineering, fermentation technologies, and downstream processing continue to reduce production costs and increase scalability, precision fermentation is increasingly recognized as a key enabling technology for the sustainable manufacture of advanced materials.

The integration of synthetic biology, precision fermentation, and metabolic engineering has significantly expanded the role of engineered microorganisms as renewable production platforms. Bacteria, yeasts, fungi, and microalgae can be programmed to synthesize a broad range of functional biomaterials, including recombinant structural proteins inspired by natural materials such as spider silk, collagen, elastin, mussel protein and keratin, as well as biodegradable polymers, bacterial cellulose, and naturally derived pigments. Owing to their renewable origin, biodegradability, and lower environmental footprint, these biologically

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produced materials are emerging as attractive alternatives to conventional fossil-derived products.

Within the textile sector, precision fermentation is creating new opportunities for the development of sustainable fibers, colorants, coatings, and functional finishes. Engineered microorganisms can be used to produce protein-based fibers with exceptional mechanical properties, bacterial cellulose with highly organized nanofibrillar architectures, and natural pigments that offer environmentally friendly alternatives to conventional textile dyes. Furthermore, microbial production platforms enable the generation of functional biomolecules with antimicrobial, antioxidant, sensing, or stimuli-responsive properties, supporting the development of next-generation textile materials. Consequently, precision fermentation is expected to play a central role in the transition towards a more sustainable, circular, and innovation-driven textile industry.

Beyond material production, synthetic biology also enables the development of advanced textile functionalities through the creation of engineered living materials and biologically active systems. By integrating biological components into textile structures, it becomes possible to develop materials with antimicrobial properties, self-healing capabilities, environmental sensing functions, pollutant degradation activity, and responsiveness to external stimuli such as temperature, humidity, light, and pH. These emerging technologies have the potential to transform conventional textiles from passive materials into dynamic and multifunctional systems capable of interacting with their environment.

The convergence of synthetic biology, precision fermentation, engineered microorganisms, and biofabrication technologies is therefore expected to play a central role in the future of textile manufacturing. By enabling the sustainable production of high-performance materials from renewable biological resources, these technologies support the transition towards a circular textile economy characterized by reduced dependence on fossil-derived feedstocks, lower environmental impacts, and the development of innovative textile products with enhanced functionality and value.

Furniture sector

The furniture industry generates substantial quantities of wood residues throughout manufacturing, including sawdust, planer shavings, sanding dust, offcuts, rejected panels and post-consumer wood products. Traditionally, much of this material has been used for low-value energy recovery or disposed of as waste. Industrial biotechnology and biorefinery concepts are fundamentally changing this approach by transforming manufacturing residues into valuable secondary raw materials, chemicals and advanced biomaterials, thereby supporting circular production systems and improving overall resource efficiency.

Modern furniture biorefineries utilise manufacturing residues as renewable feedstocks for microbial fermentation and enzyme-based conversion processes. Cellulose-rich fractions can be hydrolysed into fermentable sugars and converted into bioethanol, organic acids and biodegradable polymers. Simultaneously, lignin fractions provide renewable aromatic compounds suitable for bio-based adhesives, coatings and composite materials. These integrated processes allow manufacturers to extract significantly greater economic value from materials previously considered production waste (Teuten et al., 2009).

Industrial biotechnology also supports the development of decentralised biorefineries located close to furniture manufacturing facilities. Such regional systems reduce transportation costs while creating local circular value chains where residues generated during production become feedstocks for new materials, packaging, insulation products or renewable energy. This approach

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improves both environmental and economic sustainability while increasing resilience against fluctuating raw material markets.

Microbial cultivation provides additional opportunities for residue valorisation. Fungi can convert sawdust and wood particles into mycelium composites, biodegradable packaging and insulation materials, while edible mushroom cultivation generates food products together with valuable spent substrates suitable for composting or bioenergy production. These cascading utilisation pathways maximise biomass efficiency and minimise waste generation (European Environment Agency, 2017; Grimm & Wösten, 2018).

Beyond the valorisation of furniture manufacturing residues, current biorefinery concepts increasingly integrate biomass from other industrial sectors as feedstocks to produce materials applicable to furniture manufacturing. Agricultural residues, food-processing by-products and forestry residues are being converted through enzymatic hydrolysis, microbial fermentation and fungal cultivation into high-value products such as bio-based polyols, adhesives, coatings, natural pigments and mycelium-based composites. This cross-sectoral approach strengthens industrial symbiosis by connecting agriculture, forestry, food processing and furniture manufacturing through circular value chains, while reducing dependence on virgin raw materials and improving overall resource efficiency (A Sustainable Bioeconomy for Europe - Strengthening the Connection between Economy, Society and the Environment : Updated Bioeconomy Strategy | Knowledge for Policy, n.d.; Cherubini, 2010; Jones et al., 2017).

Biorefineries also facilitate recycling of recovered wood products at the end of their service life. Appropriate biological pretreatments assist in separating wood fibres from adhesives and coatings, enabling fibre recovery for secondary composite production. Research into enzymatic recycling technologies is expected to further improve recovery rates and material quality in the coming years.

The integration of industrial biotechnology with digital manufacturing, life-cycle assessment and sustainable product design creates new opportunities for furniture producers to reduce their environmental footprint while enhancing competitiveness. As demand for low-carbon products continues to grow, biorefineries will become an increasingly important component of sustainable furniture manufacturing, supporting closed-loop production systems that maximise the value of renewable wood resources throughout multiple product life cycles.

4.3 Green Chemistry and Enzyme Technologies

Wood sector

Green chemistry has become a key driver of innovation in the wood sector by promoting manufacturing processes that minimise hazardous chemicals, reduce energy consumption and maximise the use of renewable raw materials. The principles of green chemistry are closely aligned with the objectives of the European Green Deal and the circular bioeconomy, encouraging industries to replace fossil-derived chemicals with environmentally benign alternatives while maintaining high product performance. Biotechnology plays a central role in this transition through the application of enzymes and microorganisms that catalyse highly selective reactions under mild operating conditions (Geng et al., 2017; Judge, 2010).

Enzymes such as laccases, peroxidases, cellulases, xylanases and lipases are increasingly

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integrated into wood processing operations. Their high substrate specificity enables targeted modification of lignocellulosic components without the extensive degradation associated with conventional chemical treatments. In the pulp and paper industry, xylanases reduce bleaching chemical requirements and improve pulp brightness, while laccases facilitate lignin modification, lowering the need for chlorine-based oxidants. Similarly, enzymatic pretreatments reduce the energy required for mechanical refining and improve fibre separation, contributing to lower operational costs and greenhouse gas emissions (Cho et al., 2012; Janusz et al., 2017).

Green chemistry also supports the development of bio-based adhesives and coatings. Oxidative enzymes activate naturally occurring lignin and tannins, enabling these renewable polymers to replace phenol-formaldehyde resins in wood composites. Enzymatic cross-linking produces strong and durable adhesive systems while significantly reducing volatile organic compound emissions and improving occupational safety. In parallel, enzyme-assisted extraction technologies enable the recovery of valuable antioxidants, phenolic compounds and natural preservatives from wood biomass, creating additional value streams within integrated biorefineries (Hellmayr et al., 2022; Ugovšek et al., 2013).

The future development of green chemistry in the wood sector will increasingly combine enzyme engineering, synthetic biology and digital process optimisation. Improved enzyme stability, higher catalytic efficiency and continuous bioprocessing are expected to facilitate industrial scale-up and broaden commercial applications. By integrating renewable feedstocks with environmentally compatible processing technologies, green chemistry strengthens the competitiveness of the forest-based industry while supporting climate neutrality, resource efficiency and sustainable industrial development.

Textile sector

The textile manufacturing chain includes several wet processes that require significant use of water, energy and the use of numerous different chemicals. According to the type of textile product to be manufactured, different steps are needed like sizing/desizing, scouring, bleaching, mercerization, printing, dyeing, and finishing. These steps usually require high temperatures, mechanical agitation and huge amounts of chemicals. Enzymes have already been used for a long time and their use in wet processes is probably the first example of industrial use of biotechnology in textile manufacturing. These biomolecules catalyze chemical reactions, like those occurring in textile wet processes and they are usually non-toxic and more environmentally friendly compared to traditional chemicals, due to their protein nature. Their use allows to reduce heating, to use less chemicals and water and, thanks to genetic engineering, it is possible to customize enzymes according to specific process requests. According to the different processes during the textile production, different enzymes can be used:

Enzyme-assisted processing is one of the most established applications of industrial biotechnology in the textile industry, providing sustainable alternatives to conventional chemical treatments. Enzymes operate under mild conditions, reducing water and energy consumption, chemical use, and wastewater generation while improving product quality and process efficiency.

The first major application is desizing, where amylases hydrolyse starch-based sizing agents applied during weaving into soluble sugars, primarily glucose. Compared with conventional chemical methods, enzymatic desizing is more selective, protects fibre integrity, and generates less environmental pollution.

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During scouring, natural impurities such as pectins, proteins, and waxes are removed from fibres. Instead of using concentrated sodium hydroxide, enzyme-based scouring employs proteases, pectinases, and cellulases to degrade these impurities under milder conditions. This approach significantly reduces chemical consumption, energy demand, and wastewater while preserving fibre quality.

Bleaching can also be improved through biotechnology. Laccases are used as a pre-treatment to modify natural pigments, reducing the amount of hydrogen peroxide required to achieve the desired whiteness. After bleaching, catalases efficiently decompose residual hydrogen peroxide into water and oxygen, eliminating additional washing steps and reducing water consumption.

In the finishing stage, enzymes such as cellulases, esterases, lipases, and cutinases improve the appearance and performance of textiles. Cellulases are widely used for cotton biopolishing, removing surface fibrils that cause pilling and producing smoother fabrics with enhanced softness and colour brightness. Esterases, lipases, and cutinases modify the surfaces of synthetic fibres, improving wettability, dyeability, and compatibility with functional coatings.

Advances in enzyme engineering and biotechnology continue to expand industrial applications by increasing enzyme stability, specificity, and process efficiency. As a result, enzyme-assisted textile processing is becoming a key technology for achieving cleaner production, supporting circular economy principles, and reducing the environmental footprint of the global textile industry.(*Enzymatic Treatments in Textile Wet Processing | European Cluster Collaboration Platform*, n.d.)

Furniture sector

Green chemistry and enzyme technologies are transforming furniture manufacturing by reducing the environmental impact of production while maintaining the quality, durability and aesthetic performance expected from modern furniture products. Traditional furniture production relies heavily on synthetic adhesives, coatings and surface treatments derived from petrochemical resources. Many of these materials contain volatile organic compounds (VOCs) and formaldehyde, which are increasingly restricted by environmental legislation and consumer expectations. Biotechnology provides sustainable alternatives that enable manufacturers to reduce hazardous substances while improving product sustainability (Sukhbaatar et al., 2009; Kutnar et al., 2020).

One of the most important applications is the development of bio-based adhesive systems. Enzymes such as laccases and peroxidases catalyse the activation of lignin and tannins naturally present in wood fibres, promoting cross-linking reactions that create strong internal bonding without relying exclusively on synthetic resins. These technologies allow the partial or complete substitution of formaldehyde-based adhesives used in particleboards, fibreboards and plywood, resulting in furniture products with lower emissions and improved indoor air quality. Similar approaches are being explored for veneer lamination and engineered wood components.

Enzyme technologies also improve surface preparation and finishing processes. Lipases, cellulases and oxidoreductases modify wood surfaces in a controlled manner, enhancing coating adhesion and reducing the need for aggressive chemical primers. Bio-based coatings incorporating natural oils, waxes and enzyme-modified polymers provide durable protection against moisture, ultraviolet radiation and biological degradation while maintaining the natural appearance of wood. Furthermore, enzymatic extraction of natural pigments and antimicrobial compounds offers environmentally friendly alternatives to synthetic additives used in decorative finishes (Humar et al., 2017; Lesar et al., 2011).

Green chemistry contributes to the broader sustainability of furniture manufacturing by enabling

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recycling and circular production.

Particular attention has recently been given to polyurethane foams recycling. Several bacteria and fungi have demonstrated the ability to depolymerise polyurethane through enzymatic hydrolysis, generating low-molecular-weight compounds that may be recovered as feedstocks for the synthesis of new polymers. A broad range of enzymes, including esterases, ureases, amidases, proteases, cutinases, lipases and oxidoreductases, have been identified as key catalysts in PU depolymerisation. Despite these advances, efficient biological recycling systems for commercial flexible polyurethane foams remain at an early stage of development due to the intrinsic recalcitrance and chemical complexity of these materials, and few technologies have progressed beyond laboratory or pilot scale (Ji et al., 2024; Magnin et al., 2020; Zeng et al., 2016).

In parallel, green chemistry is driving the development of more sustainable chemical depolymerisation routes for polyurethane recycling. Alternative solvents and catalysts, including ionic liquids, deep eutectic solvents (DESs), organocatalysts and other low-toxicity catalytic and biocatalytic systems, are being investigated as environmentally preferable alternatives to conventional glycolysis processes. These technologies enable selective bond cleavage under milder operating conditions, reducing energy consumption and hazardous chemical use while improving the recovery of valuable polyols and other chemical intermediates for closed-loop recycling. Although most of these approaches are still under development, they represent one of the most promising directions for sustainable polyurethane recycling in the furniture sector (Salas et al., 2025; Villa et al., 2025).

In addition, enzymatic processes facilitate fibre recovery from wood composites, improve residue valorisation and support the production of biodegradable materials that simplify end-of-life management.

As enzyme engineering, industrial biotechnology and process automation continue to advance, green chemistry will become an essential component of next-generation furniture manufacturing, supporting low-carbon production systems that combine high performance with reduced environmental impact (Šušteršic et al., 2010).

4.4 Enzymatic and Fungal Technologies

Wood sector

Enzymatic and fungal technologies represent one of the most advanced areas of industrial biotechnology in the wood sector. These technologies utilise naturally occurring fungi and their enzymes to modify the chemical and structural properties of wood under environmentally benign conditions, replacing or complementing conventional chemical treatments. Their high selectivity allows targeted degradation of lignin, hemicellulose or extractives while largely preserving cellulose, making biological processing particularly attractive for sustainable wood utilisation.

One important application is bioincising, where selected fungi partially degrade pit membranes and other anatomical barriers that limit liquid movement in refractory wood species. This process significantly improves wood permeability, allowing deeper penetration of preservatives, fire retardants and modification agents without mechanical damage. White-rot fungi, such as *Phanerochaete chrysosporium*, together with *Trichoderma* species, have demonstrated considerable potential for increasing preservative uptake while maintaining the mechanical

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integrity of wood (Thaler et al., 2012).

Fungal pretreatment is also increasingly applied in wood biorefineries. White-rot fungi selectively remove lignin, facilitating enzymatic hydrolysis and reducing the energy demand for pulping, fibre production and biofuel manufacturing. In addition, fungal enzymes including laccases, manganese peroxidases and cellulases are widely used for lignin modification, pulp bleaching and the production of bio-based adhesives. Controlled fungal colonisation further enables decorative spalting, transforming low-grade timber into premium-value products with unique natural colour patterns.

Emerging applications include fungal bioremediation of preservative-treated wood, enzyme-assisted biomass fractionation and mycelium cultivation for sustainable biomaterials. Continuous advances in fungal biotechnology, enzyme engineering and process optimisation are expected to accelerate industrial implementation and strengthen the role of biological processing within the circular forest-based bioeconomy (Chen et al., 2017; Pelaez-Samaniego et al., 2013; Yamashita et al., 2010).

Textile sector

Current textile production systems provide fabrics with excellent mechanical and functional properties; however, these benefits are often achieved through manufacturing processes that rely heavily on fossil-derived raw materials, intensive resource consumption, and chemical treatments, resulting in considerable environmental burdens. Advances in biotechnology, biofabrication, and sustainable materials science are creating new opportunities to develop new textile materials, supporting the transformation of the textile industry towards a more sustainable and circular production model.

Biofabrication represents a promising strategy for transforming the textile industry by enabling the sustainable production of fibers, fabrics, dyes, and functional finishes using biological resources. This approach relies on the ability of living organisms and biological molecules to synthesize or assemble materials with controlled structures and properties. Compared with conventional textile manufacturing, which is often associated with significant energy demands, water consumption, and chemical waste generation, biofabrication offers environmentally friendly production pathways that support the development of renewable, biodegradable, and high-performance textile products. The growing application of biofabrication technologies in textile manufacturing has led to the development of biofabricated textiles, a new class of materials produced through biological processes and renewable resources.

Biofabricated textiles are materials produced wholly or partially through biological processes involving living organisms, cells, enzymes, or biomolecules. Unlike conventional textiles, which are predominantly derived from petrochemical-based feedstocks or manufactured through resource-intensive processes, biofabricated textiles are generated using renewable biological resources under controlled biological conditions. Depending on the production strategy, microorganisms such as bacteria, fungi, yeasts, and microalgae can be employed to synthesize fibers, polymeric matrices, pigments, and functional compounds that can be directly incorporated into textile materials. Beyond their reduced environmental footprint, biofabricated textiles offer opportunities to introduce novel functionalities and material properties that are difficult to achieve through conventional manufacturing routes. These include enhanced biodegradability, improved biocompatibility, superior mechanical performance, antimicrobial activity, environmental responsiveness, and self-repair capabilities. Such characteristics enable the development of highly specialized products for applications ranging from apparel and

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sportswear to healthcare, protective clothing, and technical textiles.

Another important advantage of biofabricated textiles is their contribution to a more sustainable and ethical textile value chain. The use of renewable biological resources and biologically driven manufacturing processes can significantly reduce water consumption, energy requirements, and the generation of hazardous by-products. Furthermore, several biofabrication approaches provide alternatives to animal-derived materials and resource-intensive production systems, addressing growing societal concerns related to environmental sustainability, animal welfare, and responsible manufacturing practices.

Recent advances in biotechnology have significantly expanded the portfolio of biologically derived materials available for textile applications. Examples include bacterial cellulose, mycelium-based materials, recombinant protein fibers, engineered living materials, and microbially produced pigments. These innovative materials offer a sustainable alternative to conventional textile raw materials while providing functionalities that are difficult to achieve through traditional manufacturing approaches. Enhanced biodegradability, improved biocompatibility, self-repair capabilities, and responsiveness to environmental stimuli such as temperature, humidity, light, and pH are among the most attractive characteristics of these emerging materials. Furthermore, the integration of synthetic biology, precision fermentation, and advanced biofabrication technologies is creating new opportunities for the design and production of high-performance textile materials with tailored properties. As a result, biofabrication is increasingly recognized as a key driver in the transition towards a circular textile economy, promoting the use of renewable biological resources, reducing dependence on fossil-based feedstocks, and minimizing waste generation and greenhouse gas emissions throughout the value chain.

Furniture sector

Enzymatic and fungal technologies are creating new opportunities for sustainable furniture manufacturing by enabling the production of innovative materials while reducing dependence on synthetic chemicals and fossil-derived resources. These biological technologies support the development of environmentally friendly products with improved functionality, lower carbon footprints and enhanced circularity throughout the furniture value chain.

Beyond the production of bio-based materials, enzymatic and fungal technologies are increasingly being investigated for the biological recycling and valorisation of furniture waste. One of the most promising applications concerns flexible polyurethane foams. Recent studies have demonstrated that bacteria, fungi and their associated enzymes can depolymerise polyurethane generating low-molecular-weight compounds. In parallel, insect-assisted biodegradation using *Tenebrio molitor* has recently emerged as an innovative biological strategy for the complete degradation of flexible polyurethane foams, opening new opportunities for circular bioeconomy models based on waste valorisation (Ros et al., 2025).

Fungal biotechnology is also being applied to the treatment of post-consumer wood residues. Several fungal species have demonstrated the ability to detoxify treated wood by removing preservatives, copper compounds, azoles and formaldehyde-based resins. White-rot fungi can selectively degrade lignin, facilitating the fractionation of lignocellulosic biomass and improving the recovery of cellulose-rich fibres, while enzymatic hydrolysis further enables the conversion of recovered polysaccharides into fermentable sugars for biorefinery processes rapidly expanding application is the production of mycelium-based composites, where fungal mycelia bind wood particles, sawdust and other lignocellulosic residues into lightweight structural materials without synthetic adhesives. These biodegradable composites are increasingly used for acoustic

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panels, packaging, insulation and non-load-bearing furniture components. Biotechnology also enables the production of mycelium foams and fungal leather, providing renewable alternatives to polyurethane foams and animal or synthetic leather used in upholstery.

Enzymes further contribute to furniture manufacturing by improving adhesive performance and surface treatment. Laccases and peroxidases activate lignin and tannins naturally present in wood fibres, enabling the production of bio-based panels with significantly reduced formaldehyde emissions. Enzyme-assisted surface modification enhances coating adhesion, improves moisture resistance and supports the application of natural finishes with lower environmental impact.

Controlled fungal modification also creates decorative wood surfaces through spalting, producing unique colour patterns highly valued in premium furniture and interior design. Together with biological recycling technologies that facilitate fibre recovery and biomass valorisation, enzymatic and fungal processes contribute to more sustainable, circular and resource-efficient furniture production. As biotechnology continues to mature, these approaches are expected to become integral components of next-generation furniture manufacturing, supporting innovation while meeting increasingly stringent environmental and consumer requirements.

4.5 Circular Production and Waste Recovery Technologies

Wood sector

Circular production has become a fundamental principle of the modern wood industry, aiming to maximise the value of renewable biomass while minimising waste generation throughout the product life cycle. Biotechnology plays an essential role in this transition by enabling the conversion of wood residues into valuable secondary products through environmentally friendly biological processes. Sawdust, bark, wood chips, lignin-rich fractions and other by-products generated during harvesting and processing can be utilised as feedstocks for producing biofuels, platform chemicals, enzymes, bioplastics and advanced biomaterials instead of being used solely for energy production.

Fungi and microorganisms are particularly important for biomass valorisation. Wood-degrading fungi convert lignocellulosic residues into edible mushrooms, mycelium-based composites and high-value bioactive compounds, while spent cultivation substrates can be further reused as compost, soil amendments or feedstock for biogas production. Biotechnology also supports the recycling of preservative-treated wood through fungal bioremediation, enabling partial removal of toxic metals and facilitating safer material recovery. Integrated biorefineries combine these biological processes to maximise resource efficiency, reduce greenhouse gas emissions and support the development of a sustainable circular bioeconomy.

Textile sector

Waste-to-Textile Approaches

The textile sector has become an important destination for the valorization of natural resources

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recovered from agro-industrial waste. Waste-to-textile approaches aim to transform agricultural residues and industrial by-products into textile fibers, dyes, finishes, coatings, and functional additives, supporting more sustainable production systems.

Natural colorants extracted from food and agricultural residues have gained considerable attention as alternatives to synthetic dyes, whose production and application are often associated with significant environmental pollution. Sources such as grape pomace, pomegranate peel, onion skins, walnut husks, acorn by-products, beetroot residues, and red cabbage waste have demonstrated potential as textile colorants capable of producing a wide range of shades while simultaneously imparting antioxidant and antimicrobial functionalities (Shahid et al., 2013).

Beyond coloration, bioactive extracts recovered from waste streams can be incorporated into textiles to provide functional properties such as antimicrobial protection, UV shielding, antioxidant activity, insect repellence, and cosmetic effects. Encapsulation technologies, nanocarriers, and surface functionalization strategies have facilitated the controlled incorporation and release of these natural compounds onto textile substrates, enabling the development of high-value functional textiles and cosmetotextiles (Ignat et al., 2011; Panzella & Napolitano, 2017; Shahid et al., 2013).

Agricultural biomass can also serve as a source of fibers and biopolymers for textile applications. Cellulose recovered from agricultural residues, bacterial cellulose produced through fermentation, protein-based fibers derived from agricultural by-products, and bio-based polymers such as polylactic acid (PLA) are increasingly explored as sustainable alternatives to conventional synthetic fibers (Mohanty et al., 2018).

These waste-to-textile strategies not only reduce waste disposal but also contribute to decreasing the environmental footprint of textile manufacturing by replacing fossil-derived raw materials and synthetic chemicals with renewable and biodegradable alternatives.

Biotechnological wastewater treatment

Microorganisms, enzymes, and algae can be used to degrade toxic substances and organic pollutants from textile effluents. Due to the massive use of water-based processes and chemicals, textile production generates significant pollution in wastewater that has to be removed before releasing water into the environment. Biotechnological alternatives to the traditional chemical treatments can use bacteria (e.g. biodegradation using *Pseudomonas* species), enzymatic breakdown (for example, using laccases), and algae (phytoremediation). Bacteria can be used to break down synthetic dyes containing azo bonds, producing non-hazardous organic compounds. Enzymes like peroxidases and laccases are useful in the oxidation of phenolic compounds, while algae can use phosphorus and nitrogen and sequester carbon, while accumulating heavy metals.

Enzymatic polymerization/depolymerization for waste management

Due to their high specificity of action, enzymes can be used to process specific textile fractions by depolymerization, a process that breaks down polymers into their original monomers. Cellulosic fibers can be depolymerized to glucose, while polyester is broken down into terephthalic acid and ethylene glycol. These building blocks can be purified and re-polymerized into virgin polymers (the same original polymer or different ones) or used for other purposes (like glucose that can be used as nutrient for microorganisms in biorefineries). This approach is currently under development for textile waste valorization, where end-of-life materials are processed by microorganisms (biological recycling) or enzymes (biochemical recycling). Enzymes specificity of action allows to process only the selected fiber, thus enabling a separation process

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of the different fiber compositions that can be present in a multifiber textile. To increase the enzymatic depolymerization efficacy and to reduce the potential negative influence of chemicals that are normally added to the fibers during manufacturing (dyes, additives, functionalization agents), pre-treatment could be needed. These preliminary processes can be represented by mechanical treatment (e.g. milling), thermal treatment and chemical treatment (e.g. hydrolysis).

Circular Bioeconomy Opportunities

The concept of the circular bioeconomy integrates renewable biological resources with circular economy principles to create sustainable production and consumption systems. Within this framework, agro-industrial residues are viewed not as waste but as valuable resources that can be continuously reintegrated into industrial value chains.

Green extraction and biomass valorization play a central role in the circular bioeconomy by enabling cascading utilization strategies, where biomass is processed sequentially to maximize resource efficiency and economic value. High-value compounds such as pigments, antioxidants, and antimicrobials can first be recovered, followed by the utilization of remaining biomass fractions for the production of fibers, biopolymers, bioenergy, or soil amendments (Carus & Dammer, 2018).

The textile industry presents significant opportunities for implementing circular bioeconomy principles due to its high consumption of raw materials, chemicals, and water. By incorporating waste-derived bioactive compounds, renewable fibers, and biodegradable materials, textile manufacturers can reduce their dependence on virgin resources while creating innovative and environmentally responsible products.

Furthermore, advances in biotechnology, green chemistry, and biorefinery concepts are facilitating the development of integrated valorization platforms capable of converting diverse biomass streams into multiple value-added products. Such approaches contribute to climate change mitigation, resource conservation, rural development, and sustainable industrial growth (D'Amato et al., 2017).

As sustainability regulations become more stringent and consumer demand for environmentally friendly products continues to grow, green extraction and valorization strategies are expected to become increasingly important drivers of innovation across multiple industrial sectors, particularly within the emerging circular bioeconomy.

Furniture sector

The furniture industry generates substantial quantities of wood residues, including sawdust, sanding dust, panel offcuts and end-of-life furniture, creating significant opportunities for circular production. Biotechnology enables these waste streams to be transformed into valuable raw materials rather than being disposed of or used solely for energy recovery. Biological conversion processes utilise microorganisms, enzymes and fungi to produce bio-based adhesives, mycelium composites, renewable chemicals and biodegradable materials that can be reintroduced into manufacturing.

Enzymatic technologies facilitate fibre recovery from wood composites, improving recycling efficiency and extending the life cycle of wood-based materials. At the same time, fungal cultivation converts production residues into lightweight packaging, insulation materials and decorative products, while simultaneously reducing waste volumes.

Beyond wood residues, circular biotechnological approaches are increasingly being applied to polymeric waste generated by the furniture industry. Flexible polyurethane foams used in

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upholstery and mattresses are emerging as promising targets for biological recycling through microbial degradation, enzymatic depolymerisation and insect-assisted biodegradation. These technologies enable the recovery of valuable chemical intermediates for polymer synthesis or their biological valorisation into high-value products, creating new circular value chains between the furniture and agricultural sectors.

Integrating these technologies with eco-design principles, digital material tracking and life-cycle assessment supports closed-loop manufacturing systems in which materials remain in productive use for as long as possible. Consequently, circular biotechnology contributes to lower carbon emissions, improved resource efficiency and enhanced sustainability, strengthening the competitiveness of the furniture industry within the emerging European circular bioeconomy.

The increasing generation of agro-industrial residues and by-products has created both environmental challenges and opportunities for the development of sustainable bio-based products. In the context of the circular bioeconomy, these residual biomass streams are increasingly recognized as valuable sources of bioactive compounds, natural colorants, fibers, and functional ingredients that can be recovered and integrated into new industrial applications. Green extraction technologies have emerged as key tools for the sustainable valorization of these resources, enabling the efficient recovery of high-value compounds while minimizing environmental impacts associated with conventional extraction processes.

Use of Agro-Industrial Waste and By-Products

Agro-industrial activities generate substantial quantities of residues, including fruit peels, seeds, pomace, shells, leaves, stalks, and processing wastewater. Traditionally considered waste, these materials often contain significant concentrations of valuable compounds such as polyphenols, flavonoids, tannins, carotenoids, anthocyanins, proteins, polysaccharides, and essential oils (Ginni et al., 2021; Mirabella et al., 2014; Tarigan, 2013).

The valorization of agro-industrial by-products contributes to waste reduction, resource efficiency, and the creation of additional revenue streams for agricultural and food-processing industries. Examples include grape pomace from the wine industry, olive leaves and pomace from olive oil production, citrus peels from juice processing, pomegranate husks, nut shells, coffee grounds, cereal bran, and forestry residues. These biomass resources can serve as sustainable feedstocks for the extraction of bioactive compounds with applications in food, cosmetics, pharmaceuticals, packaging, and textiles (Ginni et al., 2021; Tarigan, 2013).

The European Union and other international organizations increasingly promote biomass valorization strategies as part of their circular economy and bioeconomy agendas, encouraging industries to transform waste streams into value-added products while reducing environmental burdens (European Commission, 2020).

Recovery of Pigments, Antioxidants, and Antimicrobial Compounds

One of the most promising approaches for biomass valorization involves the recovery of naturally occurring bioactive compounds. Plant-derived residues are particularly rich in pigments, antioxidants, and antimicrobial molecules that can be extracted and utilized in various industrial sectors.

Natural pigments such as anthocyanins, betalains, carotenoids, chlorophylls, and tannin-based colorants are increasingly investigated as sustainable alternatives to synthetic dyes. Besides their coloring properties, many of these compounds exhibit antioxidant and antimicrobial

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activities, providing multifunctional benefits (Panzella & Napolitano, 2017).

Polyphenols represent one of the largest classes of bioactive compounds recovered from agro-industrial waste. These molecules exhibit strong antioxidant activity by scavenging reactive oxygen species and preventing oxidative degradation. Significant quantities of polyphenols can be extracted from grape seeds, grape skins, pomegranate peels, olive by-products, acorn cupules, almond shells, and numerous other agricultural residues (Ignat et al., 2011).

Similarly, antimicrobial compounds such as phenolic acids, flavonoids, terpenoids, and essential oil constituents can be recovered from plant biomass and incorporated into functional materials. These compounds have demonstrated activity against a broad spectrum of microorganisms, making them attractive candidates for applications in food preservation, biomedical products, cosmetics, and antimicrobial textiles (Burt, 2004).

The adoption of green extraction technologies has significantly improved the sustainability of bioactive compound recovery. Emerging techniques such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), supercritical fluid extraction (SFE), enzyme-assisted extraction (EAE), and extraction using natural deep eutectic solvents (NADES) offer advantages over conventional solvent-based methods by reducing extraction times, energy consumption, and solvent requirements while improving extraction efficiency (Chemat et al., 2012).

4.6 Digitalisation and Smart Biotechnologies

Wood sector

Digitalisation and smart biotechnologies are accelerating the transition of the wood sector towards more efficient, sustainable and data-driven production systems. The integration of biotechnology with digital technologies, including artificial intelligence (AI), machine learning, digital twins and Internet of Things (IoT) sensors, enables continuous monitoring and optimisation of biological processes. In industrial biorefineries, sensors provide real-time information on fermentation parameters, enzyme activity and biomass conversion efficiency, allowing process conditions to be adjusted automatically to maximise yields and minimise energy consumption. AI-supported data analysis improves microbial strain selection, predicts process performance and facilitates quality control of bio-based products. Digital technologies also enhance biomass traceability throughout the supply chain, supporting certification, life-cycle assessment and circular resource management. Together, smart biotechnologies improve production efficiency, reduce operational costs and strengthen the competitiveness of the forest-based bioeconomy.

Textile sector

The textile industry has evolved from producing materials primarily for protection and aesthetics to developing functional systems that interact with the human body and environment (Hasan et al., 2025; Y. Zhang et al., 2023).

Advances in materials science, biotechnology, nanotechnology, and textile engineering have enabled textiles with antimicrobial, antioxidant, ultraviolet (UV)-protective, thermoregulatory, self-healing, sensing, and controlled-release properties. Biotextiles are a subgroup incorporating biological materials, natural bioactive compounds, biomolecules, living systems, or

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biotechnology-derived components (Fernandes et al., 2022; W. Lu et al., 2024; Tadesse et al., 2021). Their development is driven by demand for sustainable products and growing applications in healthcare, sportswear, cosmetics, personal protection, and wearable technologies (Ribeiro et al., 2017; Tadesse et al., 2021).

Antimicrobial textiles inhibit bacteria, fungi, and viruses and are used in hospital garments, wound dressings, bedding, protective equipment, sportswear, footwear, filtration systems, and domestic textiles (Bibi et al., 2024). Conventional agents include silver compounds, quaternary ammonium salts, triclosan, and polyhexamethylene biguanide (Orasugh et al., 2025). Although effective, concerns about persistence, ecotoxicity, bioaccumulation, and antimicrobial resistance are encouraging a transition towards safer bio-based alternatives. Chitosan is especially promising because of its biodegradability, biocompatibility, low toxicity, and broad antimicrobial activity (Dastjerdi & Montazer, 2010; El-Naggar et al., 2018). Plant extracts, essential oils, enzymes, and antimicrobial peptides provide further alternatives. Extracts rich in polyphenols, flavonoids, tannins, and terpenoids can combine antimicrobial, antioxidant, and anti-inflammatory effects (Virk et al., 2004). Encapsulation helps protect volatile essential oils and enables their controlled release, while recombinant proteins and antimicrobial peptides support advanced medical and protective applications (Botelho et al., 2021; Ma et al., 2024).

Antioxidant textiles and cosmetotextiles deliver bioactive compounds to the skin, providing moisturizing, soothing, protective, anti-ageing, and antioxidant effects. Promising ingredients include vitamins, polyphenols, carotenoids, essential oils (Valdivieso-Ugarte et al., 2019), aloe vera, green tea, grape pomace, pomegranate, rosemary, honey, propolis, cork, and algae (Ivanovska et al., 2025). Nanoparticles, nanoemulsions, and encapsulation systems improve stability, durability, and controlled release (Jiang et al., 2021; Mahlapuu et al., 2016).. The use of agro-industrial by-products as sources of valuable bioactive compounds also supports circular bioeconomy strategies.

UV-protective textiles reduce the transmission of harmful solar radiation. Their performance depends on fiber composition, fabric structure, thickness, colour, moisture, and UV-absorbing additives and is expressed through the Ultraviolet Protection Factor (UPF). Bio-based absorbers such as lignin, melanin, flavonoids, tannins, and anthocyanins can provide both UV protection and antioxidant activity (Saha et al., 2024). Zinc oxide, titanium dioxide, and graphene-based materials offer strong UV shielding (Ghosh et al., 2024; Shi et al., 2019; Sundaresan et al., 2012) and may simultaneously impart antimicrobial or self-cleaning properties (Scapin et al., 2020; Tanasa et al., 2023).

Thermoregulatory textiles actively manage heat, moisture, or infrared radiation. Phase-change materials absorb and release thermal energy during melting and solidification and are commonly incorporated into fibers or coatings as microcapsules (Ghosh et al., 2024; Sundaresan et al., 2012). Bio-based phase-change materials derived from fatty acids and vegetable oils are increasingly investigated as alternatives to petroleum-based paraffins (Feldman et al., 1989). Infrared-reflective or emitting materials can reduce heat gain or improve heat retention Hsu et al., 2017; Wong et al., 2015). Combining thermal regulation, moisture management, and UV protection is particularly valuable for sportswear, outdoor clothing, military uniforms, and protective garments (He et al., 2023).

Self-healing textiles use dynamic polymers, responsive coatings, nanofibers, or nanocomposites to repair damage caused by abrasion, punctures, or microcracks (Ramesh et al., 2022). Healing may occur autonomously or be activated by heat, light, moisture, pressure, or changes in pH (Dannehl et al., 2023). These systems can extend product lifetime and reduce waste (Cai et al.,

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2023), particularly in protective clothing, medical textiles, filtration, aerospace materials, and wearable electronics. Stimuli-responsive textiles can additionally change colour, shape, permeability, insulation, conductivity, or biological activity in response to temperature, humidity, light, pH, mechanical stress, or chemical signals. Their applications include physiological monitoring, wound assessment, adaptive clothing, sensors, electronic skin, and human–machine interfaces (Lou et al., 2019; Merati, 2018).

Nanobiotechnology supports these functions through bio-based nanoparticles, nanofibers (Wan et al., 2023; Zhu et al., 2021), and nanocoatings (Hamed & Hassan, 2019). Chitosan, lignin, cellulose, starch, proteins, and lipids can form biodegradable carriers for antimicrobial agents, antioxidants, fragrances, drugs, and UV-protective compounds. Electrospun nanofibers and ultrathin coatings provide high surface area and multifunctionality while maintaining flexibility and breathability.

However, nanomaterials may be released during production, use, laundering, recycling, or disposal, creating possible occupational, health, and environmental risks (Beigzadeh et al., 2024; Dani & Shabiimam, 2025; Som et al., 2011). Their safety depends on particle size, morphology, surface chemistry, concentration, persistence, and biological interactions. Consequently, successful commercialization requires toxicological assessment, life-cycle analysis, regulatory compliance, and Safe-and-Sustainable-by-Design approaches. Future development will depend on balancing advanced functionality with durability, scalability, affordability, safety, and environmental responsibility.

Furniture sector

Digitalisation is becoming an essential component of biotechnology-enabled furniture manufacturing by improving process control, product quality and sustainability. Smart manufacturing systems integrate digital sensors, artificial intelligence and automated production with bio-based materials and biological processing technologies. Digital monitoring of fungal cultivation enables precise control of mycelium composite production, ensuring consistent material properties and reducing production variability. Artificial intelligence supports material selection, process optimisation and predictive quality control, while digital product passports facilitate traceability of renewable materials throughout the product life cycle. Combined with life-cycle assessment tools, digital technologies help manufacturers optimise resource consumption, minimise waste generation and demonstrate the environmental performance of furniture products. The convergence of digital manufacturing and industrial biotechnology will play a key role in developing highly efficient, circular and climate-neutral furniture production systems.

Beyond manufacturing digitalisation, smart biotechnologies are increasingly accelerating the development of next-generation biological solutions for the furniture sector. Advances in bioinformatics, multi-omics technologies and systems biology enable the identification of novel microorganisms and enzymes involved in the degradation of lignocellulosic materials, polyurethane and other synthetic polymers. In parallel, genetic engineering, synthetic biology and directed evolution are being applied to improve enzyme activity, substrate specificity, thermal stability and degradation efficiency, creating biological catalysts better suited for industrial applications. Machine learning and artificial intelligence further support enzyme discovery, protein structure prediction and metabolic pathway optimisation, significantly reducing the time required to develop new biotechnological processes. These digital-biological approaches are expected to play a central role in future circular manufacturing systems by enabling more

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efficient biomass conversion, waste valorisation and sustainable production of advanced bio-based materials.

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5. Best Practices and Case Studies

The successful integration of biotechnology into the wood, textile, and furniture sectors is increasingly demonstrated through innovative industrial practices and real-world applications. Across Europe and internationally, companies, research institutions, and collaborative initiatives are developing bio-based products, circular production systems, and resource-efficient technologies that illustrate the practical potential of industrial biotechnology. These examples provide valuable evidence of how biological processes can improve sustainability, reduce environmental impacts, create new business opportunities, and enhance industrial competitiveness.

This chapter presents selected best practices and case studies that highlight successful biotechnology applications across the three target sectors. The examples illustrate different levels of technological maturity, from commercially established solutions to emerging pilot-scale innovations, while demonstrating transferable approaches that can inspire future industrial implementation, research collaboration, and educational activities within the BIOWISE project.

5.1 Case Studies in the Wood Sector

General Information	
Name of the organisation/initiative	Mondi Świecie
Country	Poland
Type of entity	
Company	
TRL level	9
Website	
https://www.mondigroup.com/locations/poland/mondi-swiecie/	
Overview of the Best Practice	
Short description of the initiative	
Mondi Świecie is one of the largest integrated pulp and paper production facilities in Poland and part of the global packaging and paper group Mondi. The company operates within the forest-based bioeconomy, producing containerboards, paper, and pulp from renewable wood resources sourced through responsible forest management practices. Its activities combine industrial-scale manufacturing with sustainability-oriented innovation to improve resource efficiency and reduce environmental impacts across the value chain. The company continuously invests in advanced production technologies, including process optimization, energy-efficiency improvements, and environmentally responsible raw-material sourcing. Enzymes such as xylanases and laccases are used to reduce chemical usage in pulp production, improve efficiency, and lower environmental impact. Within the wood sector, Mondi promotes the efficient utilization of wood fibres and supports the transition towards renewable and circular materials. Biotechnology-related approaches,	

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such as enzyme-assisted pulp processing, help reduce chemical consumption, improve process efficiency, and enhance the environmental performance of pulp production.

As a major industrial actor, Mondi Świecie demonstrates how renewable forest resources can be transformed into high-value products while supporting sustainable industrial development. The company's activities contribute to circular economy objectives, responsible resource management and innovation within the European forest-based sector.

Biotechnology application area

Industrial biotechnology, Bio-based products, Waste recovery

Technological description

The company transforms renewable wood biomass into pulp, paper and packaging products, which are classic examples of bio-based products. Followed by their waste recovery system in paper and packaging production, it increasingly incorporates fiber recovery and circular resource use. On the other hand, the innovation using enzymatic treatment in pulp processing, called "WoodZymes," is the use of biological catalysts (enzymes such as xylanases and laccases) to improve pulp processing, reduce chemical consumption, and enhance process efficiency. The use of enzymes in an industrial manufacturing process is a textbook example of industrial biotechnology.

Mondi Świecie operates an integrated pulp and paper production system that combines advanced wood processing technologies with continuous process optimization to improve efficiency and sustainability. The facility converts wood biomass into pulp, containerboard, and packaging materials through mechanical and chemical pulping processes supported by modern energy and water management systems. Biotechnology-related innovations include enzyme-assisted pulp processing, in which enzymes such as xylanases and laccases are used to improve fiber processing, reduce chemical consumption, and enhance pulp quality. The company also invests in process automation, resource-efficient manufacturing, and recovery systems that maximize the utilization of wood fibres and production by-products. These technologies contribute to lower environmental impacts, improved resource efficiency, and higher production performance. By integrating renewable raw materials with innovative industrial processes, Mondi Świecie demonstrates how biotechnology and sustainable manufacturing can support the development of high-value products within the forest-based bioeconomy.

Sustainability and Industrial impact

Environmental impact	High

Mondi promotes responsible sourcing of renewable wood resources, investments in energy efficiency, water management, and emissions reduction. The company's sustainability strategy focuses on reducing environmental impacts throughout the production process.

Circularity contribution	High

The company operates within a circular fiber-based value chain in which wood fibres are renewable, recyclable, and used repeatedly in paper and packaging products. Recovery and reuse of production by-products further support circularity objectives.

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Resource efficiency	High
Mondi continuously invests in process optimization, efficient fiber utilization, energy recovery, and water management systems. These measures maximize the value extracted from raw materials and reduce resource consumption per unit of production.	
Economic/Business impact	High
Mondi Świecie is one of the largest pulp and paper facilities in Poland and part of a global packaging group. Its products serve international markets, generating significant economic value, employment, and industrial competitiveness.	
Scalability potential	High
The technologies and production systems are already implemented at an industrial scale and can be replicated across large manufacturing operations. The growing demand for sustainable fiber-based packaging further supports future expansion and market growth	
Innovation	
Key Innovation Elements	
• Integration of renewable wood fibres with advanced pulp and paper manufacturing technologies to produce sustainable packaging and paper solutions. • Development of innovative fiber-based products that support the replacement of non-renewable and fossil-based packaging materials. • Implementation of resource-efficient production systems, including energy recovery, water management, and process optimization technologies. • Promotion of circular economy principles using renewable, recyclable, and responsibly sourced raw materials. • Combination of industrial-scale manufacturing capabilities with sustainability-driven innovation to deliver tailored packaging and paper solutions for global markets.	
Skills and Knowledge opportunities	
Mondi provides valuable opportunities for developing technical, managerial, and sustainability-related skills within the forest-based bioeconomy. Employees gain knowledge in pulp and paper production, sustainable packaging, resource-efficient manufacturing, process optimization, and environmental management. The company supports continuous learning through on-the-job training, development programs, digital learning tools, and international career opportunities. Mondi also promotes leadership development, interdisciplinary collaboration, and innovation across its global operations. Through its strong commitment to diversity, inclusion, and employee well-being, the company fosters teamwork, communication, and problem-solving skills in multicultural environments. Participation in sustainability initiatives and circular economy projects further strengthens understanding of responsible resource management and sustainable industrial practices. These opportunities help employees develop both technical expertise and transferable skills relevant to the evolving packaging, paper, and wood-based	

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industries.
Challenges and Limitations
Challenges
Mondi operates in a rapidly evolving industrial environment where increasing demand for sustainable packaging must be balanced with responsible sourcing of renewable raw materials. The company faces challenges related to maintaining secure supplies of certified wood fibres while protecting biodiversity and supporting sustainable forest management. Decarbonization of energy-intensive pulp and paper production processes requires continuous investment in new technologies, energy efficiency measures, and renewable energy sources. In addition, changing environmental regulations, market expectations, and packaging requirements create pressure to continuously innovate and improve product performance. Global supply-chain disruptions, fluctuations in raw material and energy prices, and increasing competition within the packaging sector may also affect operational efficiency and long-term planning.
Limitations
The production of pulp, paper, and packaging materials remains dependent on the long-term availability of sustainably managed forest resources and fiber supply chains. Although fiber-based products offer significant environmental advantages, they may not fully replace all conventional packaging materials in applications requiring specific barrier, durability, or performance properties. The implementation of new production technologies and sustainability initiatives often requires substantial capital investment and long development periods. Furthermore, the effectiveness of circular packaging solutions depends on external factors such as recycling infrastructure, collection systems, and consumer participation. Differences in regional regulations, market conditions, and resource availability may also influence the adoption and scalability of innovative packaging solutions across different markets.

General Information	
Name of the organisation/initiative	MycoMedica
Country	Slovenia
Type of entity	
Company	
TRL level (1–9/ Market entry)	9
Website	
https://www.mycomedica.si/	
Overview of the Best Practice	
Short description of the initiative	

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MycoMedica is a European biotechnology company specializing in the cultivation, processing, and application of medicinal fungi for health-related products. Established around 2000, the company has developed more than 25 years of expertise in fungal biotechnology and operates a vertically integrated production system, controlling all stages from strain selection and cultivation to extraction and final product formulation.

A distinctive feature of MycoMedica's production approach is the use of wood-degrading fungi cultivated on lignocellulosic substrates such as sawdust and wood chips. Species including *Ganoderma lucidum* (Reishi), *Hericium erinaceus* (Lion's Mane), *Lentinula edodes* (Shiitake), and *Inonotus obliquus* (Chaga) are naturally adapted to decompose wood and synthesize a wide range of biologically active compounds. By replicating natural growth conditions on wood-based substrates, MycoMedica optimizes fungal metabolism and the production of valuable metabolites, including β-glucans, triterpenoids, phenolic compounds, and antioxidants.

The company applies advanced bioprocessing technologies and water–ethanol extraction methods to produce highly concentrated fungal extracts for nutraceutical, veterinary, and cosmetic applications. Through the valorization of renewable wood biomass and forestry residues, MycoMedica represents an excellent example of sustainable wood-based biotechnology, contributing to the circular bioeconomy while developing innovative products that support human and animal health.

Biotechnology application area

Fine chemicals, fungal biotechnology, food supplements

Technological description

MycoMedica has developed an advanced biotechnology platform based on the industrial cultivation and processing of medicinal fungi grown on lignocellulosic substrates. The company utilizes a range of wood-degrading fungal species, including *Ganoderma lucidum* (Reishi), *Hericium erinaceus* (Lion's Mane), *Lentinula edodes* (Shiitake), *Inonotus obliquus* (Chaga), and *Cordyceps* spp., which are recognized for their ability to synthesize valuable bioactive compounds.



Figure 7. Products of Mycomedica (Source: Mycomedica)

The technological process is based on controlled cultivation on sterilized wood-derived substrates such as sawdust, wood chips, and lignocellulosic mixtures. These substrates

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replicate the fungi's natural ecological niche and promote the production of ligninolytic enzymes and secondary metabolites. Cultivation parameters, including temperature, moisture content, aeration, and substrate composition, are optimized to maximize fungal growth and metabolite yield. Following biomass production, the company employs standardized water–ethanol extraction technologies to isolate and concentrate biologically active compounds, including β-glucans, triterpenoids, phenolic compounds, and antioxidants. The resulting extracts can achieve concentrations up to twenty times higher than those found in raw fungal biomass. The technology integrates renewable forest biomass into a high-value biotechnological production chain, transforming wood-processing residues into functional ingredients for nutraceutical, veterinary, and cosmetic products. This approach demonstrates the potential of wood-based fungal biotechnology within a sustainable and circular bioeconomy framework.
Sustainability and Industrial impact

Environmental impact	High
MycoMedica valorises renewable wood residues as fungal substrates, reducing waste, supporting circular bioeconomy principles, and producing sustainable high value bioproducts.	
Circularity contribution	High
MycoMedica contributes to circularity by transforming low-value wood residues into high-value bioactive products, while enabling substrate reuse and composting.	
Resource efficiency	High
MycoMedica enhances resource efficiency by converting renewable lignocellulosic biomass into concentrated bioactive compounds with minimal waste generation.	
Economic/Business impact	Medium
MycoMedica creates economic value by converting forest-based biomass into high-value nutraceutical products, supporting innovation, green jobs, and bioeconomy growth.	
Scalability potential	Medium/High
MycoMedica's technology is highly scalable due to abundant lignocellulosic feedstocks and established cultivation methods, although market growth depends on differentiation, product quality, scientific validation, and competitiveness within the rapidly expanding global medicinal mushroom sector.	

Innovation
Key Innovation Elements
• Cultivation of medicinal wood-degrading fungi on renewable lignocellulosic substrates derived from forestry and wood-processing residues. • Optimized bioprocessing platform combining controlled cultivation

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conditions with standardized extraction technologies for high bioactive compound yields.

- Production of concentrated fungal extracts rich in β-glucans, triterpenoids, antioxidants, and other health-promoting metabolites.
- Valorization of low-value wood biomass into high-value nutraceutical, veterinary, and cosmetic products within a circular bioeconomy framework.
- Fully integrated production chain ensuring traceability, quality control, and consistent product performance from fungal strain selection to final formulation.

Skills and Knowledge opportunities

MycoMedica provides valuable opportunities for developing expertise in industrial biotechnology, fungal cultivation, bioprocess optimization, and bioactive compound extraction. The company's activities strengthen knowledge in applied mycology, wood-based biotechnology, lignocellulosic biomass utilization, and sustainable biorefinery concepts. Personnel gain practical experience in strain selection, substrate formulation, process control, quality assurance, and product development for nutraceutical, veterinary, and cosmetic applications. Collaboration with research institutions supports knowledge transfer in microbiology, biotechnology, natural product chemistry, and circular bioeconomy approaches. The company also contributes to workforce development in emerging bio-based industries by demonstrating how renewable forest resources can be transformed into high-value products through innovative biological processes. These competencies are highly relevant for the growing European bioeconomy and biotechnology sectors.

Challenges and Limitations

Challenges

MycoMedica operates in a rapidly growing and highly competitive global medicinal mushroom market, where differentiation through product quality, scientific validation, and process innovation is essential. Competition from large international producers, particularly from Asia, can create pricing pressures and challenges for market expansion. Regulatory requirements for nutraceuticals, health claims, food safety, product traceability, and quality assurance are becoming increasingly stringent, especially within European markets. Maintaining consistent concentrations of bioactive compounds across production batches requires continuous process optimization and quality control. Additional challenges include securing reliable supplies of high-quality biomass, scaling production while preserving product quality, and generating robust scientific evidence to support product efficacy. Addressing these challenges requires ongoing investment in research, biotechnology development, regulatory compliance, and market differentiation strategies.

Limitations

MycoMedica's technology relies on biological cultivation processes that are inherently slower and more variable than many conventional chemical manufacturing methods.

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Product quality and metabolite yields can be influenced by fungal strain characteristics, substrate composition, and cultivation conditions, requiring rigorous process control. The availability and consistency of suitable lignocellulosic feedstocks may vary regionally. While medicinal fungi contain numerous bioactive compounds, scientific evidence supporting specific health benefits remains limited for some products, potentially restricting market claims. Production scaling requires significant investments in controlled cultivation facilities, extraction equipment, and quality assurance systems. Furthermore, consumer acceptance and market growth depend on continued education, clinical validation, and compliance with evolving food, nutraceutical, and health-product regulations.

General Information	
Name of the organisation/initiative	IWT – Iavarone Wood Technology S.r.l.
Country	Italy
Type of entity (company, research centre, start-up, project, cluster)	
Innovative Start-up / Company	
TRL level	8–9
Website	
https://www.iavaronewt.it/home	
Overview of the Best Practice	
Short description of the initiative	
IWT (Iavarone Wood Technology) is an innovative Italian start-up operating at the intersection of wood technology, biotechnology, and the circular bioeconomy. The company researches, designs, develops, manufactures, and commercializes bio-based products and structures primarily made from wood and other renewable lignocellulosic resources. Drawing on generations of expertise in wood processing, IWT combines traditional knowledge with biotechnological approaches, advanced material engineering, digital technologies, and sustainable design. The company focuses on converting locally available forest biomass into high-value products for sustainable construction, urban environments, education, tourism, and environmental applications. Its approach promotes the cascading use of biomass, resource efficiency, material circularity, and the replacement of fossil-based or non-renewable materials. Biotechnology-related opportunities include the functionalisation of wood and lignocellulosic materials, the application of bio-based adhesives, coatings and protective systems, and the integration of biological processes into new material and product development. Through collaboration with municipalities, schools, universities, forestry organisations, and bioeconomy networks—including the SPRING Cluster and the Italian Forestry Association (AFI)—IWT supports knowledge transfer and the translation of research into market-ready solutions. Its portfolio includes innovative educational furniture, smart urban	

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furniture, technology-enabled greenhouses, and modular floating structures for sustainable tourism. IWT therefore demonstrates how biotechnology, wood science, and circular design can jointly transform local forest resources into advanced bio-based products while supporting decarbonisation, regional value chains, and sustainable territorial development.
Biotechnology application area
Biomaterials; Bio-based products; Forest-based bioeconomy; Sustainable construction materials; Circular bioeconomy; Wood valorisation.
Technological description
IWT develops innovative bio-based products and structures that combine renewable wood resources with biotechnology, materials engineering, and sustainable product design. Its technological approach focuses on improving wood durability, service life, functionality, and environmental performance through careful species selection, water-based protective formulations, engineered structural systems, and design for maintenance and disassembly. The outdoor furniture system uses solid Siberian larch (*Larix sibirica*), selected for its natural durability and resistance to outdoor exposure. The wood is treated with water-based protective products, reducing dependence on solvent-based formulations, and assembled using galvanized steel mechanical connections. This approach supports longer service life, component replacement, material recovery, and circular use. The product family includes: The Larix Sibirica Bench (160 × 42.5 × 40 cm), consisting of six solid larch slats reinforced by two horizontal structural elements and anchored to a concrete foundation with galvanized steel plates. The Larix Sibirica Table (160 × 87.5 × 75 cm), featuring a tabletop composed of 12 solid larch elements, supported by vertical wooden structures and four horizontal stiffening members. The Larix Sibirica Waste Collection Unit (197 × 67 × 108 cm), incorporating three galvanized steel containers with closed bottoms, handles, and lids. Four galvanized steel plates secure the wooden structure to concrete foundations. The Green Sound Wood installation extends the use of lignocellulosic materials beyond conventional furniture by combining engineered wood construction, bioacoustics, and environmental monitoring. This fully wooden megaphone measures approximately 0.85–2.30 m in height and 2.75 m in length. Its laminated spruce substructure comprises five concentric decagonal frames connected by ten longitudinal elements and is clad internally and externally with 28 mm timber boards. The terminal frames are finished with 20 mm larch borders. An integrated bioacoustic system detects ultrasonic signals produced by animals and converts them into frequencies audible to humans. The installation therefore transforms a renewable wood structure into an interface between biological activity, digital sensing, and human perception. It supports biodiversity awareness, environmental education, and nature-based tourism while demonstrating how wood engineering can be integrated with

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biological monitoring technologies to create multifunctional bio-based products.	
Sustainability and Industrial impact	
Environmental impact	High
Promotes renewable wood as a substitute for more carbon-intensive materials, supporting carbon storage, sustainable forestry, and reduced environmental footprints in construction and product manufacturing.	
Circularity contribution	High
Supports local forest-based value chains and circular bioeconomy models by transforming renewable forest resources into durable, high-value products and structures.	
Resource efficiency	High
Maximizes the value of locally sourced wood resources through innovative applications and long-life products, reducing dependence on non-renewable materials.	
Economic/Business impact	Medium-High
Creates opportunities in sustainable tourism, bioconstruction, urban design, and educational infrastructure while stimulating local forest-based economies and green jobs.	
Scalability potential	Medium-High
Technologies and design concepts can be replicated in other regions with forest resources, although scaling depends on local supply chains and investment capacity.	
Innovation	
Key Innovation Elements	
• Integration of renewable wood resources with advanced technologies and smart functionalities (e.g. a wooden acoustic amplification device, controlled-environment wooden greenhouses for indoor cultivation, and innovative floating tourism platforms). • Development of innovative bio-based products for tourism, education, urban furniture, and construction • Valorization of local forest resources within a circular bioeconomy framework • Combination of traditional wood craftsmanship and modern engineering design • Promotion of sustainable wood-based biomaterials and bio-building solutions	
Skills and Knowledge opportunities	
IWT provides interdisciplinary expertise in wood biotechnology, sustainable product design, wood engineering, bio-based materials, forest-biomass valorisation, eco-design, circular bioeconomy, and sustainable construction. The company develops knowledge on combining renewable lignocellulosic resources with bio-based treatments, smart sensing, digital technologies, and advanced engineering to create high-value products with improved functionality, durability, and environmental performance.	

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Its activities offer opportunities to develop skills in the biotechnological functionalisation of wood, bio-based protective systems, resource-efficient processing, cascading biomass use, design for circularity, and the integration of biological and digital functions into conventional wood products. Through cooperation with universities, research institutions, forestry organisations, public authorities, and regional stakeholders, IWT supports knowledge transfer and applied research in sustainable forestry, biomaterials, bio-based construction, and forest-resource management. It also strengthens competences in green entrepreneurship, technology transfer, market-oriented innovation, and the development of local value chains within the forest-based bioeconomy.

Challenges and Limitations

Challenges

The development of the forest-based biotechnology sector faces several structural and technological challenges. A major concern is the growing imbalance between biomass availability and demand for material, biochemical, and bioenergy applications. Insufficient data on the quantity, quality, composition, and spatial distribution of lignocellulosic biomass—particularly in marginal agricultural and forest areas—limits the development of reliable biotechnological conversion pathways and industrial investment.

In Italy, the forest–wood value chain remains highly fragmented, with approximately 60% of forests under private ownership. This complicates coordinated management, biomass mobilisation, traceability, and the establishment of stable feedstock supplies. Climate-related disturbances, market volatility, and geopolitical crises further affect timber availability, quality, and prices.

The deployment of advanced biorefineries, bio-based materials, and cascading-use models requires consistent biomass quality, efficient pre-treatment and conversion technologies, improved logistics, and better-organised local supply chains. Progress therefore depends on stronger cooperation among forestry, agriculture, biotechnology, manufacturing, research organisations, and public authorities. Improved biomass mapping, digital traceability, sustainable harvesting, and regional biomass hubs will be essential for transforming heterogeneous forest resources and residues into reliable feedstocks for high-value bio-based products.

Limitations

The company's biotechnology-enabled solutions depend strongly on the reliable availability, quality, and sustainable management of forest biomass and other lignocellulosic resources. Variability in wood species, chemical composition, moisture content, natural durability, and biological susceptibility may influence material performance and the effectiveness of bio-based treatments. Some concepts remain under development and require further technical validation, pilot-scale demonstration, durability and safety assessment, investment, and process optimisation before large-scale commercialization.

Market adoption may also be limited by regulatory requirements, certification procedures, construction standards, and the established preference for conventional materials. Bio-based coatings, adhesives, preservatives, and functional components may require

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additional evaluation of their environmental performance, toxicity, stability, and long-term effectiveness. Moreover, regional differences in forest resources, supply-chain organisation, climatic exposure, and locally available wood species can restrict the direct transferability of solutions. Successful replication therefore requires adaptation of material selection, processing parameters, biological functionalisation, and product design to local resources, environmental conditions, and regulatory frameworks.

5.2 Case Studies in the Textile Sector

General Information	
Name of the organisation/initiative	Albini Group / ALBINI_next – Exteria ("Dyes from bacteria") with Colorifix
Country	Italy
Type of entity (company, research centre, start-up, project, cluster)	
Industrial company / textile innovation hub, in partnership with biotechnology company Colorifix and Kering Material Innovation Lab	
TRL level	TRL 7–8: industrial-scale validation on conventional dyeing machinery; pilot status published by ALBINI_next, with next objective to scale further for market demand.
Website	
https://www.albininext.com/progetti/exteria/; https://www.colorifix.com/solution	
Overview of the Best Practice	
Short description of the initiative	
Exteria is a pilot project led by ALBINI_next/Albini Group with Colorifix and support from Kering's Material Innovation Lab. It aims to replace synthetic textile dyes with colours produced by engineered microorganisms through synthetic biology. The project validated the dyeing of yarns on an industrial scale using conventional machinery at Albini's facility in Albino, Bergamo. Exteria is particularly relevant for BIOWISE because it is an Italian textile-industry case where biotechnology is integrated into an existing industrial process rather than requiring an entirely new value chain. It can be used as a "quick-win" pilot to explore fermentation, bio-based colour production, resource-efficiency gains, biosafety, process validation and industrial adoption of biotechnology in textile dyeing.	
Biotechnology application area	
Industrial biotechnology; synthetic biology; bio-based colourants; fermentation; sustainable textile dyeing; resource-efficient wet processing.	

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Figure 8. ALBINI_next dyed 100% cotton yarns. Source: ALBINI_next (www.albininext.com).

Technological description	
Colorifix identifies naturally occurring colours and uses DNA sequencing to locate the genes responsible for pigment production. These genetic instructions are inserted into microorganisms, which are grown in fermenters using renewable raw materials such as simple sugars, salts, and plant byproducts. In Exteria, ALBINI_next installed a fermenter and a biolaboratory at the Albini Group's Albino plant. Once peak pigment production is reached, the fermentation liquid is transferred to the regular dyeing machines along with the yarn. The bacterial liquid replaces much of the water normally used in the dyeing cycle, while the natural binding elements present in the microorganisms help fix the pigment to yarns and fabrics without the use of harmful chemicals. Albini tested two bacterial strains: one that produces beige/camel hues on cotton and wool, and one that produces a bright purple pigment from a silk production byproduct, used on 100% cotton yarn. Albini then wove and finished the fabrics and carried out quality and performance checks.	
Sustainability and Industrial impact	
Environmental impact	High
Exteria claims lower water, energy and harmful chemical use; Colorifix reports technology-level reductions of chemicals, water, gas, electricity and CO_2 versus a conventional benchmark.	
Circularity contribution	Medium/High
The process uses renewable inputs and plant by-products and reduces hazardous dyeing chemistry; circularity is strongest at process/resource level rather than end-of-life.	
Resource efficiency	High
Fermentation broth is used directly in standard dyeing equipment and can replace water normally used in dyeing, reducing resource demand.	
Economic/Business impact	Medium/High
Industrial relevance because it can use existing dyeing infrastructure; however, wider economic competitiveness and market parity still require broader scaling.	
Scalability potential	High
ALBINI_next reports validation at industrial scale on conventional machinery, with the next goal to scale further to meet market needs.	

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Innovation
Key Innovation Elements
• Bacterial/synthetic-biology route to textile colours • Fermentation integrated with conventional dyeing machinery • Industrial-scale validation at Albini Group • Reduced need for harmful chemicals and process water • Partnership model linking textile manufacturer, biotech provider and luxury/material innovation actor
Skills and Knowledge opportunities
Exteria supports training in synthetic biology, microbial fermentation, pigment biosynthesis, industrial textile dyeing, process validation, quality/fastness testing, environmental assessment, and biosafety. It is particularly suited to BIOWISE modules on how biotechnology can be integrated into existing textile wet processing lines. It also offers valuable insights into collaboration between textile companies, biotech startups/suppliers, brands, and innovation hubs, as well as the skills needed to manage interdisciplinary projects involving biology, engineering, sustainability, and textile performance.
Challenges and Limitations
Challenges
The main challenges include expanding the colour range, ensuring batch-to-batch repeatability, validating colourfastness across different fibres, managing industrial biosafety, and demonstrating cost-competitiveness compared to conventional dyeing. Since genetically modified microorganisms are used during production, the process also requires appropriate procedures for the correct use of microorganisms. Further studies are needed to demonstrate performance, economic, and environmental benefits across different substrates, colours, and production sites.
Limitations
Public information confirms the pilot project status and industrial-scale validation, but detailed quantitative performance data for Albini's specific trials, complete cost data, and the full life cycle assessment (LCA) for the Exteria pilot project are not publicly disclosed. A BIOWISE pilot project should therefore present Exteria as a solid case for process innovation.

General Information	
Name of the organisation/initiative	SQIM Srl / Mogu – MY-FI project ("Reinventing a smart, circular and competitive textile industry with advanced

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	myco-fibres")
Country	Italy
Type of entity (company, research centre, start-up, project, cluster)	
Company / innovative SME and EU Horizon 2020 project coordinator (MY-FI)	
TRL level	TRL 6–7: pilot-scale demonstration achieved; some Mogu mycelium-based products are already market-facing, while the MY-FI myco-fibre textile route remains in pilot/scale-up and market-entry preparation.
Website	
https://mogu.bio/ https://cordis.europa.eu/project/id/101000719/reporting	
Overview of the Best Practice	
Short description of the initiative	
Mogu/SQIM is an Italian biomaterials company using fungal biotechnology to transform low-value organic and residual substrates into mycelium-based materials. Through the H2020 MY-FI project, coordinated by SQIM, the initiative developed advanced myco-fibres and nonwoven materials for fashion and automotive applications. The case is highly relevant for BIOWISE because it shows a complete pathway from bio-fabrication to pilot-scale production, prototyping, biodegradability testing, LCA/LCC assessment, and market-readiness work. It is suitable as a flagship case on bio-fabricated textile materials, circular feedstocks, industrial biotechnology, and scale-up from laboratory to pilot production.	
Biotechnology application area	
Biomaterials; fungal biotechnology; industrial biotechnology; bio-based products; valorisation of residual substrates / waste recovery; circular bioeconomy.	



Figure 9. Bioreactor and raw mycelium material. Source: MY-FI Project (www.my-fi.eu).

Technological description	
The MY-FI case is based on fungal mycelium as a living biological system capable of binding and transforming substrates into new types of bio-based materials. The project developed	

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two bio-fabrication processes: surface liquid fermentation and dynamic liquid fermentation. Surface liquid fermentation achieved a pilot-scale capacity of approximately 1,900 m2/year and produced materials suitable for prototyping in the fashion and automotive sectors. Dynamic liquid fermentation achieved 1,500 litters, but the resulting material quality was still insufficient for large-scale application, indicating the need for further optimization. The technology uses environmentally friendly processes designed to reduce energy, water, land, and chemical consumption while avoiding toxic compounds. Post-treatment/wet processing was improved during the project, resulting in reduced water consumption and the implementation of wastewater treatment. The materials were tested for industrial performance, biodegradability under industrial and marine composting conditions, microplastic release, life cycle assessment (LCA), and life cycle costing (LCC). The result is a robust pilot case for studying bio-fabrication, material finishing, testing, production scale-up, business modelling, and circularity claims.
Sustainability and Industrial impact

Environmental impact	High
The project targets low water, energy, land and chemical inputs, waste reduction, non-toxic manufacturing and promising LCA results.	
Circularity contribution	High
Use of residual/local substrates, biodegradability testing, reduced dependency on fossil/non-EU resources, and focus on full material circularity.	
Resource efficiency	High
Bio-fabrication is designed around mild processes and valorisation of low-value substrates; wet processing improvements reduced water use.	
Economic/Business impact	Medium/High
Strong market potential and 19 Key Exploitable Results were identified, but LCC indicates that more efficiency and economies of scale are needed.	
Scalability potential	Medium/High
Pilot scale reached for both routes; Surface Liquid Fermentation appears scalable and suitable for industrial upscaling, while Dynamic Liquid Fermentation still needs quality improvement.	

Innovation
Key Innovation Elements
• Mycelium-based nonwoven/myco-fibre material platform • Transformation of low-value residual substrates into high-value materials • Surface Liquid Fermentation scaled to 1,900 m^2/year • Cross-sector prototypes for fashion and automotive

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• Integration of LCA/LCC, biodegradability and business planning in the pilot pathway
Skills and Knowledge opportunities
The case study offers training opportunities in fungal biotechnology in terms of bio-fabrication, evaluating the most suitable substrate, controlling the fermentation process, testing fabrics/materials, assessing biodegradability, assessing microplastic release, LCA/LCC, and market entry analyses. For BIOWISE, it can support practical modules and case studies on how a biomaterial moves from lab cultivation to pilot scale and application prototypes.
Challenges and Limitations
Challenges
Key challenges include process reproducibility, material standardization, and optimization of wet processes in an industrial context. Overall, further studies are needed to validate circularity pathways and further strengthen the scientific evidence regarding biodegradability, microplastic release, and end-of-life performance.
Limitations
A potential limitation is the limited availability of public information on the technology's intellectual property status, particularly whether specific patents, patent applications, or exclusive licenses cover the biotechnological process, material formulation, or industrial application. This could make it difficult to fully assess the initiative's freedom to operate, replicability, and transferability to other textile industry players or supply chains.

General Information	
Name of the organisation/initiative	RadiciGroup
Country	Italy
Type of entity (company, research centre, start-up, project, cluster)	
Company	
TRL level	TRL 9 (Commercialized)
Website	
https://www.radicigroup.com/en/	
Overview of the Best Practice	
Short description of the initiative	
RadiciGroup has developed a portfolio of sustainable solutions aimed at supporting circular economy principles in the textile and polymer sectors. The initiative combines recycled materials, bio-based feedstocks, bio-circular raw materials certified under ISCC Plus, and environmentally responsible manufacturing processes. Through products such as	

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Renycle® (recycled polyamide), Bionside®, Radipol® (from bio-based sources) and Radiplus® (Bio-circular) solutions, the company reduces dependence on virgin fossil resources while maintaining industrial-grade performance. Sustainability is embedded throughout the value chain through eco-design, recyclability, Life Cycle Assessment (LCA), renewable energy use, and collaboration with customers and suppliers. The initiative addresses climate change, resource scarcity, and waste reduction challenges while providing commercially viable solutions for textiles, automotive, industrial applications, and consumer products.

Biotechnology application area

Bio-based products; Biomaterials; Industrial biotechnology; Waste recovery and recycling; Circular materials management

Technological description

RadiciGroup's sustainable materials portfolio is based on advanced polymer engineering, recycling technologies and renewable feedstock integration. Renycle® engineering polymers are manufactured through mechanical recycling processes that recover and reprocess PA6 and PA66 from post-industrial and post-consumer waste streams. The resulting materials maintain high mechanical performance while significantly reducing environmental impacts and supporting end-of-life material recovery.

Radipol® comprises a wide range of polyamide polymers, including PA6, PA66, PA610, PA612 and PA66/PA6 copolyimides, designed for a wide range of industrial applications, particularly in the production of engineering plastics and yarns, thanks to their excellent thermal and chemical resistance, dimensional stability and versatility. Engineering plastics made with Radipol® are ideal to produce components for the automotive industry, as well fabrics for vehicles and household appliances. The fibres obtained from Radipol® offer an optimal balance between comfort and resistance to intense movements or mechanical stress, making them particularly suitable for fashion clothing, sportswear and leisurewear.

Bionside® extends the Radilon® family with bio-based polyamides, particularly PA610 materials derived primarily from castor oil. These renewable polymers reduce reliance on fossil resources, lower carbon emissions and require limited agricultural water inputs while maintaining high technical performance for industrial applications.

Radiplus® is used in the production of polyamides (PA66) for versatile textile and industrial applications, but also for making engineering plastics used in electrical and electronic components and in the automotive industry (including e-mobility vehicles).

Sustainability and Industrial impact

Source of data: Sustainability Report 2024, available at https://www.radicigroup.com/wp-content/uploads/2025/02/BdS_2023_EN_Web.pdf

Environmental impact	High

Compared to 2013 data:

- -30% total energy consumption from fossil sources per tonne processed
- -44% total primary energy from fossil sources destined to electricity, per tonne

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• -42% total emissions per tonne processed • -58% direct emissions per tonne processed • -20% indirect emissions per tonne processed • •59% Electricity from renewable sources	
Circularity contribution	High
• Supports circular economy principles using waste-derived feedstock: • 73% of non-hazardous waste directed to recovery (56% of which destined to internal recovery); • •4% Hazardous waste directed to recover	
Resource efficiency	High
Optimises raw material use, reuses waste streams, employs recovered feedstocks, and improves process efficiency through advanced manufacturing technologies (79% of water saved compared to theoretical requirement).	
Economic/Business impact	High
Creates market-ready sustainable materials that meet customer demand for lower-carbon products while maintaining performance and competitiveness across multiple sectors.	
Scalability potential	High
Technologies are already commercialised globally and integrated into existing industrial production systems, enabling replication across sectors and regions.	
Innovation	
Key Innovation Elements	
• Development of high-performance recycled nylon and engineering polymers. • Integration of bio-based and - feedstocks into commercial products. • Application of Life Cycle Assessment (LCA) and Environmental Footprint methodologies in product design. • Eco-design based on recyclability and monomaterial concept. • Industrial-scale implementation of circular economy principles through material recovery and reuse.	
Skills and Knowledge opportunities	
RadiciGroup provides valuable knowledge in sustainable polymer chemistry, renewable-carbon feedstocks, bio-circular materials, certification systems, and industrial decarbonization strategies. The initiative demonstrates practical implementation of the mass-balance approach, including traceability, chain-of-custody management, and ISCC	

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PLUS certification requirements. It offers learning opportunities in life-cycle assessment (LCA), sustainable supply-chain management, circular economy implementation, and advanced polyamide technologies. The company is particularly relevant for professionals working in sustainable materials development, chemical engineering, industrial biotechnology, environmental management, and product sustainability assessment. It also illustrates how renewable feedstocks can be integrated into existing large-scale industrial processes without compromising product quality or operational efficiency.
Challenges and Limitations
Challenges
Key challenges may include ensuring a stable supply of high-quality recyclable feedstocks, maintaining technical performance equivalent to virgin materials, managing certification and traceability requirements for bio-based and circular materials, and meeting sustainability regulations. The company must also balance sustainability goals with cost competitiveness and market acceptance. Collaboration across the value chain is necessary to enable product collection, sorting, recycling, and circular business models.
Limitations
Availability of renewable feedstocks and recyclable waste streams may constrain expansion. Mechanical recycling can face challenges depending on waste composition. Furthermore, the success of circular systems depends on infrastructure for collection, sorting, and recycling.

General Information	
Name of the organisation/initiative	TINTEX TEXTILES
Country	Portugal
Type of entity (company, research centre, start-up, project, cluster)	
Company	
TRL level	6 (non-commercialized)
Website	
https://www.tintextextiles.com/	
Overview of the Best Practice	
Short description of the initiative	
Tintex Textiles has developed a portfolio of sustainable solutions for dyeing aimed at supporting circular economy principles in the textile sector. The initiative combines bio-based feedstocks, extraction processes with green solvents, and environmentally responsible manufacturing processes. Through products including extracts from acorn, cork, almond, grapes, among others, the company reduces dependence on the synthetic dyes while maintaining industrial-grade performance. Sustainability is embedded	

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throughout the value chain through eco-design, recyclability, Life Cycle Assessment (LCA), renewable energy use, and collaboration with customers and suppliers. The initiative addresses climate change, resource scarcity, and waste reduction challenges while providing commercially viable solutions for textiles, and consumer products.
Biotechnology application area
Bio-based products; Biomaterials; Industrial biotechnology; Waste recovery and recycling; Circular materials management
Technological description
Tintex's sustainable materials portfolio is based on bio-based natural extracts from agro- and food wastes (cork, acorn, almond, berries, grapes, among others). The extracts containing pigments are manufactured through mechanical recycling processes that recover and reprocess the wastes. The resulting materials maintain the pigments and the bioactive compounds from natural sources while significantly reducing environmental impacts and supporting end-of-life material recovery.
Sustainability and Industrial impact Source of data: https://www.tintextextiles.com/sustainability

Environmental impact	High
• -20% total energy consumption from fossil sources per tonne processed • Reduced amount of toxic water effluents • Less energy consumption on wastewater treatment	
Circularity contribution	High
• Supports circular economy principles using waste-derived feedstock: • 73% of non-hazardous waste directed to recovery (56% of which destined to internal recovery); • 4% Hazardous waste directed to recover	
Resource efficiency	High
Optimises raw material use, reuses waste streams, employs recovered feedstocks, and improves process efficiency through advanced manufacturing technologies (79% of water saved compared to theoretical requirement).	
Economic/Business impact	High
Creates market-ready sustainable materials that meet customer demand for lower-carbon products while maintaining performance and competitiveness across multiple sectors.	
Scalability potential	High

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Technologies are already commercialised globally and integrated into existing industrial production systems, enabling replication across sectors and regions.

Innovation

Key Innovation Elements

- Development of high-performance cotton and lyocell fabrics.
- Integration of bio-based and bio-circular feedstocks into commercial products.
- Application of Life Cycle Assessment (LCA) and Environmental Footprint methodologies in product design.
- Eco-design based on recyclability and monomaterial concept.
- Industrial-scale implementation of circular economy principles through material recovery and reuse.

Skills and Knowledge opportunities

Tintex, a leading textile finishing company with strong expertise in sustainable processing, offers significant opportunities for the development of skills and knowledge related to the industrial application of natural extracts for textile coloration. Through its experience in dyeing and finishing cotton and lyocell fabrics, the company provides a valuable environment for understanding the challenges and requirements associated with replacing conventional dyes with bio-based alternatives.

Collaboration with Tintex enables the acquisition of knowledge in extract preparation, process optimization, colour reproducibility, scale-up strategies, and industrial dyeing technologies. It also offers opportunities to develop competencies in sustainable textile manufacturing, resource efficiency, wastewater reduction, and circular bioeconomy approaches. Furthermore, exposure to industrial quality control procedures, colour fastness assessment, and market requirements strengthens the practical skills needed to accelerate the adoption of natural colorants in the textile sector, supporting the transition towards more sustainable and environmentally responsible textile production.

Challenges and Limitations

Challenges

Despite the significant potential of natural extracts for textile dyeing, several challenges must be addressed to enable their successful industrial implementation. One of the main difficulties is the natural variability of bio-based raw materials, which can lead to fluctuations in pigment composition, colour intensity, and extraction yields, affecting process reproducibility and colour consistency. Achieving standardized extraction protocols and ensuring a stable supply of raw materials are therefore critical challenges.

Additional obstacles include the generally lower colour fastness of some natural dyes compared to synthetic alternatives, requiring the development of optimized dyeing processes and eco-friendly mordanting strategies. Scale-up from laboratory to industrial production also presents technical challenges, as extraction, storage, and application

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conditions must be adapted to large-scale operations while maintaining efficiency and sustainability. Furthermore, regulatory requirements, cost competitiveness, and market acceptance remain important considerations. Addressing these challenges requires interdisciplinary expertise in biotechnology, textile engineering, chemistry, and industrial processing, creating valuable opportunities for innovation and knowledge transfer between research institutions and industry partners such as Tintex.
Limitations
The implementation of natural extracts as textile colorants presents several limitations that may affect their large-scale industrial adoption. A major limitation is the lower availability and seasonal dependence of many natural raw materials, which can restrict supply continuity and lead to variations in extract composition. This variability often results in inconsistencies in colour shade, intensity, and performance between production batches. Another limitation is the generally lower colour yield and reduced washing, rubbing, and light fastness exhibited by some natural colorants when compared with conventional synthetic dyes. Consequently, higher quantities of extracts or additional fixation treatments may be required, potentially increasing processing costs and complexity. The extraction and purification of natural pigments can also be resource-intensive, requiring careful optimization to ensure economic viability and environmental sustainability. In addition, many natural colorants possess limited stability during storage and processing, making formulation and preservation strategies necessary. Finally, the current industrial infrastructure is primarily designed for synthetic dyes, meaning that the integration of natural extracts may require process modifications, additional quality control measures, and extensive validation to ensure consistent product performance and compliance with market requirements. These limitations highlight the need for continued research, technological development, and industry–academia collaboration to facilitate the broader adoption of bio-based textile coloration systems.

General Information	
Name of the organisation/initiative	**LENERA**
Country	Portugal
Type of entity (company, research centre, start-up, project, cluster)	
Company	
TRL level	TRL 5-6 (non-commercialized)
Website	
https://lenera.eu/	
Overview of the Best Practice	

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Short description of the initiative
Lenera is a next-generation biotechnology company dedicated to precision-crafting bespoke, ethical, and sustainable luxury biomaterials through innovative, species-agnostic cellular agriculture technology. The company is dedicated to the research and development (R&D) of laboratory-grown animal skin, aiming to support its entry into the luxury market and foster international commercialization. The aim is the valorisation of native species from the inland regions of Portugal through the isolation of cells obtained from indigenous wild animals undergoing veterinary treatment, their use in laboratory-based skin reconstruction, and the development of sustainable tanning methodologies using plant extracts derived from agroforestry and forestry residues and by-products abundant in these regions. This integrated approach promotes the simultaneous valorisation of native fauna and flora, contributing to biodiversity conservation, natural resource preservation, and the development of high-value-added products. Within this framework, the company aims to develop plant-based crosslinking agents from phenolic compounds extracted from agroforestry residues, specifically tailored for the tanning of laboratory-grown skin produced from animal cells. These agents are intended to replace conventional tanning and crosslinking chemicals, such as glutaraldehyde and chromium salts, which are associated with environmental and health concerns. The expected outcome is the production of a high-quality, eco-friendly, and cruelty-free leather material that aligns with the principles of circular bioeconomy and sustainable manufacturing.
Biotechnology application area
The activities are positioned at the intersection of several biotechnology application domains, including biomaterials, industrial biotechnology, waste recovery, bio-based products, and circular bioeconomy. They combine advanced cell culture technologies with sustainable bioprocessing approaches to develop innovative leather alternatives derived from laboratory-grown animal skin. Within the biomaterial's domain, the activities focused on the production of high-value, cruelty-free leather through the cultivation and engineering of animal-derived tissues. They further integrate industrial biotechnology by developing environmentally friendly tanning processes based on naturally derived crosslinking agents obtained from agroforestry residues. A key component of the activities is the valorisation of waste and by-products, transforming underutilized agroforestry biomass into valuable phenolic-rich extracts for leather processing. This waste-to-product approach contributes to resource efficiency and supports the transition towards a circular bioeconomy. By replacing conventional chromium- and aldehyde-based tanning chemicals with renewable bio-based alternatives, Lenera promotes the development of safer and more sustainable manufacturing practices. Overall, the Lenera's objectives exemplify how biotechnology can simultaneously support biodiversity conservation, waste recovery, sustainable materials development, and the creation of innovative bio-based products for high-value markets.
Technological description
Lenera combines tissue engineering, cell culture technologies, green extraction processes, and sustainable biomaterial development to create an innovative platform for the production and tanning of laboratory-grown animal skin. Technology begins with the isolation of primary cells from native wild animal species undergoing veterinary treatment,

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followed by their expansion and cultivation under controlled conditions to generate biologically relevant skin tissues. To enable the transformation of these tissues into leather-like biomaterials, the project develops novel plant-based tanning agents obtained from agroforestry and forestry residues. Phenolic compounds are extracted using environmentally friendly extraction technologies and subsequently characterized and optimized for their crosslinking capacity. These natural compounds are designed to interact with collagen and other extracellular matrix proteins, improving the mechanical strength, stability, and durability of the cultivated skin while avoiding the use of toxic tanning chemicals such as chromium salts and glutaraldehyde. Lenera integrates advanced analytical techniques to evaluate the physicochemical, mechanical, thermal, and morphological properties of the resulting biomaterials. Process optimization will focus on maximizing tanning efficiency, material performance, and scalability while minimizing environmental impacts. By combining cellular agriculture with waste valorisation and green chemistry principles, Lenera establishes a sustainable technological pathway for producing high-value, cruelty-free leather. The resulting technology contributes to the development of innovative bio-based materials, promotes circular use of agroforestry resources, and supports the transition towards more sustainable manufacturing practices in the luxury leather sector.
Sustainability and Industrial impact

Environmental impact	High
Lenera's system level approach, which combines a patented biological process with engineered automation reduces variability, times down cycling loops from years to weeks, allows for full customization and integration into tanneries while decreasing pollution levels by 80%.	
Circularity contribution	High
• Reduction of process-generated waste by 60% and complete elimination of toxic waste streams through the implementation of bio-based tanning technologies • Valorisation of agroforestry waste and by-products, including acorns, almonds, cork, garlic, and pine biomass • Traditional tanning methods based on chromium salts or glutaraldehyde are not environmentally sustainable; however, they remain the dominant technologies in the leather industry, accounting for more than 85% of global leather production.	
Resource efficiency	High
Optimises raw material use, reuses waste streams, employs recovered feedstocks, and improves process efficiency through advanced manufacturing technologies (60% of water saved compared to theoretical requirement).	
Economic/Business impact	High
Pioneering the next era of high-performance, non-animal derived luxury biomaterials that are simultaneously circular and regenerative	

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Scalability potential	High

Technologies will be commercialised globally and integrated into existing industrial production systems, enabling replication across sectors and regions.

Innovation

Key Innovation Elements

- Development of non-animal luxury materials
- Integration of bio-based and bio-circular feedstocks into commercial products.
- Application of Life Cycle Assessment (LCA) and Environmental Footprint methodologies in product design.
- Eco-design based on recyclability and monomaterial concept.
- Industrial-scale implementation of circular economy principles through material recovery and reuse.

Skills and Knowledge opportunities

Lenera provides valuable opportunities for the development of multidisciplinary skills and knowledge at the interface of biotechnology, biomaterials, and sustainable leather production. Through its expertise in leather processing and product development, the company offers practical insights into industrial requirements, quality standards, and market expectations for high-value leather goods.

Collaboration with Lenera enables the acquisition of knowledge related to leather characterization, material performance assessment, product design, and manufacturing processes. It also provides opportunities to understand the technical challenges associated with integrating innovative biomaterials, such as laboratory-grown leather and bio-based tanning technologies, into existing production chains.

Furthermore, participants can develop competencies in sustainability assessment, circular economy strategies, regulatory compliance, and technology transfer. Exposure to real industrial environments strengthens skills in process optimization, product validation, scalability evaluation, and commercialization pathways, supporting the successful translation of research outcomes into market-ready solutions for the luxury and sustainable materials sectors.

Challenges and Limitations

Challenges

Lenera faces several challenges related to the integration of innovative and sustainable technologies into the leather value chain. One of the main challenges is ensuring that emerging biomaterials, such as laboratory-grown leather and bio-based tanning systems, achieve performance levels comparable to conventional leather in terms of durability, flexibility, appearance, and long-term stability.

Another challenge involves adapting existing manufacturing processes and equipment to

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accommodate new materials and tanning agents while maintaining production efficiency and product quality. The variability associated with bio-based raw materials may also affect process reproducibility and material consistency, requiring robust quality control strategies. Market acceptance represents an additional challenge, particularly in the luxury sector, where consumers and brands demand premium aesthetics, performance, and traceability. Demonstrating the value, reliability, and sustainability benefits of alternative leather products is therefore essential. Furthermore, compliance with evolving environmental regulations and sustainability standards requires continuous innovation and validation efforts. Addressing these challenges will provide valuable knowledge on industrial implementation, product development, and commercialization strategies, ultimately supporting the transition towards a more sustainable and circular leather industry.
Limitations
The adoption of Lenera's sustainable leather technologies faces several limitations. Laboratory-grown leather and bio-based tanning systems are still emerging technologies that require further optimization to achieve the durability, appearance, and performance standards expected by the luxury market. The scalability of production processes remains a challenge, as industrial implementation may involve higher costs and process adaptations compared to conventional leather manufacturing. Additionally, the variability of bio-based raw materials can affect product consistency and reproducibility, requiring robust quality control measures. Market acceptance may also be limited by consumer perceptions and the need to demonstrate long-term performance and reliability. Regulatory compliance, certification requirements, and validation processes can further extend the time needed for commercialization. Addressing these limitations is essential to ensure the successful integration of sustainable biomaterials into existing leather value chains and to support their large-scale market adoption.

5.3 Case Studies in the Furniture Sector

General Information	
Name of the organisation/initiative	Rutena d. o. o. (business unit Mycopor)
Country	Slovenia
Type of entity (company, research centre, start-up, project, cluster)	
Company	
TRL level	6–7
Website	
https://mycopor.eu/	
Overview of the Best Practice	
Short description of the initiative	

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MYCOPOR is an innovative initiative focused on developing sustainable, biodegradable materials based on mycelium, the root structure of fungi. Its objective is to replace conventional, resource-intensive materials such as plastics and synthetic insulation with environmentally friendly bio-composites produced from agricultural residues and natural growth processes. By leveraging low-energy production methods and circular economy principles, MYCOPOR aims to reduce carbon emissions and material waste across industries.

The initiative addresses key environmental challenges by offering versatile solutions for applications including packaging, construction panels, insulation, and acoustic materials. Its technology enables the creation of lightweight, customisable products that are fully biodegradable and safe for the environment, contributing to the transition towards greener industrial practices.

MYCOPOR is particularly relevant in the context of increasing regulatory and societal pressure to reduce plastic use and promote sustainable materials. By combining biotechnology with material engineering, the initiative supports innovation in green manufacturing and fosters the adoption of nature-based solutions in commercial applications. Overall, MYCOPOR represents a promising step towards scalable, eco-friendly alternatives in multiple sectors.

Biotechnology application area

Bio-based materials/biomaterials (primary classification), Fungal biotechnology, Industrial biotechnology, Circular bioeconomy/waste valorisation (secondary)

Technological description

MYCOPOR's technology relies on the controlled growth of mycelium within organic substrates to produce bio-based composite materials. The process starts with agricultural residues such as sawdust, hemp, or straw, which are combined with water and nutrients to create a growth medium. This substrate is then inoculated with selected fungal strains, which colonise the material by forming a dense network of hyphae that bind the particles into a solid, cohesive structure.

The material is shaped during growth using moulds, allowing the production of customised geometries and tailored mechanical properties. Once the desired structure is achieved, a drying or heat treatment is applied to stop fungal growth and stabilise the composite. The resulting material is lightweight, biodegradable, and exhibits functional properties such as thermal insulation, acoustic absorption, and structural stability.

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Figure 10. Mycopor producs (Source: University of Ljubljana)

The technology incorporates principles of industrial biotechnology and the circular bioeconomy by using low-energy processes and renewable raw materials. It enables the transformation of low-value agricultural by-products into high-value functional materials. This approach supports the replacement of conventional fossil-based materials in applications such as packaging, construction panels, and insulation systems, offering a scalable and environmentally sustainable alternative to traditional manufacturing methods.

Sustainability and Industrial impact	
Environmental impact	High
Technology replaces fossil-based materials (e.g., plastics, foams) with biodegradable, bio-based composites produced from renewable resources. The low-energy production process and absence of harmful chemicals significantly reduce greenhouse gas emissions and environmental pollution.	
Circularity contribution	High
MYCOPOR strongly supports circular economy principles by utilising agricultural by-products (e.g., sawdust, hemp, straw) as feedstock and producing fully biodegradable materials that re-enter natural cycles without waste accumulation.	
Resource efficiency	High
The process converts low-value biomass into high-value functional materials, maximising	

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resource use. It requires relatively low energy input compared to conventional material production and minimises raw material waste.	
Economic/Business impact	Medium
The initiative targets multiple growing markets (packaging, construction, insulation), offering sustainable alternatives with increasing demand. However, large-scale adoption may still be limited by cost competitiveness, certification requirements, and industrial partnerships.	
Scalability potential	Medium/High
The production process is inherently scalable due to mould-based growth and use of widely available raw materials. However, scaling depends on process standardisation, industrial automation, and regulatory approvals for construction and packaging applications.	
Innovation	
Key Innovation Elements	
• Mycelium-based material engineering: Utilises fungal growth to naturally bind agricultural residues into solid, functional composite materials without synthetic additives. • Low-energy bio-fabrication process: Production depends on biological growth rather than high-temperature or energy-intensive industrial methods, significantly reducing the environmental footprint. • Circular feedstock utilisation: Converts agricultural by-products (e.g., sawdust, hemp, straw) into high-value materials, supporting waste valorisation and circular economy models. • Customisable mould-based manufacturing: Enables materials to be grown directly into desired shapes and forms, allowing tailored properties and reducing post-processing requirements. • Multi-sector application potential: The material's versatility suits packaging, construction, insulation, and acoustic uses, facilitating broad industrial adoption.	
Skills and Knowledge opportunities	
The MYCOPOR initiative offers opportunities for interdisciplinary skills development at the intersection of biotechnology, materials science, and sustainable manufacturing. Key knowledge areas include fungal biology and cultivation techniques, bio-composite material design, and circular bioeconomy principles. It also promotes competencies in process engineering and the scale-up of bio-based production systems, as well as expertise in mould-based fabrication and product customisation. From an industrial perspective, the initiative supports learning in quality control, standardisation, and certification of novel biomaterials for applications in packaging and construction. Additionally, MYCOPOR fosters innovation-driven skills such as eco-design, life cycle	

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assessment (LCA), and sustainable product development. Collaboration between researchers, engineers, and industry stakeholders further enhances knowledge transfer and supports workforce development in emerging bio-based industries.
Challenges and Limitations
Challenges
The MYCOPOR initiative faces several challenges typical of emerging bio-based materials. A key issue is achieving consistent material performance and quality at industrial scale, as biological processes are sensitive to environmental conditions. Standardisation and certification, particularly for construction and packaging applications, may require extensive testing, time, and regulatory approval. Cost competitiveness with established fossil-based materials remains another challenge, especially during early-stage scaling when production volumes are limited. Market acceptance may also be gradual, as industries tend to rely on proven conventional materials. Additionally, scaling up production requires investment in infrastructure, automation, and supply chain development for reliable sourcing of raw materials. Finally, educating stakeholders and customers about the benefits and limitations of mycelium-based materials is essential to support broader adoption and integration into existing industrial systems.
Limitations
MYCOPOR technology has several inherent limitations related to the performance of bio-based materials and process control. Mechanical strength and long-term durability may be lower than those of conventional synthetic materials, limiting use in load-bearing or high-stress environments. Sensitivity to moisture and environmental conditions may also affect product stability if not properly treated or protected. The biological growth process requires precise control of conditions such as temperature, humidity, and contamination, which can introduce variability and reduce production efficiency. Production cycle times are also longer than those of conventional manufacturing, potentially affecting throughput. Material standardisation and reproducibility remain challenging, particularly when using variable natural feedstocks. Finally, although biodegradable, the material's end-of-life performance depends on specific environmental conditions, which may limit degradation in certain applications or disposal systems.

General Information	
Name of the organisation/initiative	EnzyclO3 and FOAMBLOOM
Country	Spain
Type of entity (company, research centre, start-up, project, cluster)	

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Projects	
TRL level	4
Website	
N/A	
Overview of the Best Practice	
Short description of the initiative	
EnzyclO3 and FOAMBLOOM are complementary Spanish projects focused on developing sustainable solutions for the management and valorisation of flexible polyurethane foam waste. Flexible polyurethane foams are widely used in the furniture and bedding sectors, particularly in sofas, chairs and mattresses, and currently represent a difficult-to-recycle waste stream. The projects explore two integrated technological pathways. EnzyclO3 focuses on the oxidative depolymerisation of flexible polyurethane foams using ozone to obtain an oxidised liquid extract, known as OLE, which can subsequently be valorised through fermentation. FOAMBLOOM investigates the biodegradation of flexible polyurethane foams using *Tenebrio molitor* larvae and associated microorganisms. Expected outputs include laboratory-validated processes for polyurethane foam degradation and valorisation, cultivation routes for plant growth-promoting bacteria using OLE, improved enzymes for polyurethane hydrolysis, and potential bio-based products such as biofertilizers, bio-stimulants, biocontrol products, insect biomass and chitin. Together, the projects aim to create a circular route for transforming end-of-life polyurethane foam waste into higher-value biological and agricultural products, while advancing knowledge in polymer biodegradation, microbial biotechnology and sustainable waste recovery.	
Biotechnology application area	
Waste recovery, Bio-based products	
Technological description	
The technological approach is based on the integration and optimisation of complementary biological and physicochemical processes for the recycling and valorisation of flexible polyurethane foam waste. The projects focus on two core pathways: oxidative depolymerisation and enzymatic, microbial and insect-assisted biodegradation. EnzyclO3 investigates ozone-based depolymerisation of polyurethane foams to generate an oxidised liquid extract that can be further valorised through fermentation. FOAMBLOOM focuses on the biological degradation of polyurethane foams using *Tenebrio molitor* larvae and their associated microbiota. The projects aim to improve degradation efficiency, reaction yields and substrate applicability across different polyurethane waste streams. Key parameters such as reaction kinetics, mass transfer limitations, microbial activity, enzyme stability and biological variability are being studied to support future transfer to pilot and industrial environments. The research combines biotechnology, polymer chemistry, microbiology, process engineering and agronomy to ensure that degradation products can be safely and effectively valorised. In addition, the projects explore the discovery and optimisation of new biological tools for polyurethane degradation, including the isolation of efficient microorganisms, enzyme discovery, omics technologies, bioinformatics and computational	

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enzyme engineering. These activities are intended to improve catalytic performance and deepen understanding of degradation mechanisms at molecular and process levels.	
Sustainability and Industrial impact	
Environmental impact	High
The projects address the reduction of flexible polyurethane foam waste through innovative bio-based recycling and valorisation pathways. By targeting a waste stream that is commonly landfilled or incinerated, the initiative can contribute to lower environmental pressure, reduced pollution and improved management of complex polymeric waste.	
Circularity contribution	High
The initiative supports circular economy principles by transforming end-of-life polyurethane foam waste into potentially valuable bio-based products. It extends the lifecycle of materials, reduces dependence on virgin resources and creates new opportunities for the recovery of value from synthetic polymer waste.	
Resource efficiency	High
The projects recover value from polyurethane foam waste that would otherwise have limited recycling options. Through combined chemical and biological processes, existing materials are converted into useful intermediate streams and potential agricultural inputs, supporting more sustainable production and consumption patterns across waste management, biotechnology and agronomy.	
Economic/Business impact	Medium
The projects create potential business opportunities in the valorisation of flexible polyurethane foam waste through sustainable biotechnological processes. They respond to growing market demand for circular recycling solutions and bio-based agricultural products, while opening new value-chain opportunities between waste management, industrial biotechnology and sustainable agriculture. At this stage, the business impact remains prospective, as techno-economic validation, regulatory acceptance and market deployment are still pending.	
Scalability potential	High
The underlying processes have potential to be adapted from laboratory to pilot and, in the longer term, industrial scale. The projects aim to progress towards demonstrator-level validation of polyurethane foam biodegradation using *Tenebrio molitor* and associated microorganisms, as well as ozone-based depolymerisation and subsequent biological valorisation. However, further optimisation is required to ensure process stability, reproducibility, cost-effectiveness and regulatory compliance at larger scales.	
Innovation	
Key Innovation Elements	
• Integrated hybrid recycling strategy for flexible polyurethane foam, combining oxidative depolymerisation, microbial degradation and insect-assisted biodegradation.	

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- Cascade chemical–biological treatment approach for converting recalcitrant polyurethane foam waste into valorisable intermediate and final products.
- Valorisation of degradation products into bio-based agricultural inputs, including potential biofertilizers, bio-stimulants and biocontrol products.
- Development of new biological tools for polyurethane degradation, including microorganisms, enzymes and microbiota associated with *Tenebrio molitor*.
- Creation of a potential waste-to-agriculture value chain linking polyurethane waste management, industrial biotechnology and sustainable agronomy.

Skills and Knowledge opportunities

The projects will generate significant skills and knowledge development across biotechnology, polymer science and bioprocess engineering. They will strengthen expertise in polyurethane biodegradation, ozone-based depolymerisation, enzymatic and microbial degradation pathways, and insect-assisted bioconversion using *Tenebrio molitor*. Knowledge will also be developed on enzyme functionality, polymer–microorganism interactions, structure–degradability relationships and the biological transformation of complex synthetic polymers. The initiative will provide practical experience in bioprocess design and scale-up, including the operation of hybrid chemical–biological systems and the optimisation of parameters such as reaction kinetics, mass transfer, biological activity and process stability. Additional competencies will be developed in omics technologies, bioinformatics and computational enzyme engineering for enzyme and pathway identification. Transversal skills include multidisciplinary collaboration, sustainability-driven industrial design, innovation management, intellectual property exploitation and circular economy implementation.

Challenges and Limitations

Challenges

A key challenge is the intrinsic resistance of flexible polyurethane foams to microbial and enzymatic degradation. Achieving efficient and reproducible degradation of highly recalcitrant polyurethane structures remains technically demanding, particularly when moving beyond controlled laboratory conditions. Another major challenge is scale-up. Transferring the processes from laboratory to pilot or industrial scale requires a detailed understanding of how critical parameters evolve with increased volume, operational complexity and heterogeneous waste composition. Larger-scale operation may introduce mixing limitations, reduced process uniformity and lower substrate accessibility. In biological systems, maintaining consistent degradation performance using *Tenebrio molitor* larvae and microbial consortia requires improved control of biological variability, process kinetics and environmental conditions. Finally, the integration of chemical and biological steps into a stable, reproducible and economically viable hybrid process remains a critical technological hurdle.

Limitations

Current limitations include the early stage of industrial validation for both ozonation and biological valorisation technologies, which are still mainly demonstrated at laboratory

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scale. The oxidised liquid extract obtained from ozonation shows potential for agronomic applications; however, its variability and low molecular weight composition may limit its suitability for polyurethane repolymerisation. Repolymerisation pathways are also constrained by irreversible polymer chain scission, particularly in the polyol fraction. For *Tenebrio molitor*-based processes, substantial degradation has been demonstrated under laboratory conditions, but scalability to industrial bio-factories remains unproven and requires validation of process efficiency, product consistency and regulatory acceptance. Microbial degradation approaches are further limited by incomplete understanding of metabolic pathways and relatively low natural degradation rates. In addition, regulatory validation and safety assessment will be essential before agricultural application of products derived from polyurethane foam degradation. The lack of established industrial benchmarks for integrated polyurethane biological recycling systems also limits immediate deployment.

General Information	
Name of the organisation/initiative	MUSH MYCOTECHNOLOGY
Country	Spain
Type of entity (company, research centre, start-up, project, cluster)	
Start-up	
TRL level	Market entry
Website	
https://mushmyco.com/en/	
Overview of the Best Practice	
Short description of the initiative	
MUSH MycoTechnology is a Spanish deep-tech start-up focused on the design and engineering of sustainable biomaterials based on fungal mycelium and lignocellulosic waste streams. The company develops bio-based materials by replicating natural recycling processes found in ecosystems, where organic matter is transformed into new functional structures without generating waste. Its approach combines biotechnology, design and circular economy principles to convert low-value organic residues into compostable and functional materials. MUSH develops sustainable solutions with acoustic insulation properties, low energy requirements and potential applications in interior design, furniture, architecture and other sectors seeking alternatives to petroleum-based or resource-intensive materials. Its products are described as lightweight, resistant, fire-retardant and aesthetically distinctive, with natural textures and colours. The initiative is relevant as a best practice because it demonstrates how fungal biotechnology can be applied beyond laboratory research to create market-oriented biomaterials, contributing to waste valorisation, resource efficiency and the transition towards a circular bioeconomy.	
Biotechnology application area	

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Biomaterials, Bio-based products, Fungal biotechnology
Technological description
MUSH MycoTechnology operates at the intersection of biotechnology, materials science, design and circular economy. Its core technology is based on the controlled cultivation of fungal mycelium, the vegetative network of fungi, on selected organic substrates such as agricultural, forestry and lignocellulosic residues. During the growth process, the mycelium acts as a natural biological binder, connecting and consolidating biomass particles into structured composite materials without the need for synthetic resins or petroleum-based binders. Material properties can be influenced through substrate formulation, fungal strain selection, growth conditions, mould design and post-processing methods such as drying or thermal treatment. This enables the production of rigid or semi-rigid bio-fabricated materials with acoustic, thermal, lightweight and aesthetic functionalities. The company develops mycelium-based materials for applications such as acoustic panels, interior design elements, furniture components, packaging and architectural products. Its R&D activities focus on improving growth efficiency, material consistency, mechanical performance, fire behaviour, moisture resistance and scalability of production systems. Overall, MUSH represents a market-oriented fungal biotechnology platform for developing next-generation bio-based materials that can replace selected conventional plastics, foams and composite materials in design, furniture and construction-related applications.
Sustainability and Industrial impact

Environmental impact	High
MUSH's approach contributes to the reduction of environmental impacts associated with conventional petroleum-based materials, synthetic foams and resource-intensive composites. Its production process is based on biological growth, uses organic residues as feedstock and avoids the use of toxic synthetic binders. The resulting materials are bio-based and compostable, offering lower-impact alternatives for applications where biodegradability, reduced chemical use and lower embodied energy are relevant.	
Circularity contribution	High
The initiative strongly supports circular economy principles by transforming agricultural, forestry and other lignocellulosic residues into higher-value biomaterials. Instead of treating organic residues as waste, MUSH uses them as inputs for bio-fabrication processes, creating new material loops and contributing to the development of circular value chains in design, furniture, construction and packaging.	
Resource efficiency	High
A key feature of the company's approach is the upcycling of low-value organic waste streams into functional materials. This improves resource efficiency by reducing dependence on virgin raw materials and by giving new value to locally available biomass. The relatively low-energy nature of mycelium cultivation also supports more efficient production compared with several conventional material manufacturing processes.	
Economic/Business impact	Medium/High

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MUSH operates in a growing market for sustainable biomaterials and circular material solutions. Its technology creates business opportunities in sectors seeking alternatives to fossil-based materials, including interior design, furniture, packaging and architecture. As a start-up already moving towards market entry, it has potential to attract investment, generate skilled employment and support the competitiveness of industries adopting bio-based materials. However, broader economic impact will depend on production scale, cost competitiveness, technical certification, customer acceptance and the ability to compete with established materials.

Scalability potential	High

MUSH shows strong scalability potential due to the wide availability of agricultural, forestry and lignocellulosic residues that can be used as feedstocks, as well as the relatively low-energy characteristics of mycelium cultivation. The technology can potentially be scaled for applications in acoustic products, furniture, interior design, packaging and construction-related components. Nevertheless, large-scale deployment will require further optimisation of production capacity, process control, quality standardisation, drying and post-processing efficiency, logistics, certification and cost reduction.

Innovation

Key Innovation Elements

- Mycelium-based bio-fabrication technology using fungal growth as a natural binding process to transform organic residues into functional composite materials.
- Valorisation of agricultural, forestry and lignocellulosic waste streams into higher-value bio-based materials for design, furniture, packaging and architectural applications.
- Development of compostable and bio-based alternatives to selected plastics, synthetic foams and conventional composite materials.
- Tailoring of material properties through biological growth parameters, including substrate composition, fungal strain selection, moulding conditions and post-processing.
- Low-impact manufacturing model based on biological growth, reduced use of hazardous chemicals and integration of circular economy principles.

Skills and Knowledge opportunities

MUSH MycoTechnology provides valuable opportunities for developing technical and transversal skills in the emerging field of bio-fabricated materials. Its activities combine fungal biotechnology, microbiology, biomaterials science, circular economy, sustainable design and industrial product development. The initiative supports knowledge development in mycelium cultivation, substrate formulation, waste valorisation, biomaterial characterisation, acoustic and thermal performance, product design and life cycle thinking. It also contributes to practical learning in scale-up, process control, material testing, eco-design and market-oriented innovation. Collaboration with designers,

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engineers, architects, sustainability professionals and industrial partners can foster interdisciplinary problem-solving skills and strengthen understanding of how biotechnology can support the transition towards more sustainable furniture, construction, packaging and consumer product industries.
Challenges and Limitations
Challenges
One of the main challenges for MUSH MycoTechnology is achieving material performance levels that can compete with conventional synthetic, mineral and wood-based materials while maintaining the environmental advantages of mycelium-based products. Optimising mechanical strength, durability, moisture resistance, fire performance, dimensional stability and long-term reliability remain important for broader industrial adoption. Another challenge is scaling production while ensuring consistent material quality and reproducibility, since biological systems are sensitive to variations in temperature, humidity, contamination risk, substrate composition and growth conditions. Market acceptance also remains a challenge, as mycelium-based materials are still relatively new and require greater awareness among manufacturers, designers, architects and end users. Certification, technical standards and regulatory validation will also be important for construction, interior and acoustic applications.
Limitations
Current limitations are mainly related to production capacity, material performance, cost competitiveness and market maturity. Mycelium-based materials often require longer production times than conventional industrial materials because manufacturing depends on biological growth. Some applications may also be limited by moisture sensitivity, mechanical strength, dimensional stability or long-term durability when compared with synthetic or mineral alternatives. From a commercial perspective, the sector is still emerging, with less developed supply chains, industrial infrastructure and technical standards than established materials industries. Production costs may remain higher until economies of scale are achieved and automated production systems are further developed. In addition, regulatory frameworks and certification pathways for bio-fabricated materials are still evolving, which may slow large-scale market penetration in construction, furniture and other regulated markets.

General Information	
Name of the organisation/initiative	Nutico
Country	Poland
Type of entity (company, research centre, start-up, project, cluster)	
Company	
TRL level	8
Website	

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https://www.nutico.bio/

Overview of the Best Practice

Short description of the initiative

Nutico is a company based in Warsaw, Poland, that produces new-generation materials derived from cocoa husks and walnut shells. Produced with no water waste, Nutico is biodegradable and PU & PVC-free. Bio2Materials, founded in 2018, develops new-generation materials without using new resources. This company was committed to circularity, supply chain transparency, and cross-industry collaboration to help drive real, sustainable change. Nutico's first innovation is the world's first leather alternative derived from waste cocoa husks and walnut shells. High-performance and durable, Nutico is the product of seven years of intense research and development. Strong focus on biomaterials, circular economy aspects, and innovative use of agricultural waste. Good balance of technology and sustainability.

Biotechnology application area

Biomaterials, Bio-based products

Technological description

Nutico develops bio-based composite materials from agricultural waste, particularly walnut shells and other lignocellulosic residues. The technology aims to transform underutilized biomass into sustainable alternatives to conventional leather, plastics, and synthetic surface materials used in furniture and interior applications.

The production process involves collecting and processing agricultural by-products into fine particles, which are then combined with bio-based binding components to form durable composite sheets. Through material engineering and formulation optimization, the company achieves products with controlled mechanical properties, surface quality, and aesthetic characteristics. The materials can be manufactured in different textures, thicknesses, and finishes to meet industrial requirements.

The technological approach focuses on maximizing the value of renewable resources while reducing dependence on fossil-based raw materials. Nutico’s composites provide durability, flexibility, and design versatility suitable for furniture, interior design, and consumer products.

The development of these materials integrates principles of biomaterials science and circular resource management. By converting agricultural residues into value-added products, the company supports waste valorization and resource efficiency. The technology demonstrates the potential of agricultural biomass as a feedstock for innovative bio-based materials and contributes to the transition towards more sustainable and circular manufacturing systems.

Sustainability and Industrial impact

Environmental impact	High

Nutico reduces the environmental footprint of material production by replacing fossil-

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based and synthetic materials with bio-based alternatives derived from agricultural waste. The use of renewable feedstocks reduces resource extraction and supports more sustainable manufacturing practices.	
Circularity contribution	High
The company applies circular economy principles by transforming agricultural by-products, such as walnut shells, into value-added materials. This approach extends the lifecycle of biomass resources and diverts waste streams from disposal or low value uses.	
Resource efficiency	High
Nutico maximises the use of existing agricultural residues as raw materials, reducing the need for virgin resources. The valorisation of waste biomass improves material efficiency and promotes more sustainable resource management.	
Economic/Business impact	High
The growing demand for sustainable and bio-based materials creates significant market opportunities for Nutico across furniture, interior design and consumer product sectors. The technology enables manufacturers to respond to environmental regulations and changing consumer preferences for sustainable products.	
Scalability potential	High
Agricultural residues are widely available and can provide a stable feedstock for large-scale production. The material can be adapted to multiple applications and industries, supporting broader commercial adoption and future market expansion.	
Innovation	
Key Innovation Elements	
• Development of bio-based composite materials from agricultural waste streams, particularly walnut shells and other lignocellulosic residues. • Valorization of underutilized biomass into high-value materials for furniture, interior design, and consumer product applications. • Replacement of conventional leather, plastic, and fossil-based surface materials with renewable and sustainable alternatives. • Integration of circular economy principles through waste-to-material conversion, extending the value chain of agricultural by-products. • Customizable material technology enabling diverse textures, finishes, and design solutions while maintaining durability and functional performance.	
Skills and Knowledge opportunities	
Nutico provides valuable opportunities for developing technical and interdisciplinary skills in biomaterials innovation and sustainable material development. Its activities combine biomaterials science, agricultural waste valorization, circular economy principles, and product design. The company supports knowledge development in biomass processing,	

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bio-based composite formulation, material characterization, and sustainable manufacturing. Learners and professionals can gain experience in transforming agricultural residues into high-value materials, optimizing material properties, and evaluating performance for furniture and interior applications. The initiative also promotes understanding of resource efficiency, life cycle thinking, and the replacement of fossil-based materials with renewable alternatives. Collaboration between material scientists, engineers, designers, and industrial partners fosters interdisciplinary problem-solving and innovation skills. These activities contribute to building expertise in bio-based products and support the transition towards more sustainable and circular manufacturing systems within the furniture and design sectors.
Challenges and Limitations
Challenges
Nutico faces challenges in scaling up the production of bio-based composite materials while maintaining consistent quality and performance. Agricultural waste feedstocks can vary in composition, moisture content, and physical properties, requiring careful process control and material standardization. The company must also demonstrate that its materials can meet industrial requirements for durability, aesthetics, and long-term performance across different applications. Additionally, market adoption may require convincing manufacturers and consumers to transition from well-established conventional materials to novel bio-based alternatives while ensuring competitive pricing and reliable supply chains.
Limitations
The performance of bio-based composites may depend on the availability and quality of agricultural residues used as feedstocks. Compared with conventional synthetic materials, some bio-based alternatives may face limitations regarding large-scale production capacity, market maturity, and established industry standards. The technology may also require further validation across diverse applications and environmental conditions to demonstrate long-term durability and functionality. As a relatively new material solution, commercial expansion could depend on continued investment, industrial partnerships, and market acceptance.

6. Economic, Market and Business Perspectives

The economic and market outlook for industrial biotechnology across the wood, furniture, and textile sectors is increasingly positive, driven by the accelerating transition towards sustainable manufacturing, circular business models, and climate-neutral production systems. Rising demand for renewable materials, increasing regulatory pressure to reduce greenhouse gas emissions, volatility in fossil-based raw material markets, and growing consumer preference for environmentally responsible products are reshaping industrial value chains and creating favourable conditions for biotechnology-based innovation. In parallel, European policy initiatives (including the European Green Deal, the Circular Economy Action Plan, the EU Bioeconomy Strategy, and the New European Bauhaus) are encouraging investment in renewable biological resources, resource-efficient manufacturing, and low-carbon industrial processes. Within this

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evolving landscape, industrial biotechnology is emerging as a strategic enabler of industrial transformation, supporting the development of innovative products, sustainable production systems, and resilient bio-based value chains while strengthening Europe's long-term competitiveness.

Although the pace and direction of technological adoption differ among sectors, biotechnology is generating significant opportunities throughout the wood, textile, and furniture industries. In the wood sector, advances in integrated biorefineries, enzyme-assisted processing, microbial and fungal technologies, lignin valorisation, nanocellulose, and engineered wood products are enabling the comprehensive utilisation of lignocellulosic biomass and the production of high-value bio-based chemicals, materials, and energy. The furniture sector is increasingly embracing biotechnology through the development of bio-based adhesives, natural coatings, fungal pigments, biodegradable composites, biological recycling technologies, and renewable materials that reduce dependence on petrochemical products while supporting circular manufacturing. Particularly promising are mycelium-based composites, which are rapidly progressing from research laboratories to commercial applications. Produced by cultivating fungal mycelium on agricultural and forestry residues, these materials combine low embodied carbon, minimal waste generation, biodegradability, and remarkable design flexibility. Their applications now extend beyond sustainable packaging to include acoustic and thermal insulation, furniture components, interior architecture, biodegradable foams, and innovative leather alternatives, positioning mycelium technology as one of the most disruptive biofabrication platforms for future manufacturing.

The textile sector is undergoing perhaps the most profound transformation, driven by the urgent need to reduce water consumption, hazardous chemical use, greenhouse gas emissions, and dependence on fossil-derived synthetic fibres. Industrial biotechnology is enabling cleaner and more resource-efficient production through enzymatic processing, microbial fermentation, bio-based polymers, bacterial cellulose, fungal materials, biosynthetic fibres, natural colourants, and advanced biological recycling technologies. These innovations not only reduce environmental impacts but also create opportunities for high-performance functional textiles, biodegradable materials, and entirely new product categories that support the transition towards a circular textile economy.

The convergence of biotechnology with digital technologies–including artificial intelligence, advanced sensors, automation, machine learning, and digital twins–is further accelerating industrial innovation by improving process optimisation, quality control, traceability, and manufacturing efficiency. At the same time, biotechnology is stimulating new business models centred on biomass valorisation, industrial symbiosis, waste-to-value strategies, and regional bioeconomy ecosystems, creating opportunities for companies of all sizes. Large industrial enterprises can integrate biotechnology into existing manufacturing systems to improve productivity, environmental performance, and resource efficiency, while SMEs, start-ups, and university spin-offs are well positioned to develop specialised, high-value bio-based products that address rapidly evolving market demands.

The case studies presented throughout this report demonstrate the diversity and maturity of biotechnology applications already reaching industrial implementation. Large-scale manufacturers such as Mondi Świecie illustrate the successful integration of enzyme-assisted processing and resource-efficient production within established forest-based industries. MycoMedica demonstrates how lignocellulosic substrates can be transformed into high-value

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fungal products through industrial biotechnology. Companies including MUSH MycoTechnology and MYCOPOR showcase the commercial potential of mycelium-based materials, while initiatives such as Exteria, MY-FI, RadiciGroup, Tintex Textiles, and Lenera highlight emerging opportunities in sustainable textile processing, biofabricated materials, circular polymers, renewable coatings, and advanced bio-based alternatives to conventional leather and synthetic materials. Together, these examples demonstrate that biotechnology has progressed well beyond proof-of-concept research and is becoming an increasingly important driver of industrial innovation and market differentiation.

The following sections examine the principal market trends, investment and funding opportunities, evolving business models, the competitiveness of European SMEs, and the main barriers influencing the commercial adoption of industrial biotechnology. In addition to providing an economic and business perspective, this analysis identifies the regulatory drivers, innovation ecosystems, skills requirements, and knowledge opportunities that will shape the next generation of biotechnology-enabled industries. Collectively, these insights provide a strategic foundation for industry, academia, education providers, and policymakers to anticipate future technological developments and prepare for the next wave of biotechnological innovation across the wood, furniture, and textile sectors.

6.1 Market Trends in Industrial Biotechnology

Industrial biotechnology is emerging as one of the principal drivers of industrial transformation, supporting Europe's transition towards a competitive, circular, and climate-neutral economy. Increasing pressure to reduce greenhouse gas emissions, improve resource efficiency, minimise waste generation, and replace fossil-based materials with renewable alternatives is fundamentally reshaping manufacturing across the wood, textile, and furniture sectors. At the same time, growing consumer awareness, corporate sustainability commitments, and investor interest in environmentally responsible technologies are accelerating the commercial adoption of biotechnology-based solutions. Consequently, industrial biotechnology is evolving from a niche research field into a strategic industrial platform capable of generating new products, value chains, and business opportunities.

The European policy landscape strongly reinforces these market developments. Initiatives such as the European Green Deal, the Circular Economy Action Plan, the EU Bioeconomy Strategy, the Net-Zero Industry Act, and the New European Bauhaus promote the sustainable use of biological resources, circular production systems, and low-carbon manufacturing. Together with increasing Environmental, Social and Governance (ESG) requirements, carbon reporting obligations, and sustainable finance instruments, these policies are encouraging investment throughout the entire biotechnology value chain–from biomass production and biorefineries to advanced manufacturing, biological recycling, and bio-based product certification. As regulatory frameworks continue to evolve, biotechnology is expected to play an increasingly important role in helping European industries achieve sustainability targets while strengthening international competitiveness.

Although the specific market dynamics differ among industrial sectors, common trends are emerging across the wood, furniture, and textile industries. These include the transition from fossil-based to renewable raw materials, greater utilisation of industrial side streams, the adoption of circular production models, increasing digitalisation of manufacturing, and the development of high-performance bio-based products with lower environmental footprints.

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These trends are not only improving production efficiency but are also creating entirely new market segments centred on sustainable materials, biological manufacturing, and circular bioeconomy solutions.

In the wood sector, biotechnology is transforming the traditional forest-based industry into a modern bioeconomy built upon the comprehensive utilisation of lignocellulosic biomass. Integrated biorefineries increasingly convert cellulose, hemicellulose, and lignin into multiple high-value products, including bio-based chemicals, advanced biomaterials, renewable fuels, nanocellulose, functional additives, and engineered wood products. Enzyme-assisted pulping, microbial fermentation, lignin valorisation, and biomass fractionation technologies are improving resource efficiency while reducing energy consumption and chemical inputs. Rather than viewing forestry residues as waste, companies are increasingly recognising them as valuable feedstocks capable of generating multiple revenue streams through cascading biomass utilisation and industrial symbiosis.

The textile industry represents one of the most dynamic markets for industrial biotechnology due to its urgent need to reduce water consumption, hazardous chemicals, greenhouse gas emissions, and dependence on fossil-derived synthetic fibres. Biological processing technologies are enabling a transition towards cleaner and more resource-efficient manufacturing through enzymatic pretreatments, microbial dyes, bacterial cellulose, bio-based polymers, biosynthetic fibres, fungal materials, precision fermentation, and biological recycling technologies. These innovations not only improve environmental performance but also enable the production of high-value functional textiles with antimicrobial properties, enhanced durability, biodegradability, and improved end-of-life recyclability. As sustainability regulations become increasingly stringent, biotechnology is expected to become a major competitive differentiator within global textile markets.

The furniture sector is experiencing a parallel transformation driven by eco-design principles, circular manufacturing, and demand for healthier and more sustainable products. Biotechnology enables the development of bio-based adhesives, natural coatings, fungal pigments, biodegradable composites, and formaldehyde-free materials that reduce environmental impacts while maintaining high technical performance. Particularly significant is the emergence of mycelium-based materials, which represent one of the fastest-growing areas of industrial biofabrication. By cultivating fungal mycelium on agricultural and forestry residues, manufacturers can produce lightweight, biodegradable composites suitable for furniture components, acoustic and thermal insulation, packaging, interior architecture, biodegradable foams, and decorative products. Ongoing advances in cultivation technologies, material engineering, and industrial processing are steadily improving their mechanical performance, durability, and design flexibility, positioning mycelium composites as promising alternatives to petroleum-based plastics and foams. These innovations are also stimulating entirely new business models based on local biomass utilisation, waste valorisation, and distributed manufacturing.

Across all three sectors, one of the most significant market developments is the rapid expansion of advanced bio-based materials capable of replacing conventional fossil-derived products. Mycelium composites, nanocellulose, lignin-derived polymers, bacterial cellulose, bio-based resins, engineered biomaterials, and biodegradable packaging are moving from laboratory research towards commercial production. These materials combine renewable feedstocks with

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favourable mechanical properties, lower carbon footprints, and improved circularity, making them attractive alternatives for industries seeking sustainable product portfolios. Continued advances in synthetic biology, industrial fermentation, materials science, and process engineering are expected to further improve production efficiency while reducing manufacturing costs, thereby accelerating market adoption.

Market demand is also increasingly influenced by sustainability criteria extending across entire value chains. Public procurement policies, corporate ESG commitments, carbon accounting frameworks, and consumer preferences are driving demand for certified sustainable materials with transparent environmental credentials. Consequently, certification systems such as FSC, PEFC, EU Ecolabel, Environmental Product Declarations (EPDs), LCA, and emerging digital product passports are becoming increasingly important competitive assets for biotechnology-enabled products. Companies capable of demonstrating reduced environmental impacts, responsible sourcing, and product traceability are likely to gain significant competitive advantages within European and global markets.

Digitalisation is further reinforcing these developments by enabling the integration of biotechnology with Industry 4.0 technologies. Artificial intelligence, machine learning, advanced sensors, hyperspectral imaging, robotics, digital twins, and real-time process monitoring allow biological production systems to operate with greater precision, consistency, and resource efficiency. Data-driven optimisation supports predictive process control, improves microbial cultivation, reduces waste generation, and enhances quality assurance throughout biotechnology-enabled manufacturing systems. The convergence of biotechnology with digital manufacturing therefore represents one of the most important technological trends shaping future industrial competitiveness.

The case studies analysed throughout this report clearly illustrate that industrial biotechnology is already creating measurable economic, environmental, and commercial value. Mondi Świecie demonstrates the successful integration of biotechnology into large-scale forest-based manufacturing through enzyme-assisted processing and resource-efficient production. MycoMedica illustrates the commercial utilisation of fungal biotechnology for producing high-value products from lignocellulosic substrates. MUSH MycoTechnology, MYCOPOR, and other companies specialising in mycelium-based materials demonstrate the rapid emergence of biofabricated products with applications ranging from sustainable packaging to interior architecture and furniture. Similarly, Exteria, MY-FI, RadiciGroup, Tintex Textiles, and Lenera showcase how biotechnology is enabling cleaner textile processing, circular polymers, innovative biomaterials, and advanced alternatives to conventional leather and synthetic materials.

Taken together, these developments demonstrate that industrial biotechnology is evolving from an emerging technology into a strategic industrial ecosystem that integrates biological sciences, advanced materials, digital technologies, and circular economy principles. As technological maturity increases and commercial barriers continue to decline, biotechnology is expected to play a central role in creating resilient, competitive, and sustainable manufacturing systems across the wood, textile, and furniture sectors.

6.2 Investment and Funding Opportunities

The successful translation of industrial biotechnology from scientific discovery to commercial application depends not only on technological excellence but also on sustained investment, effective innovation ecosystems, and access to appropriate funding throughout the entire

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innovation cycle. Biotechnology-based innovations typically require long development timelines, specialised research infrastructure, pilot-scale validation, multidisciplinary expertise, and compliance with evolving regulatory frameworks before they can achieve commercial maturity. Consequently, investment mechanisms that support technology development from fundamental research to industrial deployment are essential for reducing financial risks, accelerating innovation, and strengthening Europe's bio-based economy.

Industrial biotechnology has become a strategic investment priority within the European Union's green and digital transition agendas. Recognising its potential to enhance industrial competitiveness while addressing climate change, resource efficiency, and circular economy objectives, the European Union has established a comprehensive funding landscape supporting research, demonstration, commercialisation, and industrial scale-up across the wood, textile, and furniture sectors. These investments not only stimulate technological innovation but also facilitate collaboration between academia, industry, public authorities, and investors, creating integrated innovation ecosystems capable of accelerating market adoption.

Horizon Europe remains the European Union's flagship programme for research and innovation, supporting collaborative projects focused on advanced biomaterials, industrial biotechnology, synthetic biology, circular manufacturing, sustainable production systems, and digital transformation. Complementing Horizon Europe, the Circular Bio-based Europe Joint Undertaking (CBE JU) specifically promotes the development of competitive bio-based industries by funding collaborative projects that convert renewable biological resources into high-value products through innovative biotechnological processes. Together, these programmes provide critical support for advancing biotechnology from laboratory research to industrial implementation while strengthening collaboration among research organisations, universities, technology centres, and industrial partners.

Additional European funding instruments further expand opportunities for biotechnology innovation. The LIFE Programme supports environmental, climate, and circular economy projects that facilitate the deployment of sustainable industrial solutions. Interreg programmes encourage cross-border cooperation, enabling regional innovation ecosystems and knowledge transfer between research institutions and industry. The European Innovation Council (EIC), particularly through the EIC Accelerator, provides financial support to highly innovative SMEs and start-ups developing disruptive technologies with strong commercial potential. Likewise, the European Circular Bioeconomy Fund (ECBF) has emerged as one of Europe's leading investment vehicles dedicated to scaling companies operating within the bioeconomy, providing growth capital for innovative enterprises developing bio-based materials, industrial biotechnology, and circular manufacturing solutions. At national and regional levels, many Member States complement these initiatives through dedicated bioeconomy strategies, innovation agencies, tax incentives, pilot plant support, and industrial modernisation programmes tailored to regional industrial priorities and biomass resources.

Alongside public investment, private financing has become an increasingly important driver of biotechnology innovation. Venture capital funds, corporate investment programmes, family offices, and impact investors are demonstrating growing confidence in biotechnology's capacity to address global sustainability challenges while generating long-term economic value. Investment is increasingly directed towards companies developing scalable technologies capable of replacing fossil-derived materials, reducing industrial emissions, improving resource efficiency, and creating new value from biological feedstocks. Particularly attractive investment areas include synthetic biology, industrial enzymes, precision fermentation, advanced

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biomaterials, biological recycling technologies, microbial manufacturing, and mycelium-based materials, which have attracted significant international interest due to their broad application potential and strong alignment with circular economy principles. The rapid emergence of companies commercialising mycelium composites, fungal leather alternatives, biodegradable packaging, and biofabricated construction materials illustrates the growing confidence of investors in biotechnology-enabled business models.

Despite this favourable investment landscape, one of the greatest challenges remains financing the transition from laboratory research to commercial-scale production. This critical phase(commonly referred to as the "Valley of Death")requires substantial investment in pilot plants, demonstration facilities, process optimisation, regulatory validation, certification, and industrial scale-up before technologies begin generating sustainable commercial revenues. For many biotechnology companies, particularly SMEs and university spin-offs, securing capital during this stage remains difficult because technological uncertainties remain relatively high while market acceptance and production costs are still being established. Bridging this funding gap has therefore become one of the principal priorities for both public and private investment programmes.

Public-private partnerships play a central role in overcoming these challenges by combining scientific excellence with industrial experience, financial resources, and market knowledge. Collaboration among universities, research organisations, technology centres, industrial companies, investors, and public authorities facilitates technology transfer, shared infrastructure, pilot-scale testing, and joint commercialisation strategies. The case studies presented throughout this report clearly demonstrate that successful biotechnology innovations rarely emerge from isolated organisations but rather from collaborative innovation ecosystems where scientific research, industrial development, entrepreneurship, and policy support evolve together. Such partnerships reduce technological risks, accelerate knowledge transfer, strengthen intellectual property development, and facilitate the commercial deployment of innovative biotechnology solutions.

Investment strategies are also increasingly recognising that successful industrial biotechnology depends not only on technological readiness but equally on human capital and organisational capacity. Consequently, many European programmes now combine research and innovation funding with activities supporting workforce development, specialised training, knowledge transfer, entrepreneurship, and lifelong learning. Investments in education and skills development are becoming essential components of industrial competitiveness, ensuring that companies have access to professionals capable of managing advanced bioprocesses, operating pilot facilities, integrating biotechnology with digital manufacturing technologies, and translating scientific discoveries into commercially viable products.

Looking ahead, investment opportunities in industrial biotechnology are expected to expand significantly as sustainability regulations become more ambitious, carbon reduction targets tighten, and demand for renewable materials continues to grow. Emerging technologies–including synthetic biology, artificial intelligence-assisted bioprocess optimisation, advanced fermentation, biological recycling, and mycelium-based biofabrication–are likely to attract increasing levels of both public and private investment due to their potential to transform manufacturing across multiple industrial sectors. Continued collaboration between investors, policymakers, research organisations, and industry will therefore be essential to accelerate technology commercialisation, strengthen European industrial leadership, and ensure that

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biotechnology fulfils its potential as a cornerstone of the competitive, circular, and climate-neutral bioeconomy.

6.3 Business Models and Commercialisation

Industrial biotechnology is transforming not only manufacturing technologies but also the way companies create, deliver, and capture value. Across the wood, furniture, and textile sectors, biotechnology is enabling the emergence of new business models based on renewable biological resources, circular production systems, and high-value bio-based products. Rather than simply replacing conventional materials or processes, biotechnology is reshaping industrial value chains by integrating biological manufacturing, waste valorisation, digital technologies, and sustainability into product development and business strategy. This transition is opening new commercial opportunities for established industries, SMEs, start-ups, and research-driven spin-offs while strengthening Europe's position within the global bioeconomy.

One of the most significant developments is the shift from resource-based manufacturing towards knowledge-intensive, value-added bioeconomy models. In these models, biological resources are utilised more efficiently through cascading biomass use, industrial symbiosis, and integrated biorefinery concepts. Wood residues, agricultural biomass, textile waste, and other industrial side streams are increasingly regarded as valuable feedstocks rather than waste, providing raw materials for bio-based chemicals, biomaterials, enzymes, pharmaceuticals, nutraceuticals, renewable energy, and functional ingredients. Through enzymatic conversion, microbial fermentation, fungal biotechnology, and advanced biomass processing, companies are creating additional revenue streams while simultaneously improving resource efficiency and reducing environmental impacts.

The commercial landscape is becoming increasingly diverse as companies adopt business models adapted to their size, technological capabilities, and market positioning. Large industrial enterprises typically pursue integrated biotechnology strategies, embedding biological processes within existing manufacturing systems to improve productivity, reduce emissions, optimise raw material utilisation, and develop higher-value product portfolios. Rather than replacing established industrial infrastructure, biotechnology enhances production efficiency through enzyme-assisted processing, biological pretreatments, advanced biorefineries, and circular manufacturing approaches. Companies such as Mondi Świecie demonstrate how biotechnology can be successfully integrated into industrial-scale forest-based manufacturing while maintaining high production capacity and economic competitiveness.

SMEs, meanwhile, are increasingly building competitive advantage through specialised biotechnology solutions that address emerging market demands for sustainable, high-performance products. Their flexibility enables rapid innovation and the development of niche markets centred on bio-based materials, circular products, and environmentally responsible manufacturing. Particularly dynamic is the commercial expansion of mycelium-based technologies, where companies are producing biodegradable packaging, acoustic and thermal insulation, interior products, furniture components, engineered leather alternatives, and biofabricated materials using fungal mycelium cultivated on agricultural and forestry residues. These technologies not only create innovative products but also establish entirely new value chains based on local biomass resources and distributed manufacturing. Companies such as MUSH MycoTechnology, MYCOPOR, and other emerging biofabrication enterprises illustrate how fungal biotechnology is generating commercially viable alternatives to conventional petroleum-based materials while contributing to regional circular economies.

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Another rapidly expanding commercial model involves the development of regional and integrated biorefineries, where renewable biological resources are converted into multiple high-value products through cascading utilisation strategies. Instead of focusing on a single product, modern biorefineries simultaneously generate biomaterials, bio-based chemicals, renewable fuels, industrial enzymes, and energy from the same biomass stream, significantly improving economic viability and resource efficiency. This integrated approach reduces waste generation, diversifies revenue sources, and strengthens the resilience of regional bioeconomy ecosystems while supporting the broader transition towards circular manufacturing.

Commercial success increasingly depends on collaborative innovation ecosystems that connect industry, academia, technology centres, investors, and public authorities. Because industrial biotechnology combines biology, engineering, materials science, digital technologies, and sustainability, successful commercialisation rarely occurs within isolated organisations. Innovation clusters, living laboratories, technology platforms, incubators, and European collaborative projects facilitate knowledge exchange, pilot-scale validation, access to specialised infrastructure, and technology transfer. These collaborative environments accelerate innovation, reduce development risks, and enable companies to move more efficiently from scientific discovery to market-ready products.

Intellectual property has become an increasingly important component of biotechnology business models. Universities, research organisations, and technology centres play a central role by generating patents, proprietary technologies, microbial strains, engineered enzymes, novel biomaterials, and production processes that form the basis of commercial innovation. Technology transfer offices, licensing agreements, collaborative research contracts, joint ventures, and university spin-offs provide effective mechanisms for translating scientific discoveries into industrial applications. Emerging fields such as synthetic biology, precision fermentation, enzyme engineering, biofabrication, and advanced biomaterials are generating growing patent activity, highlighting the increasing strategic importance of intellectual property for maintaining international competitiveness.

Digitalisation is further transforming biotechnology business models through the integration of Industry 4.0 technologies. Artificial intelligence, machine learning, digital twins, advanced sensors, robotics, and real-time process monitoring enable companies to optimise biological production systems, improve product quality, enhance traceability, and reduce resource consumption. Digital technologies also facilitate predictive maintenance, supply chain transparency, life-cycle assessment, and environmental reporting, allowing biotechnology-enabled companies to respond more effectively to evolving regulatory requirements and market expectations.

New commercial opportunities are also emerging through service-oriented business models that complement traditional product manufacturing. Companies increasingly provide biotechnology-based consultancy, technology licensing, contract fermentation, pilot-scale testing, material characterisation, environmental assessment, certification support, and digital monitoring services. These knowledge-intensive services create additional revenue streams while facilitating the broader adoption of biotechnology across industrial sectors. Universities and research organisations increasingly contribute to these innovation ecosystems through specialised research infrastructure, contract research, continuing education, and technology transfer activities.

Despite the considerable commercial potential of industrial biotechnology, successful market

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implementation remains dependent on several interrelated factors. Production scalability, manufacturing costs, regulatory compliance, certification procedures, consumer acceptance, and supply chain integration continue to determine whether innovative technologies achieve widespread industrial adoption. Demonstrating reliable technical performance, environmental benefits, and economic competitiveness is particularly important for emerging technologies such as mycelium composites, biofabricated materials, biological recycling systems, and advanced biomaterials. Companies capable of combining technological innovation with robust intellectual property strategies, collaborative partnerships, digital capabilities, and market-oriented product development are most likely to achieve sustainable competitive advantage.

As biotechnology continues to mature, commercialisation strategies are expected to become increasingly interdisciplinary, integrating biological sciences, advanced materials, digital manufacturing, circular economy principles, and sustainable business innovation. This convergence is creating entirely new industrial ecosystems that extend beyond conventional manufacturing and position biotechnology as a strategic driver of future economic growth, industrial resilience, and sustainable competitiveness across the European wood, furniture, and textile sectors.

6.4 European Competitiveness and SMEs

Industrial biotechnology represents a strategic opportunity to strengthen the competitiveness of European industries while supporting the transition towards a more sustainable, resilient and knowledge-based economy. Europe has established itself as a global leader in sustainability policies, bioeconomy strategies and biotechnology research, creating favourable conditions for the development of innovative bio-based products and manufacturing processes. Nevertheless, maintaining this competitive position will depend on the ability to accelerate technology transfer, improve industrial adoption and equip the workforce with the skills required for emerging biotechnological applications.

The European Union benefits from a strong scientific and technological ecosystem, supported by internationally recognised universities, research centres, innovation clusters and public funding programmes. This research capacity has positioned Europe at the forefront of several biotechnology fields, including industrial enzymes, lignocellulosic biorefineries, advanced biomaterials, fungal biotechnology and circular manufacturing systems. At the same time, ambitious policy initiatives such as the European Green Deal, the Circular Economy Action Plan and the Bioeconomy Strategy provide a favourable regulatory environment for companies investing in sustainable innovation.

Within the wood, furniture and textile sectors, biotechnology offers important opportunities to increase productivity, diversify product portfolios and improve international competitiveness. Companies that successfully integrate biotechnology into their manufacturing processes are better positioned to reduce resource consumption, minimise waste generation, comply with increasingly demanding environmental regulations and respond to growing market demand for sustainable products. These competitive advantages are particularly relevant as global value chains increasingly reward products with lower environmental impacts, certified sustainable origins and transparent production processes.

SMEs play a particularly important role in this transition. SMEs represent the vast majority of companies operating in the European wood, furniture and textile industries and constitute a

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major source of employment, regional development and industrial innovation. Their flexibility allows them to adopt niche technologies, develop specialised products and respond rapidly to changing market demands. Biotechnology therefore provides SMEs with new opportunities to differentiate themselves through innovation rather than competing solely on production costs.

However, SMEs also face greater challenges than large industrial companies when introducing biotechnology into their operations. Limited financial resources, restricted access to specialised equipment, smaller research and development capacities and difficulties in recruiting highly qualified personnel often reduce their ability to adopt emerging technologies. The implementation of biotechnology frequently requires multidisciplinary expertise combining biology, engineering, materials science, digital technologies and sustainability management, competences that are not always available within smaller organisations.

Technology transfer therefore becomes a critical factor for improving SME competitiveness. Collaboration between companies, universities, research organisations and technology centres facilitates access to scientific knowledge, specialised infrastructure and pilot-scale testing facilities that individual SMEs would often be unable to develop independently. European innovation ecosystems, including Digital Innovation Hubs, Bioeconomy Clusters and Knowledge and Innovation Communities (KICs), play an increasingly important role in supporting this collaborative approach by connecting research with industrial applications.

Another important aspect of European competitiveness is the growing importance of regional innovation ecosystems. Many successful biotechnology initiatives emerge from close collaboration between local industries, research institutions and public authorities. Regional specialisation strategies, often supported through Smart Specialisation (S3) programmes and European Regional Development Funds, encourage the development of biotechnology solutions adapted to local biomass resources, industrial capabilities and market opportunities. This regional approach strengthens industrial resilience while promoting more sustainable and decentralised bio-based value chains.

Despite Europe's strong research base, one of its main competitive challenges remains the commercialisation and industrial scaling of biotechnology innovations. While European organisations generate a significant proportion of global biotechnology research, the transition from laboratory-scale innovation to large-scale manufacturing is often slower than in competing regions. Addressing this gap requires stronger collaboration between academia and industry, improved access to demonstration facilities, increased private investment and more effective mechanisms for supporting technology commercialisation.

The availability of appropriately skilled professionals is equally important for maintaining European competitiveness. As biotechnology becomes increasingly integrated into traditional manufacturing sectors, companies require professionals capable of combining biological knowledge with engineering, digital technologies, sustainability assessment and industrial process management. This growing demand for interdisciplinary competences reinforces the importance of education, vocational training and lifelong learning initiatives capable of preparing the future workforce for the evolving needs of the bioeconomy.

Overall, biotechnology represents not only a technological opportunity but also a strategic instrument for strengthening the long-term competitiveness of European SMEs and manufacturing industries. By fostering innovation, supporting sustainable production,

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encouraging collaboration and developing new professional competences, industrial biotechnology can contribute significantly to the resilience, productivity and international positioning of the European wood, furniture and textile sectors.

6.5 Barriers to Adoption

Despite the remarkable scientific advances and expanding market opportunities described throughout this report, the widespread adoption of industrial biotechnology across the wood, furniture, and textile sectors continues to face a range of interconnected technological, economic, regulatory, organisational, and societal challenges. While numerous biotechnology solutions have successfully demonstrated their technical feasibility at laboratory and pilot scales, translating these innovations into commercially competitive industrial processes remains a complex undertaking. Addressing these barriers will be essential to unlock the full potential of biotechnology as a driver of sustainable industrial transformation and the European circular bioeconomy.

One of the principal barriers concerns the economic viability of industrial implementation. Biotechnology-based manufacturing frequently requires significant upfront investment in specialised equipment, pilot plants, bioprocess infrastructure, quality control systems, and process optimisation before commercial production becomes economically viable. Compared with established manufacturing technologies, biological production systems often involve longer development cycles, higher technological uncertainty, and extended return-on-investment periods. These challenges are particularly pronounced for SMEs and start-ups, which frequently have limited access to capital and fewer opportunities to absorb technological risks during the commercialisation process.

A closely related challenge is the transition from laboratory research to industrial-scale production. Many emerging biotechnology solutions—including advanced biomaterials, biological recycling systems, fungal biotechnology, precision fermentation, and mycelium-based composites—have demonstrated excellent technical performance under controlled experimental conditions but require further optimisation before achieving reliable, large-scale manufacturing. Biological systems are inherently sensitive to environmental variables such as temperature, pH, humidity, nutrient availability, oxygen concentration, and microbial contamination. Scaling these processes while maintaining consistent product quality, reproducibility, and economic efficiency requires sophisticated bioprocess engineering, automation, advanced monitoring technologies, and specialised industrial expertise. Bridging this technology readiness gap remains one of the most significant challenges for industrial biotechnology.

Regulatory complexity represents another important obstacle. Companies developing biotechnology-based products must navigate an increasingly comprehensive regulatory landscape covering product safety, chemical legislation, environmental protection, waste management, sustainability reporting, and product certification. Depending on the technology, additional regulatory requirements may apply to genetically modified organisms (GMOs), novel biomaterials, biological products, microbial production systems, or biofabricated materials. Furthermore, differing regulatory approaches across international markets can complicate product commercialisation and export. Although these regulations are fundamental for ensuring consumer and environmental safety, simplifying regulatory pathways, improving guidance, and harmonising standards would facilitate innovation while maintaining high levels of protection.

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The lack of harmonised standards and certification frameworks also affects the commercial uptake of many emerging biotechnology products. Novel materials such as mycelium composites, biofabricated materials, biological adhesives, biodegradable polymers, and microbial textiles often lack established testing methodologies, performance standards, and certification schemes. This creates uncertainty for manufacturers, investors, regulators, and consumers, making it more difficult to compare new products with conventional alternatives or demonstrate compliance with existing building, furniture, and textile standards. The development of internationally recognised standards and life-cycle assessment methodologies will therefore play an important role in accelerating market acceptance.

Another important challenge concerns market acceptance and consumer confidence. Although demand for sustainable products continues to increase, biotechnology-based materials must compete with mature fossil-derived products that benefit from established supply chains, economies of scale, and widespread market recognition. Companies introducing innovative biomaterials must demonstrate not only environmental advantages but also equivalent or superior technical performance, durability, safety, reliability, aesthetics, and cost-effectiveness. Public perception may also influence market acceptance, particularly for technologies involving genetic engineering or unfamiliar biological manufacturing processes. Effective science communication, transparent environmental information, and robust certification systems will therefore be essential for building confidence among consumers and industrial users.

The availability of sustainable feedstocks and resilient supply chains represents an additional strategic consideration. Industrial biotechnology depends on reliable supplies of renewable biomass, agricultural residues, forestry by-products, textile waste, and other biological resources with consistent quality characteristics. Seasonal variability, geographical dispersion of biomass resources, competing uses of feedstocks, transportation costs, and fluctuations in biomass quality may all influence process efficiency and commercial viability. Developing regional bioeconomy clusters, strengthening industrial symbiosis, and improving biomass logistics will therefore be essential to ensure stable and sustainable feedstock supply for future biotechnology industries.

Skills shortages and workforce development remain among the most critical barriers identified throughout this report. As biotechnology increasingly converges with materials science, engineering, digital technologies, sustainability assessment, and advanced manufacturing, industries require professionals with highly interdisciplinary competences. Expertise is needed not only in microbiology and biotechnology but also in process engineering, artificial intelligence, data analytics, automation, circular economy, life-cycle assessment, regulatory affairs, and innovation management. Many companies, particularly SMEs, report difficulties in recruiting professionals with these integrated skills, highlighting the growing importance of interdisciplinary higher education, vocational training, lifelong learning, and industry-academia collaboration.

Organisational readiness and innovation capacity also strongly influence technology adoption. Successfully integrating biotechnology often requires significant organisational change, including new production methods, revised quality management systems, digital transformation, and closer collaboration between traditionally separate scientific and engineering disciplines. Companies with limited research capacity, low levels of digitalisation, or conservative organisational cultures may encounter greater difficulties when adopting biotechnology-enabled manufacturing. Strategic leadership, innovation management, and

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collaborative partnerships are therefore becoming increasingly important determinants of successful industrial transformation.

The rapid pace of technological development also presents challenges related to intellectual property management and technology transfer. Universities and research organisations continue to generate significant scientific advances, but efficient mechanisms for transferring knowledge into commercial applications remain uneven across Europe. Strengthening technology transfer offices, supporting university spin-offs, promoting collaborative research, and improving access to pilot-scale infrastructure will help accelerate the commercial deployment of biotechnology innovations while increasing the economic impact of publicly funded research.

Finally, biotechnology adoption is increasingly linked with digital transformation. While artificial intelligence, digital twins, advanced sensors, robotics, and real-time process monitoring create significant opportunities for improving bioprocess efficiency and product quality, many companies(particularly SMEs) still face challenges related to digital infrastructure, data management, cybersecurity, and investment in Industry 4.0 technologies. Supporting the simultaneous adoption of biotechnology and digital manufacturing will therefore become increasingly important for maintaining industrial competitiveness.

Despite these challenges, the overall outlook for industrial biotechnology remains highly positive. Continued advances in synthetic biology, enzyme engineering, microbial fermentation, fungal biotechnology, advanced biomaterials, precision manufacturing, and artificial intelligence are steadily improving process efficiency, reducing production costs, and expanding commercial opportunities. At the same time, supportive European policies, growing public and private investment, expanding innovation ecosystems, and increasing market demand for sustainable products are progressively reducing many of the traditional barriers to biotechnology adoption.

Ultimately, overcoming these challenges will require coordinated action across the entire innovation ecosystem. Policymakers, research organisations, educational institutions, industry, investors, technology providers, and standardisation bodies must work together to strengthen technology transfer, facilitate access to finance, harmonise regulatory frameworks, develop common standards, improve digital and research infrastructure, and equip the workforce with the interdisciplinary skills required by the emerging bioeconomy. Through these coordinated efforts, industrial biotechnology can realise its full potential as a strategic driver of sustainable innovation, economic growth, industrial resilience, and European leadership in the transition towards a competitive, circular, and climate-neutral manufacturing economy.

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7. Regulatory Framework, Standards and Patents

The successful implementation of industrial biotechnology within the wood, furniture and textile sectors depends not only on technological innovation but also on a supportive regulatory environment that promotes sustainability, ensures product safety, facilitates market access and encourages investment. European legislation is increasingly driving the transition towards a circular, climate-neutral economy by promoting renewable raw materials, reducing hazardous substances, improving product traceability and stimulating the development of bio-based industries. At the same time, companies introducing innovative biotechnological products and processes must navigate an increasingly complex framework of regulations, certification schemes, environmental standards and intellectual property requirements. As demonstrated by the case studies presented in this report, successful commercialisation depends not only on technological excellence but also on regulatory compliance, certification, market acceptance and effective innovation management.

7.1 European Policies and Green Deal Context

European policies provide the strategic framework supporting the development, commercialisation, and large-scale deployment of industrial biotechnology across the wood, furniture, and textile sectors. During the last decade, the European Union has progressively positioned biotechnology as one of the key enabling technologies underpinning the transition towards a competitive, resource-efficient, and climate-neutral economy. Rather than promoting biotechnology as an isolated scientific discipline, European policies increasingly recognise its capacity to transform manufacturing systems, strengthen industrial competitiveness, reduce dependence on fossil resources, and accelerate the development of a sustainable circular bioeconomy.

The European Green Deal represents the overarching policy framework driving this transformation. Its objective of achieving climate neutrality by 2050 has stimulated the adoption of renewable raw materials, cleaner production technologies, low-carbon manufacturing, and circular business models across European industry. Industrial biotechnology contributes directly to these ambitions through the development of bio-based materials, biological production systems, enzyme-assisted processing, integrated biorefineries, and renewable alternatives to fossil-derived chemicals. These innovations enable industries to reduce greenhouse gas emissions while improving resource efficiency, environmental performance, and long-term resilience.

Complementing the European Green Deal, the Circular Economy Action Plan (CEAP) promotes the transition from linear production systems towards circular value chains based on prevention, reuse, repair, remanufacturing, recycling, and resource recovery. Biotechnology plays a central role in this transition by enabling the valorisation of lignocellulosic biomass, agricultural residues, industrial side streams, and organic waste through enzymatic processing, microbial fermentation, fungal biotechnology, and integrated biorefinery concepts. These technologies maximise resource utilisation, extend material life cycles, and generate high-value bio-based products while reducing waste generation and dependence on virgin fossil resources.

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The EU Bioeconomy Strategy further reinforces biotechnology as a cornerstone of sustainable industrial development by promoting the conversion of renewable biological resources into food, feed, chemicals, materials, energy, and advanced industrial products. The strategy encourages closer integration between forestry, agriculture, biotechnology, and manufacturing industries, recognising biological resources as strategic assets for future economic growth. This approach is particularly relevant to the wood, furniture, and textile sectors, where lignocellulosic biomass, agricultural by-products, and renewable feedstocks provide significant opportunities for developing innovative biomaterials, circular production systems, and high-value bio-based products.

Industrial competitiveness is also strengthened through the EU Industrial Strategy, which identifies biotechnology among Europe's strategic enabling technologies for improving technological sovereignty, industrial resilience, and sustainable economic growth. Similarly, the EU Forest Strategy for 2030 promotes sustainable forest management, the cascading use of wood, and higher-value utilisation of forest biomass through advanced processing technologies, including biotechnology and integrated biorefineries. Together, these initiatives reinforce the contribution of the forest-based sector to Europe's circular bioeconomy while encouraging innovation throughout forest value chains.

Recent legislation places increasing emphasis on sustainable product design, transparency, and circularity. The Ecodesign for Sustainable Products Regulation (ESPR) introduces requirements relating to product durability, reparability, recycled content, resource efficiency, and environmental performance. One of its most important innovations is the Digital Product Passport (DPP), which will provide accessible digital information on product composition, origin, environmental footprint, repairability, and end-of-life management. These measures are expected to significantly influence biotechnology-enabled products by improving traceability, supporting circular business models, and increasing confidence among manufacturers, regulators, and consumers.

Within the textile sector, the EU Strategy for Sustainable and Circular Textiles provides a dedicated framework for accelerating the adoption of biotechnology. The strategy promotes durable, recyclable, and resource-efficient textiles while encouraging innovation in bio-based fibres, microbial colourants, enzyme-assisted processing, biological recycling, bacterial cellulose, and mycelium-derived materials. Together with Extended Producer Responsibility (EPR) schemes and emerging digital product passport requirements, these policies are expected to accelerate investment in biotechnology-based textile solutions.

Environmental objectives are further supported through the Zero Pollution Action Plan, which encourages cleaner production processes and the replacement of hazardous chemicals with environmentally compatible alternatives. Biotechnology contributes directly through biological wastewater treatment, enzyme-assisted manufacturing, bioremediation, and environmentally benign processing technologies. Likewise, initiatives such as the New European Bauhaus create new opportunities for biotechnology in sustainable construction by encouraging the use of engineered timber, bio-based construction materials, advanced biomaterials, and mycelium composites within climate-resilient buildings.

Looking ahead, the proposed European Biotech Act is expected to integrate many of these initiatives into a coherent policy framework for industrial biotechnology. The Act aims to strengthen Europe's competitiveness by expanding biomanufacturing capacity, accelerating

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industrial scale-up, improving access to finance—particularly for SMEs and start-ups—and simplifying regulatory procedures to reduce time-to-market for innovative biotechnology products.

These policy frameworks are complemented by substantial financial instruments supporting research, demonstration, and commercial deployment. Programmes such as Horizon Europe, the CBE JU, LIFE, Interreg, the EEIC, and numerous national bioeconomy initiatives provide funding across the entire innovation pathway, from fundamental research and pilot facilities to industrial demonstration and commercial scale-up. Collectively, these programmes foster collaboration between universities, research organisations, technology centres, SMEs, industrial companies, and policymakers, thereby strengthening Europe's innovation ecosystem.

Overall, the European policy landscape provides a strong foundation for accelerating biotechnology adoption across the wood, furniture, and textile sectors. By combining ambitious climate objectives with industrial innovation, circular economy principles, and targeted financial support, these initiatives are creating favourable conditions for the commercialisation of biotechnology-enabled products and processes. At the same time, companies must continuously adapt to evolving regulatory requirements, sustainability standards, and market expectations to maintain competitiveness within an increasingly innovation-driven European bioeconomy.

7.2 Regulatory Challenges

For products intended for the construction and furniture industries, compliance with the Construction Products Regulation (CPR) and harmonised European standards is essential to demonstrate performance, durability and safety. In parallel, manufacturers must increasingly consider legislation governing indoor air quality, formaldehyde emissions, fire performance and recyclability, particularly as environmental and health requirements become more demanding across European markets.

The regulatory framework is also evolving rapidly in response to the European Union's circular economy objectives. The recently adopted ESPR will progressively introduce sustainability requirements covering product durability, reparability, recycled content, resource efficiency and environmental performance across a wide range of industrial products. One of its most significant innovations is the introduction of the Digital Product Passport (DPP), which will improve traceability by providing standardised digital information on product composition, origin, environmental characteristics and end-of-life management. These developments are expected to have a major impact on the wood, furniture and textile sectors, requiring companies to improve data management systems and supply chain transparency.

Environmental reporting obligations are also becoming increasingly important. Companies are expected to generate reliable information on carbon emissions; material flows and environmental impacts throughout the product life cycle. Methodologies such as LCA and the Product Environmental Footprint (PEF) are increasingly used to support regulatory compliance, sustainability reporting and green public procurement. At the corporate level, the implementation of the Corporate Sustainability Reporting Directive (CSRD) is further increasing expectations regarding environmental transparency, traceability and sustainability performance, particularly for larger companies and those operating within international supply chains.

Another significant challenge concerns the regulation of advanced biotechnologies, including

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Genetically Modified Microorganisms (GMMs), synthetic biology applications and gene-editing technologies such as CRISPR. While these technologies offer considerable potential for improving industrial efficiency and developing innovative biomaterials, they are subject to strict European regulatory oversight. Regulatory uncertainty surrounding some emerging technologies may slow industrial adoption and discourage investment, even where scientific evidence demonstrates significant environmental and economic benefits.

SMEs are particularly affected by these regulatory complexities. Limited financial resources, restricted access to specialised legal expertise and the administrative burden associated with certification and compliance can significantly delay the commercialisation of innovative biotechnology solutions. Navigating multiple regulatory frameworks simultaneously often represents a substantial cost for smaller companies, reducing their capacity to bring innovations to market despite strong technological potential.

Addressing these challenges will require greater regulatory harmonisation, clearer technical guidance and stronger support mechanisms for companies introducing biotechnology into industrial production. Increased cooperation between regulatory authorities, research organisations, industry associations and innovation support agencies can facilitate technology transfer while ensuring that high standards of environmental protection and consumer safety are maintained. As biotechnology continues to evolve, the regulatory framework will need to balance precaution with innovation, creating conditions that encourage the development and commercialisation of sustainable bio-based solutions across the European wood, furniture and textile sectors.

7.3 Sustainability Certifications and Standards

Sustainability certifications and technical standards play an increasingly important role in facilitating the market adoption of biotechnology-based products. Beyond ensuring compliance with legal requirements, certification schemes provide independent verification of environmental performance, responsible sourcing, product quality and social responsibility. As customers, public authorities and investors increasingly demand transparent sustainability information, certifications have evolved from voluntary market differentiators into strategic business tools that improve competitiveness, strengthen consumer confidence and facilitate access to international markets.

Within the wood sector, sustainable forest management remains a fundamental prerequisite for the development of bio-based value chains. Certification schemes such as the FSC® and the Programme for the Endorsement of Forest Certification (PEFC) verify that timber and other forest products originate from responsibly managed forests that balance environmental, economic and social objectives. These certifications are increasingly required by manufacturers, retailers and public procurement programmes, particularly for construction materials, engineered wood products and furniture components. For biotechnology companies using lignocellulosic biomass as feedstock, certified raw materials provide assurance of supply chain sustainability and support compliance with broader circular economy objectives.

Environmental performance is also assessed through internationally recognised methodologies such as LCA and the PEF. These tools evaluate environmental impacts throughout the entire product life cycle, from raw material extraction and manufacturing to product use and end-of-

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life management. Increasingly, manufacturers communicate these results through EPDs, which provide independently verified environmental information and are widely used within construction markets and green public procurement. For biotechnology-based products, these assessment methods help demonstrate reductions in greenhouse gas emissions, resource consumption and environmental impacts compared with conventional fossil-based alternatives.

Within the furniture sector, compliance with technical standards governing product safety, indoor air quality, durability and recyclability has become increasingly important. European standards regulating formaldehyde emissions, VOCs, structural performance and product longevity contribute to improving consumer health while supporting sustainable product design. In addition, environmental labels such as the EU Ecolabel recognise products with reduced environmental impacts throughout their life cycle and encourage manufacturers to adopt renewable materials, cleaner production processes and circular design principles. Biotechnology contributes to achieving these requirements through the development of bio-based adhesives, low-emission coatings, biodegradable composites and environmentally friendly surface treatments. Within the Material impact area, the pan-European FEMB – LEVEL® certification, verifies the content of toxic substances in wood and based materials, coatings, adhesives and glues, textile and leathers and upholstery materials. These standards encourage the use of bio – based materials and biomass as source of renewable energy.

The textile sector has experienced a rapid expansion of sustainability certification schemes in response to increasing consumer awareness and stricter environmental regulations. Standards such as the Global Organic Textile Standard (GOTS) promote the use of organically produced fibres and environmentally responsible manufacturing processes, while OEKO-TEX® Standard 100 certifies that textile products are free from harmful substances and safe for human use. Bluesign® focuses on resource efficiency, chemical management and environmental performance throughout textile production, whereas the Global Recycled Standard (GRS) verifies recycled content and responsible processing practices. These certification systems are becoming increasingly relevant for biotechnology-based textiles incorporating microbial fibres, bio-based polymers, enzymatic finishing technologies or mycelium-derived materials.

The growing importance of traceability and transparency is further transforming sustainability certification. The introduction of the DPP under the ESPR will require manufacturers to provide accessible digital information on product composition, material origin, environmental performance, repairability and end-of-life options. Biotechnology-based products are expected to benefit from these developments, as their renewable origin, reduced environmental impacts and circular characteristics can be documented more effectively through digital traceability systems. Similarly, increasing ESG reporting requirements are encouraging companies to integrate sustainability metrics into product development and supply chain management.

International standardisation organisations also contribute to the harmonisation of biotechnology-related products and processes. Standards developed by ISO, CEN and other standardisation bodies provide common methodologies for testing product performance, biodegradability, compostability, environmental management and quality assurance. These harmonised standards facilitate international trade, improve market confidence and reduce barriers to commercialisation by establishing consistent technical requirements across different markets.

As industrial biotechnology continues to evolve, sustainability certification is expected to

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become even more important for demonstrating the environmental and economic benefits of bio-based products. Companies capable of integrating certification, life-cycle assessment and transparent sustainability reporting into their innovation strategies will be better positioned to meet regulatory requirements, access international markets and respond to increasing customer expectations. Consequently, sustainability standards should no longer be viewed solely as compliance instruments but as strategic assets that support competitiveness, innovation and long-term market acceptance within the European wood, furniture and textile sectors.

7.4 Patent Landscape and Intellectual Property Trends

The patent landscape reflects the rapid evolution of industrial biotechnology and its growing strategic importance across the wood, furniture and textile sectors. Intellectual property (IP) has become a key instrument for protecting technological innovation, attracting investment and supporting the commercialisation of new bio-based products and manufacturing processes. As biotechnology continues to converge with materials science, digital technologies and circular economy principles, companies increasingly recognise patents and other forms of intellectual property as strategic assets that strengthen competitiveness and facilitate access to international markets.

Patent activity has expanded considerably over the past decade, reflecting the increasing maturity of industrial biotechnology and the growing commercial interest in sustainable technologies. Significant innovation is taking place in areas such as enzyme engineering, fungal biotechnology, lignocellulosic biorefineries, nanocellulose production, lignin valorisation, bio-based polymers, mycelium composites, and advanced biomaterials. More recently, patent applications have increasingly focused on synthetic biology, gene-editing technologies such as CRISPR, engineered microorganisms, biofabrication, and living materials, demonstrating the rapid diversification of biotechnology applications beyond traditional industrial processes.

Patent trends also reflect the specific innovation priorities of each industrial sector. Within the wood sector, intellectual property activity is concentrated on technologies related to lignin extraction and valorisation, advanced cellulose materials, enzyme-assisted pulping, biomass fractionation, engineered wood products and integrated biorefinery systems. Many innovations seek to maximise the value obtained from lignocellulosic biomass while reducing chemical consumption, improving energy efficiency and supporting circular production models.

Within the textile sector, biotechnology has generated substantial innovation in microbial fibres, bacterial cellulose, enzyme-assisted dyeing and finishing processes, bio-based polymers, biosynthetic colourants and mycelium-derived leather alternatives. These technologies aim to reduce water consumption, eliminate hazardous chemicals and replace petroleum-based synthetic fibres with renewable biological alternatives. As sustainability becomes a key competitive factor within the global textile industry, patent activity in these areas is expected to continue expanding rapidly.

In the furniture sector, patent applications increasingly focus on sustainable product development, including bio-based adhesives, formaldehyde-free resins, biodegradable composites, natural coatings and innovative wood modification technologies. Companies are also developing new manufacturing processes that improve durability, reduce emissions and facilitate recycling, responding to increasing environmental regulations and consumer demand

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for sustainable furniture products.

Although multinational corporations continue to hold substantial patent portfolios, innovation within industrial biotechnology increasingly originates from a diverse ecosystem that includes universities, public research organisations, start-ups and small and medium-sized enterprises (SMEs). Universities play a particularly important role in generating early-stage scientific discoveries that later become commercial technologies through technology transfer mechanisms. Technology Transfer Offices (TTOs), spin-off companies and collaborative research projects facilitate the conversion of academic research into industrial applications, supporting the development of innovative biotechnology solutions across European manufacturing sectors.

For many SMEs, however, extensive patent portfolios are not always the most appropriate intellectual property strategy. Limited financial resources, high patenting costs and rapidly evolving technologies often encourage smaller companies to combine patents with alternative forms of intellectual property protection, including trade secrets, proprietary know-how, design rights, copyright and trademarks. In many cases, maintaining confidential production methods or specialised biological processes provides a stronger competitive advantage than pursuing formal patent protection, particularly where manufacturing processes are difficult to reverse engineer.

At the same time, industrial biotechnology is increasingly characterised by open innovation and collaborative research models. Rather than relying exclusively on internally developed technologies, companies frequently establish partnerships with universities, research centres, technology providers and other industrial partners. Licensing agreements, joint ventures, collaborative research programmes and public-private partnerships enable organisations to share knowledge, reduce development risks and accelerate technology commercialisation. European collaborative initiatives funded through programmes such as Horizon Europe and the Circular Bio-based Europe Joint Undertaking (CBE JU) have further strengthened these innovation ecosystems by promoting cross-sectoral cooperation and facilitating technology transfer across Member States.

The growing convergence of biotechnology with digital technologies is also influencing intellectual property strategies. Artificial intelligence, digital process optimisation, advanced modelling and automation increasingly support the development of novel biotechnological solutions, creating new opportunities for patentable inventions while raising important questions regarding ownership, data protection and collaborative innovation. As biological manufacturing systems become more digitally integrated, companies will need to manage not only biological inventions but also software, algorithms and data-driven process innovations as part of their intellectual property portfolios.

Looking ahead, intellectual property will continue to play a fundamental role in shaping the European biotechnology ecosystem. The increasing integration of biotechnology, advanced materials, artificial intelligence and circular manufacturing is expected to generate new innovation opportunities while reinforcing the importance of effective knowledge management and technology transfer. Companies capable of combining strong intellectual property strategies with collaborative innovation, research partnerships and market-oriented product development will be better positioned to commercialise biotechnology solutions, attract investment and strengthen their competitiveness within the emerging European bioeconomy.

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8. Skills Challenges and Knowledge Gaps

Building upon the thematic areas validated during WP2-A1 and the technological, market and regulatory analysis presented throughout this report, the successful deployment of industrial biotechnology ultimately depends on the availability of appropriately skilled professionals. Technological innovation alone is insufficient to transform the wood, furniture and textile sectors if companies lack the knowledge, competences and multidisciplinary expertise required to adopt, implement and scale biotechnology-based solutions. As industries increasingly integrate biotechnology with advanced materials, digital technologies and circular economy principles, traditional occupational profiles are evolving towards new professional roles that combine biological sciences, engineering, sustainability, digitalisation and innovation management.

The analysis conducted in this report demonstrates that biotechnology is no longer confined to research laboratories but is becoming an integral component of industrial manufacturing, product development and sustainable resource management. Consequently, companies require professionals capable of understanding biological processes while simultaneously addressing engineering challenges, regulatory requirements, environmental performance and market demands. The successful implementation of enzyme-assisted processing, fungal biotechnology, biomaterials, biorefineries and circular production systems therefore relies not only on technological maturity but also on the capacity of the workforce to integrate these innovations into industrial practice.

Stakeholder consultations carried out during WP2-A1 consistently highlighted the growing importance of interdisciplinary knowledge, practical competences and continuous professional development to support the transition towards a sustainable bioeconomy. These findings are reinforced by the market trends, technological advances and best practices analysed throughout this report, which collectively demonstrate that future competitiveness will increasingly depend on the ability of companies to recruit and develop professionals with hybrid skill profiles that bridge biotechnology, manufacturing, sustainability and digital technologies.

For this reason, education and training systems must evolve alongside industrial innovation. Universities, Vocational Education and Training (VET) providers, research organisations and lifelong learning institutions play a critical role in preparing both current and future professionals for the rapidly changing requirements of the bio-based economy. The identification of emerging skills and knowledge opportunities presented in this chapter provides an important foundation for the design of the BIOWISE elective course, ensuring that future curricula remain aligned with industrial needs, technological developments and European sustainability objectives.

8.1 Emerging Skills Needs

The rapid evolution of industrial biotechnology is generating profound changes in the knowledge and competences required across the wood, furniture and textile sectors. As biological processes become increasingly integrated into manufacturing systems, professionals are expected to combine expertise from multiple disciplines rather than relying solely on traditional sector-specific knowledge. Future occupational profiles will require a balanced combination of technical, digital, environmental and innovation-related competences capable of supporting the transition towards sustainable, circular and knowledge-intensive industries.

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One of the most significant emerging competence areas concerns industrial biotechnology and advanced bioprocesses. Professionals will increasingly require practical knowledge of microbial cultivation, enzyme technologies, fungal biotechnology, biomass fractionation, biorefineries, fermentation systems and bio-based material production. Understanding the biological mechanisms underpinning industrial processes will become essential for improving production efficiency, developing innovative products and implementing biotechnology solutions within existing manufacturing environments.

The growing importance of advanced biomaterials and circular product development also requires new technical competences. Future professionals must understand the properties, processing and applications of bio-based materials such as nanocellulose, mycelium composites, lignin-derived products, bio-based polymers and engineered wood materials. Skills related to material selection, performance evaluation, durability testing and circular material design will become increasingly valuable as industries seek sustainable alternatives to conventional fossil-based products.

Sustainability is emerging as a core competence across all industrial sectors. Companies increasingly require professionals capable of applying life-cycle assessment (LCA) methodologies, carbon footprint calculations, resource efficiency indicators and circular economy principles throughout product development and manufacturing. Knowledge of eco-design, waste valorisation strategies, environmental impact assessment and sustainable supply chain management is becoming essential for ensuring compliance with European regulations while improving environmental performance.

Digital transformation is also reshaping biotechnology-related occupations. The integration of Industry 4.0 technologies into biological production systems creates growing demand for competences in artificial intelligence, data analysis, process automation, sensor technologies, digital twins and real-time process monitoring. These digital tools enable the optimisation of biological manufacturing processes, improve traceability and support predictive maintenance, making digital literacy an increasingly important component of biotechnology education.

In parallel, professionals must develop stronger competences in regulatory compliance and quality management. As biotechnology products become subject to increasingly demanding environmental, safety and traceability requirements, companies require personnel capable of understanding certification systems, sustainability reporting, environmental legislation and product compliance. Knowledge of regulatory frameworks, environmental standards and product certification procedures is therefore becoming an important competitive advantage.

Beyond technical expertise, biotechnology also requires a broad range of innovation and business competences. Future professionals should understand technology transfer processes, intellectual property management, commercialisation strategies and innovation management to facilitate the successful transition of research results into industrial applications. Entrepreneurial thinking, project management and collaboration with multidisciplinary teams are becoming increasingly important as biotechnology innovation frequently occurs within collaborative ecosystems involving universities, research centres, SMEs and large industrial organisations.

Finally, the convergence of biotechnology with sustainability and digitalisation reinforces the need for professionals who can operate across disciplinary boundaries. The future workforce

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must combine scientific knowledge with engineering capabilities, environmental awareness, digital competences and business understanding in order to address complex industrial challenges. These hybrid skill profiles will be fundamental for supporting innovation, increasing industrial competitiveness and accelerating the adoption of biotechnology across the European wood, furniture and textile sectors.

8.2 Skills Gaps in Industry

Despite the increasing strategic importance of industrial biotechnology, significant skills gaps remain across the European wood, furniture and textile sectors. These gaps affect the capacity of companies to adopt emerging technologies, integrate biological processes into existing production systems and translate research results into commercially viable products. The challenge is particularly pronounced among small and medium-sized enterprises, which often operate with limited research capacity, restricted access to specialised infrastructure and fewer opportunities for continuous workforce development.

One of the most evident gaps concerns the shortage of professionals with combined expertise in biotechnology and industrial manufacturing. Many employees possess strong knowledge of conventional wood processing, furniture production or textile manufacturing, but have limited experience with microbial systems, enzyme technologies, fungal biotechnology, fermentation processes or bio-based material development. Conversely, biotechnology graduates may have strong scientific knowledge but insufficient understanding of production constraints, industrial equipment, quality requirements and scale-up conditions. This disconnect limits the effective integration of biotechnology into real manufacturing environments.

A second gap relates to process scale-up and industrial implementation. Companies frequently report difficulties in finding professionals capable of moving technologies from laboratory validation to pilot and commercial production. Skills are needed in bioprocess engineering, process control, contamination management, feedstock variability, quality assurance and techno-economic assessment. These competences are essential for maintaining process stability, product consistency and cost competitiveness when biological systems are transferred to larger production volumes.

Knowledge gaps are also evident in the field of advanced biomaterials. While research on nanocellulose, mycelium composites, lignin-based adhesives, bio-based polymers and functional textiles is expanding rapidly, many companies lack personnel able to evaluate material properties, assess durability, select appropriate processing methods and determine whether new biomaterials are compatible with existing manufacturing systems. This gap is especially relevant in the furniture and textile sectors, where product performance, aesthetics, safety and consumer acceptance are decisive for market adoption.

Sustainability assessment represents another area of weakness. Although companies increasingly need to demonstrate environmental performance, many lack internal expertise in life-cycle assessment, carbon accounting, circularity indicators, environmental product declarations and sustainable supply chain management. As regulatory and market expectations become more demanding, insufficient knowledge in these areas may affect access to funding, certification schemes and international markets.

Digital skills gaps further constrain biotechnology adoption. The increasing use of sensors,

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automation, artificial intelligence, digital twins and data-driven process optimisation requires personnel capable of interpreting biological and production data. However, many traditional manufacturing companies, particularly SMEs, still have limited digital maturity. The absence of professionals who can combine biotechnology with data analysis and industrial automation reduces the ability of firms to optimise processes, improve traceability and implement smart manufacturing systems.

Regulatory knowledge is also unevenly distributed. Companies introducing new biomaterials, biological treatments or biotechnology-based products must navigate complex requirements related to chemical safety, biosafety, product certification, traceability and sustainability reporting. SMEs often lack dedicated regulatory specialists and may depend on external consultants, increasing costs and delaying commercialisation. Skills related to intellectual property, freedom-to-operate analysis and technology licensing are similarly limited, particularly among research-driven start-ups.

The stakeholder consultations conducted during WP2-A1 also highlighted a broader gap between academic education and industrial practice. Higher education programmes often provide strong theoretical foundations but may offer limited exposure to production environments, scale-up challenges, market requirements and regulatory constraints. At the same time, companies may have insufficient capacity to communicate their emerging skills needs to educational institutions. This weak alignment can result in graduates whose competences do not fully match the practical demands of bio-based industries.

Differences also exist between large companies and SMEs. Larger firms are generally better positioned to recruit specialised personnel, invest in internal training and establish collaborations with universities and research centres. SMEs, by contrast, often require professionals with broader hybrid profiles who can simultaneously contribute to technical development, sustainability assessment, regulatory compliance and commercialisation. However, such multidisciplinary profiles remain difficult to find.

Addressing these gaps will require closer cooperation between industry, universities, VET providers, technology centres and innovation clusters. Training should place greater emphasis on applied biotechnology, industrial problem-solving, multidisciplinary teamwork and direct exposure to manufacturing environments. Flexible upskilling and reskilling opportunities will also be necessary for the existing workforce, particularly through short courses, micro-credentials and company-based training.

8.3 Educational and Training Needs

The technological transformation of the wood, furniture and textile sectors requires a corresponding transformation of education and training systems. As demonstrated throughout this report, the successful implementation of industrial biotechnology depends not only on scientific advances but also on the availability of professionals capable of applying biotechnology within real industrial environments. Consequently, education providers must move beyond traditional discipline-specific curricula and develop learning programmes that integrate biotechnology with engineering, sustainability, digital technologies and industrial innovation.

Universities, VET providers and lifelong learning institutions all have a crucial role to play in preparing both new entrants and the existing workforce for the transition towards a circular

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bioeconomy. Traditional educational pathways often treat biology, engineering, materials science and manufacturing as separate disciplines. However, industrial biotechnology increasingly requires graduates capable of working across these fields, understanding both biological mechanisms and industrial production systems while considering sustainability, regulatory and business requirements.

One of the main educational priorities is the development of interdisciplinary curricula that combine theoretical knowledge with practical industrial applications. Future programmes should integrate subjects such as industrial biotechnology, biomaterials, enzyme technologies, fungal biotechnology, circular manufacturing, bio-based product development, life-cycle assessment, digital manufacturing and environmental management into coherent learning pathways. This interdisciplinary approach will better reflect the complexity of modern industrial systems and prepare learners to address real-world challenges.

Practical experience should become a central component of biotechnology education. Laboratory activities, pilot-scale demonstrations, industrial placements, company visits and challenge-based learning provide students with opportunities to apply theoretical concepts in realistic production environments. Exposure to industrial equipment, quality control procedures, regulatory requirements and process optimisation enables learners to develop the practical competences that companies increasingly identify as essential for successful employment.

Closer collaboration between education providers and industry is equally important. The stakeholder consultations conducted during WP2-A1 highlighted the need for stronger partnerships between universities, VET institutions, research centres and companies to ensure that educational programmes remain aligned with rapidly evolving industrial requirements. Co-designed curricula, guest lectures from industry experts, collaborative research projects and work-based learning opportunities can significantly improve the relevance of biotechnology education while facilitating knowledge transfer between academia and industry.

Given the rapid pace of technological change, education should also extend beyond initial qualifications. Lifelong learning, continuous professional development and flexible reskilling opportunities will become increasingly important as companies adopt new biotechnological processes and production systems. Short specialised courses, modular learning programmes, professional certificates and micro-credentials provide flexible mechanisms for updating competences throughout working careers without requiring professionals to undertake full academic programmes.

Digital learning methodologies can further enhance access to biotechnology education. Online learning platforms, virtual laboratories, simulation tools and blended learning approaches allow learners to acquire both theoretical knowledge and practical problem-solving skills in flexible formats. These methodologies are particularly valuable for SMEs and professionals who may have limited opportunities to participate in traditional full-time education while remaining employed.

Another important educational priority is the integration of entrepreneurship and innovation management into biotechnology programmes. Future professionals should understand not only how biotechnology works but also how innovations are transferred to industry, commercialised and scaled. Knowledge of intellectual property, technology transfer, regulatory frameworks, business model development and project management will become increasingly valuable as

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biotechnology generates new business opportunities across the bioeconomy.

International and cross-sectoral learning should also be encouraged. Many biotechnology solutions developed within one industrial sector can be successfully adapted to others, as illustrated by several best practices presented in this report. Educational programmes should therefore promote collaboration across the wood, furniture and textile sectors, enabling learners to recognise common technological principles, sustainability challenges and innovation opportunities while fostering interdisciplinary thinking and knowledge exchange.

Ultimately, future education systems must become more flexible, collaborative and responsive to industrial change. Rather than preparing learners for static occupational profiles, education should equip them with adaptable competences that support continuous learning, multidisciplinary collaboration and innovation throughout their professional careers. These educational priorities provide the foundation for the development of the BIOWISE elective course, ensuring that the future curriculum responds directly to the technological trends, market developments and skills needs identified throughout this report while supporting Europe's transition towards a competitive, sustainable and knowledge-based bioeconomy.

8.4 Interdisciplinary Competences

The successful implementation of industrial biotechnology depends not only on specialised technical expertise but also on the ability to integrate knowledge across multiple scientific, engineering and business disciplines. As demonstrated throughout this report, biotechnology applications within the wood, furniture and textile sectors increasingly combine biological sciences with materials engineering, digital technologies, environmental management, manufacturing processes and innovation strategies. Consequently, future professionals must develop interdisciplinary competences that enable them to work effectively in complex and rapidly evolving industrial environments.

One of the most important interdisciplinary competences is systems thinking. Biotechnology-based production systems operate within broader industrial, environmental and economic contexts where decisions regarding raw materials, manufacturing processes, product design and end-of-life management are closely interconnected. Professionals therefore need the ability to understand entire value chains, evaluate interactions between different industrial processes and identify opportunities for improving sustainability, efficiency and resource utilisation through integrated solutions.

Equally important is the ability to collaborate across disciplines. Industrial biotechnology projects frequently involve multidisciplinary teams composed of biologists, chemists, engineers, materials scientists, environmental specialists, digital technology experts, designers and business professionals. Effective communication between these disciplines is essential to ensure that scientific discoveries can be translated into practical industrial solutions. Professionals must therefore be capable of communicating complex technical information to colleagues with different backgrounds while facilitating collaboration between research organisations, manufacturers, policymakers and end users.

Problem-solving and critical thinking have become essential competences within biotechnology-driven industries. Many emerging technologies are still evolving and require continuous experimentation, optimisation and adaptation to different industrial contexts. Professionals

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must be able to analyse complex problems, evaluate alternative solutions, interpret experimental results and make informed decisions under conditions of technological uncertainty. These analytical skills are particularly important during process optimisation, product development and technology scale-up.

Innovation and entrepreneurship are also becoming increasingly relevant. Biotechnology creates opportunities not only for improving existing manufacturing systems but also for developing entirely new products, services and business models. Professionals should therefore understand the principles of innovation management, technology transfer, intellectual property, commercialisation and market analysis. Entrepreneurial competences support the creation of start-ups, spin-offs and collaborative innovation initiatives while helping established companies identify new market opportunities arising from the bioeconomy.

Project management represents another key interdisciplinary competence. Biotechnology projects often involve multiple stakeholders, long development timelines, regulatory requirements and complex technical activities that require effective planning and coordination. Future professionals should be able to manage multidisciplinary teams, coordinate research and industrial activities, allocate resources efficiently and monitor project performance throughout the innovation process.

Given the increasing importance of sustainability within industrial decision-making, professionals must also develop competences related to environmental assessment and responsible innovation. Understanding life-cycle thinking, circular economy principles, carbon footprint assessment, environmental risk management and sustainable resource use enables organisations to design biotechnology solutions that generate environmental, economic and social value simultaneously. These competences also support compliance with emerging European sustainability policies and reporting requirements.

Cross-sectoral knowledge is another increasingly valuable competence. As illustrated by the case studies presented in this report, many biotechnology solutions are transferable between the wood, furniture and textile sectors. Technologies such as enzyme-assisted processing, fungal biotechnology, biomaterials, waste valorisation and circular manufacturing have applications across multiple industries. Professionals capable of recognising these synergies can accelerate innovation, facilitate technology transfer and promote collaborative approaches that maximise the impact of biotechnology throughout the bio-based economy.

Finally, adaptability and lifelong learning should be regarded as fundamental professional competences. Industrial biotechnology is evolving rapidly, driven by advances in synthetic biology, biomaterials, digitalisation and artificial intelligence. Professionals will therefore need to continuously update their knowledge and acquire new skills throughout their careers. The ability to learn, adapt and integrate emerging technologies into industrial practice will become one of the defining characteristics of the future biotechnology workforce.

Developing these interdisciplinary competences will be essential for enabling professionals to bridge the gap between scientific research and industrial implementation. Beyond technical expertise, future graduates and workers must be able to collaborate across disciplines, manage innovation processes, respond to evolving regulatory and market requirements, and contribute to the development of sustainable and competitive bio-based industries. These competences should therefore form a core component of future education and training programmes, including

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the BIOWISE elective course, ensuring that learners are equipped to address the complex challenges of Europe's green and digital transitions.

8.5 Integration of Digital and Green Competences

The transition towards a competitive European bioeconomy is being driven by the simultaneous convergence of three major industrial transformations: biotechnology, digitalisation and sustainability. Rather than evolving independently, these domains are becoming increasingly interconnected, creating demand for professionals capable of integrating biological knowledge with digital technologies and environmental management. Future industrial competitiveness will therefore depend on the development of hybrid competences that enable organisations to optimise production systems while improving both economic and environmental performance.

Digital technologies are rapidly transforming the way biotechnology is implemented within industrial environments. Artificial intelligence, machine learning, sensor technologies, automation, digital twins and advanced data analytics are increasingly used to monitor biological processes, optimise fermentation systems, predict production performance and improve resource efficiency. Professionals working in biotechnology-based industries will therefore require strong digital literacy, including the ability to interpret production data, manage digital monitoring systems and support data-driven decision-making throughout biological manufacturing processes.

At the same time, sustainability has become a core industrial competence rather than a specialised environmental discipline. Companies are increasingly expected to evaluate environmental performance throughout the entire product life cycle while complying with evolving European regulations related to climate neutrality, circular economy and sustainable production. Consequently, future professionals should be capable of applying life-cycle assessment (LCA), carbon footprint methodologies, circularity indicators, environmental product declarations (EPDs) and sustainability reporting frameworks when developing and implementing biotechnology solutions.

The growing emphasis on product traceability and transparency further reinforces the integration of digital and green competences. Emerging regulatory instruments such as the DPP, together with increasing ESG reporting requirements, require companies to collect, manage and communicate reliable environmental information across increasingly complex supply chains. Professionals must therefore understand not only biological production systems but also digital traceability tools, sustainability metrics and environmental data management.

Another emerging competence concerns the use of digital technologies to support circular manufacturing. Digital platforms facilitate biomass traceability, waste stream management, resource optimisation and industrial symbiosis, enabling companies to identify opportunities for material recovery and resource sharing. These capabilities are particularly relevant within the wood, furniture and textile sectors, where biotechnology increasingly relies on the valorisation of secondary raw materials and industrial by-products.

Artificial intelligence is also expected to play an increasingly important role in biotechnology research and industrial implementation. AI-assisted modelling, predictive analytics and computational optimisation are accelerating the development of enzymes, biomaterials and biological production systems while reducing development time and experimental costs.

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Although these technologies are still emerging within many industrial applications, future professionals will increasingly require a basic understanding of AI-supported biotechnology, digital process optimisation and responsible data management.

The integration of digital and green competences should therefore be considered a strategic priority for future education and training programmes. Rather than treating digitalisation and sustainability as separate learning domains, educational programmes should incorporate them across biotechnology curricula through interdisciplinary projects, industrial case studies and practical problem-solving activities. This integrated approach reflects the reality of modern industrial environments, where technological innovation, environmental responsibility and digital transformation increasingly operate as interconnected components of the same production system.

Ultimately, the professionals leading the next generation of bio-based industries will not simply be biotechnology specialists, digital engineers or sustainability experts. They will be multidisciplinary professionals capable of combining biological innovation, digital intelligence and environmental responsibility to develop resilient, circular and competitive manufacturing systems. Developing these integrated competences represents one of the most important knowledge opportunities identified throughout this report and should constitute a central pillar of future education initiatives, including the BIOWISE elective course.

8.6 Knowledge Opportunities and Implications for the BIOWISE Consortium

The analysis presented throughout this report demonstrates that industrial biotechnology is evolving rapidly across the wood, furniture and textile sectors, generating new technological opportunities while simultaneously transforming industrial processes, business models, regulatory requirements and workforce competences. These developments highlight the need for education and training programmes that are capable of responding to rapidly changing industrial environments and preparing professionals with the interdisciplinary knowledge required by the emerging bioeconomy.

The stakeholder consultations carried out during WP2-A1, together with the technological, market and regulatory analysis developed in WP2-A2, have identified a series of priority knowledge domains that should underpin future education and training initiatives. These domains reflect both current industrial needs and future technological developments, ensuring that learners acquire competences that remain relevant throughout the ongoing green and digital transitions.

One of the principal knowledge opportunities concerns industrial biotechnology fundamentals. Future professionals should understand the biological principles underpinning industrial applications, including microbial biotechnology, fungal biotechnology, enzyme technologies, fermentation processes, biomass conversion and bioprocess engineering. This scientific foundation should be complemented by an understanding of how biotechnology is integrated into industrial production systems across different manufacturing sectors.

The growing importance of bio-based materials and advanced biomaterials also represents a key curriculum priority. Educational programmes should address emerging materials such as

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nanocellulose, lignin-derived products, mycelium composites, bacterial cellulose, bio-based polymers and engineered wood materials, while developing learners' capacity to evaluate material performance, sustainability and industrial applicability.

A second priority concerns the transition towards circular manufacturing systems. Future curricula should provide learners with knowledge of circular economy principles, biomass valorisation, industrial symbiosis, waste recovery technologies and cascading use of biological resources. Particular emphasis should be placed on understanding how biotechnology contributes to resource efficiency, waste reduction and the development of sustainable industrial value chains.

The report also highlights the growing convergence between biotechnology and digital technologies. Consequently, future learning programmes should incorporate competences related to digital biotechnology, including data analysis, process monitoring, artificial intelligence, automation, sensor technologies, digital twins and digital traceability systems. These technologies increasingly support biological manufacturing processes and are becoming essential for improving efficiency, quality control and sustainability performance.

Regulatory and sustainability competences should also constitute a core component of future curricula. Learners should develop a practical understanding of European regulatory frameworks, sustainability certification systems,,LCA,EPDs, DPPs, ESG reporting and environmental compliance. These competences are increasingly required by companies operating within international value chains and represent an important competitive advantage for future professionals.

The report further demonstrates that biotechnology innovation is closely linked to entrepreneurship and technology transfer. Therefore, education programmes should also integrate knowledge related to innovation management, intellectual property, commercialisation strategies, project management and business model development. Understanding how scientific discoveries are transformed into commercially viable products will enable learners to contribute more effectively to industrial innovation ecosystems and support the growth of bio-based enterprises.

From a pedagogical perspective, the findings of this report suggest that future biotechnology education should move beyond traditional lecture-based approaches towards more practice-oriented and learner-centred methodologies. Challenge-based learning, problem-solving activities, laboratory practice, industrial case studies, work-based learning, multidisciplinary projects and collaboration with companies should become integral components of curriculum design. Such approaches better reflect the complexity of real industrial environments while supporting the development of technical, digital and transversal competences simultaneously.

Another important implication concerns the need for flexible and lifelong learning pathways. Given the rapid pace of technological change, education should not be limited to initial qualifications but should also support continuous professional development through modular learning, micro-credentials, short specialised courses and upskilling programmes. These flexible learning formats are particularly important for professionals already employed within SMEs, who require opportunities to update their competences without interrupting their professional activities.

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Ultimately, the findings presented throughout this report provide a robust evidence base for the development of the BIOWISE elective course. By combining the priorities identified during stakeholder consultations with the analysis of emerging technologies, industrial trends, market developments, regulatory frameworks and future skills requirements, the curriculum can be designed to reflect both present industrial realities and future innovation trajectories. This evidence-based approach will help ensure that the BIOWISE course equips learners with the interdisciplinary knowledge, practical competences and innovation mindset required to support the sustainable transformation of the European wood, furniture and textile sectors.

The knowledge opportunities identified in this report should therefore be understood not as static educational topics, but as dynamic learning priorities that will continue to evolve alongside technological innovation and industrial change. Maintaining close collaboration between industry, higher education institutions, VET providers, research organisations and policymakers will be essential to ensure that future curricula remain responsive to emerging technologies, labour market needs and the strategic objectives of the European bioeconomy.

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9. Emerging Knowledge Opportunities

The analysis presented throughout this report demonstrates that industrial biotechnology is no longer an emerging niche technology but an increasingly important driver of industrial transformation across the European wood, furniture and textile sectors. Advances in bio-based materials, enzyme technologies, fungal biotechnology, biorefineries and circular manufacturing are creating new opportunities to improve resource efficiency, reduce environmental impacts and develop innovative products with higher added value. At the same time, market developments, evolving regulatory frameworks and changing workforce requirements highlight that technological innovation must be accompanied by appropriate investments, supportive policies and the development of new knowledge and competences.

The transition towards a sustainable bioeconomy therefore requires coordinated action across the entire innovation ecosystem. Research organisations, higher education institutions, vocational education providers, industrial companies, SMEs, policymakers and innovation support organisations all have complementary roles in accelerating the adoption of biotechnology and translating scientific advances into practical industrial solutions. As demonstrated by the best practices analysed in this report, successful innovation depends not only on technological excellence but also on effective collaboration, knowledge exchange, technology transfer and multidisciplinary partnerships.

Building upon the technological trends, market perspectives, regulatory analysis and skills needs identified in the previous chapters, this final section outlines the principal opportunities that are expected to shape the future development of industrial biotechnology. It also proposes strategic recommendations aimed at supporting research, industrial deployment, innovation ecosystems and future policy actions, providing a forward-looking perspective that can contribute to strengthening Europe's competitiveness and resilience within the emerging circular bioeconomy.

9.1 Research and Innovation Priorities

Continued investment in research and innovation will be essential to unlock the full potential of industrial biotechnology within the wood, furniture and textile sectors. Although significant technological advances have already been achieved, many biotechnology applications remain at pilot or early commercial stages and require further development before widespread industrial implementation becomes feasible. Future research should therefore prioritise not only scientific discovery but also the optimisation, scalability and commercial viability of biotechnology solutions capable of addressing the environmental and economic challenges facing European manufacturing.

One of the principal research priorities concerns the development of next-generation bio-based materials with improved technical performance and environmental characteristics. Future innovation is expected to focus on advanced biomaterials such as nanocellulose, lignin-derived polymers, bacterial cellulose, mycelium composites, engineered wood products and bio-based functional textiles. Research should aim to improve mechanical properties, durability, fire resistance, moisture resistance, antimicrobial performance and recyclability while maintaining low environmental impacts and economic competitiveness.

Further advances in industrial biotechnology and bioprocess engineering will also be required to

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improve production efficiency and facilitate industrial scale-up. Research into enzyme engineering, microbial fermentation, fungal biotechnology, biomass fractionation and integrated biorefineries will continue to expand opportunities for converting renewable biological resources into high-value products. Particular attention should be given to increasing process robustness, reducing energy consumption, improving feedstock flexibility and lowering production costs to support commercial deployment.

The optimisation of biomass valorisation and circular resource management represents another strategic research priority. Future studies should explore more efficient methods for converting forestry residues, agricultural by-products and industrial side streams into biomaterials, bio-based chemicals, renewable energy and functional products. The development of cascading biomass utilisation systems and industrial symbiosis models will further strengthen resource efficiency while supporting the objectives of the European circular economy.

Emerging technologies such as synthetic biology, gene editing and biofabrication are expected to create entirely new opportunities for industrial biotechnology. Advances in synthetic biology enable the engineering of microorganisms with enhanced production capabilities, while gene-editing technologies such as CRISPR offer new possibilities for improving industrial strains, enzyme performance and biomass characteristics. Biofabrication techniques combining biological systems with advanced manufacturing processes may also facilitate the production of highly customised materials with novel functional properties for applications in construction, furniture and textiles.

Digital technologies will increasingly support biotechnology research and industrial implementation. Artificial intelligence, machine learning, digital twins, advanced modelling and sensor technologies can accelerate the optimisation of biological processes, improve predictive process control and reduce experimental development time. The integration of digital tools with biotechnology is expected to become a major research area, enabling more efficient, data-driven and sustainable manufacturing systems.

Despite rapid scientific progress, one of the greatest challenges remains the transition from laboratory research to industrial application. Consequently, future innovation efforts should place greater emphasis on technology readiness and scale-up, including pilot demonstrations, industrial validation and techno-economic assessment. Strengthening collaboration between universities, technology centres and industrial partners will be essential for reducing the gap between scientific research and commercial implementation while accelerating the adoption of biotechnology across the three target sectors.

Future research should also adopt increasingly interdisciplinary approaches that integrate biotechnology with materials science, engineering, environmental sciences, digital technologies and industrial design. Many of the most promising innovations identified in this report emerge precisely from the convergence of these disciplines rather than from biotechnology alone. Supporting multidisciplinary research environments will therefore be fundamental for generating the next generation of sustainable industrial solutions.

Ultimately, the future competitiveness of the European bioeconomy will depend not only on scientific excellence but also on the capacity to transform research into practical industrial innovation. Research priorities should therefore balance fundamental scientific advances with market-oriented development, ensuring that biotechnology continues to generate sustainable

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products, resilient industrial value chains and long-term economic opportunities across the wood, furniture and textile sectors.

9.2 Industrial Deployment Opportunities

The successful industrial deployment of biotechnology represents one of the greatest opportunities for strengthening the competitiveness, sustainability and resilience of the European wood, furniture and textile sectors. While many biotechnology applications have already demonstrated their technical feasibility, the coming years will be characterised by their progressive integration into mainstream industrial production. Companies that successfully adopt these technologies will be better positioned to respond to increasingly demanding environmental regulations, evolving customer expectations and the growing demand for sustainable, high-value products.

Within the wood sector, significant opportunities exist for expanding the industrial application of enzyme-assisted processing, integrated biorefineries, biomass valorisation and advanced wood modification technologies. The efficient utilisation of lignocellulosic biomass enables companies to produce not only traditional wood products but also bio-based chemicals, renewable fuels, engineered materials and high-performance biomaterials. Technologies such as lignin valorisation, nanocellulose production and fungal pretreatment are expected to become increasingly integrated into existing manufacturing systems, improving both resource efficiency and economic performance.

Within the textile sector, biotechnology is expected to drive one of the most significant industrial transformations. Enzymatic processing technologies, microbial fermentation, biosynthetic fibres, bacterial cellulose, mycelium-based leather alternatives and bio-based colourants provide sustainable alternatives to conventional textile production, reducing water consumption, chemical inputs and greenhouse gas emissions. As consumer demand for sustainable fashion continues to grow, biotechnology offers textile manufacturers opportunities to develop innovative products that combine high performance with significantly improved environmental credentials.

The furniture sector offers considerable opportunities for the adoption of biotechnology through the development of sustainable materials and cleaner manufacturing processes. Bio-based adhesives, low-emission coatings, biodegradable composites and mycelium-based materials are creating new possibilities for reducing dependence on fossil-derived chemicals while improving environmental performance. At the same time, biotechnology supports circular manufacturing strategies by facilitating the recovery and valorisation of wood residues, enabling manufacturers to develop products with lower environmental impacts and longer life cycles. These innovations also contribute to compliance with emerging European requirements related to product sustainability, circularity and indoor environmental quality.

The deployment of biotechnology also creates opportunities to establish regional circular bioeconomy ecosystems, where forestry residues, agricultural by-products and industrial side streams become valuable feedstocks for new production systems. Industrial symbiosis, cascading biomass utilisation and integrated resource management enable companies from different sectors to collaborate in creating higher-value products while reducing waste generation and improving overall resource efficiency. Such regional value chains strengthen

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industrial resilience, reduce dependence on imported raw materials and promote more sustainable local economies.

For SMEs, biotechnology provides important opportunities to compete through innovation rather than production scale. By focusing on specialised bio-based products, niche markets and high-value applications, SMEs can differentiate themselves from larger competitors while taking advantage of their flexibility and capacity for rapid innovation. Participation in European research projects, regional innovation clusters and collaborative technology platforms enables SMEs to access scientific expertise, pilot-scale facilities and funding mechanisms that would otherwise be difficult to obtain independently.

Successful industrial deployment will also depend on stronger collaboration across the innovation ecosystem. Demonstration plants, pilot facilities, Living Labs and Digital Innovation Hubs provide essential environments for validating emerging technologies under industrial conditions before large-scale implementation. These collaborative infrastructures reduce technological risks, facilitate knowledge exchange and accelerate the commercialisation of biotechnology-based solutions by bringing together companies, universities, technology centres and public authorities.

However, wider industrial deployment will require continued efforts to overcome challenges related to scale-up, investment, workforce development and regulatory compliance. Companies will need to invest not only in new technologies but also in organisational change, digital infrastructure and continuous workforce training to fully realise the benefits of biotechnology. Public support mechanisms, targeted investment programmes and favourable regulatory frameworks will remain essential to accelerate this transition.

Overall, the industrial deployment of biotechnology offers far-reaching opportunities to modernise manufacturing systems, diversify product portfolios and strengthen the long-term competitiveness of European industry. By integrating biological innovation with circular economy principles, advanced manufacturing and digital technologies, companies across the wood, furniture and textile sectors will be better equipped to respond to future environmental, economic and societal challenges while contributing to a resilient and sustainable European bioeconomy.

9.3 Innovation Ecosystems and Collaborative Networks

The transition towards a competitive and sustainable bioeconomy will depend not only on technological advances but also on the strength of the innovation ecosystems that support their development and deployment. Industrial biotechnology is inherently multidisciplinary and requires close collaboration between universities, research organisations, technology centres, industrial companies, public authorities and innovation support organisations. No single actor possesses all the expertise, infrastructure or resources necessary to develop, validate and commercialise biotechnology solutions independently. Consequently, collaborative innovation has become a defining characteristic of successful biotechnology ecosystems.

Universities and research organisations provide the scientific knowledge that underpins technological innovation, generating advances in areas such as enzyme engineering, fungal biotechnology, synthetic biology, biomaterials and industrial bioprocesses. However, transforming scientific discoveries into commercially viable products requires close interaction

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with industry. Companies contribute practical manufacturing expertise, market knowledge, production infrastructure and a clear understanding of customer needs, enabling research outcomes to be translated into scalable industrial applications.

Technology centres and applied research institutes play an important intermediary role within this innovation ecosystem. By providing pilot-scale facilities, specialised equipment and technical expertise, these organisations help bridge the gap between laboratory research and industrial production. Demonstration plants, pilot facilities and validation platforms allow emerging technologies to be tested under realistic operating conditions, reducing technical uncertainty and facilitating commercial scale-up.

Innovation clusters, Living Labs and Digital Innovation Hubs further strengthen collaboration by bringing together companies, researchers, public authorities and end users within shared innovation environments. These collaborative platforms encourage knowledge exchange, accelerate technology transfer and promote the co-development of new products and manufacturing processes. They are particularly valuable for SMEs, which often lack internal research capacity and benefit significantly from access to external expertise, specialised infrastructure and collaborative networks.

European collaborative programmes have also become powerful drivers of biotechnology innovation. Initiatives supported through Horizon Europe, the CBE JU, Interreg, EIT Manufacturing and other European partnerships encourage cross-border collaboration between industry and academia while facilitating access to funding, international expertise and demonstration opportunities. These programmes not only accelerate technological development but also strengthen European innovation capacity by connecting complementary competences across regions and sectors.

Cross-sectoral collaboration represents another important opportunity. As illustrated by the best practices analysed in this report, many biotechnology solutions—including enzyme-assisted processing, biomaterials, fungal technologies and biomass valorisation—can be successfully transferred between the wood, furniture and textile industries. Promoting collaboration across these sectors enables knowledge sharing, reduces duplication of research efforts and creates opportunities for developing integrated circular value chains that maximise resource efficiency.

Ultimately, successful biotechnology deployment depends on the ability of innovation ecosystems to connect research, education, industry and policy within a shared framework of collaboration and continuous learning. Strengthening these collaborative networks will accelerate technology transfer, reduce barriers to industrial adoption and support the development of resilient regional bioeconomy ecosystems capable of responding to future technological and environmental challenges.

9.4 Strategic Recommendations for Stakeholders

The findings presented throughout this report demonstrate that the successful deployment of industrial biotechnology requires coordinated action across the entire innovation ecosystem. Technological advances alone will not be sufficient to achieve the transition towards a competitive and sustainable bioeconomy unless they are supported by appropriate investments, effective knowledge transfer, adaptive education systems and enabling policy frameworks. The following strategic recommendations are intended to guide the main stakeholder groups

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involved in the development and adoption of biotechnology across the wood, furniture and textile sectors.

Recommendations for Industry

Industrial companies should adopt a long-term innovation strategy that integrates biotechnology into broader sustainability and digital transformation agendas. Rather than viewing biotechnology as a standalone technological solution, organisations should consider its potential to improve resource efficiency, reduce environmental impacts, develop new products and strengthen competitiveness. Companies are encouraged to increase investment in pilot projects, demonstration activities and collaborative research while fostering a culture of continuous innovation and workforce development.

Particular attention should be given to the adoption of circular manufacturing principles, including biomass valorisation, waste recovery, sustainable product design and the integration of bio-based materials into existing production systems. Companies should also strengthen collaboration with universities, research centres and technology providers to facilitate technology transfer and accelerate industrial implementation.

Recommendations for SMEs

SMEs should leverage their flexibility and capacity for innovation by focusing on specialised, high-value biotechnology applications that respond to emerging market demands. Participation in regional innovation ecosystems, European research projects and industrial clusters can significantly improve access to funding, technical expertise and demonstration facilities.

SMEs should also prioritise workforce upskilling, digitalisation and sustainability assessment while developing partnerships that allow them to overcome limitations related to infrastructure, specialised personnel and research capacity. Collaborative innovation models will be particularly important for enabling smaller companies to adopt biotechnology without assuming the full cost and risk of technology development independently.

Recommendations for Universities, VET Providers and Training Organisations

Education providers should continue modernising curricula to reflect the rapidly evolving requirements of industrial biotechnology. Future programmes should promote interdisciplinary learning that combines biotechnology, materials science, engineering, sustainability, digital technologies and innovation management. Greater emphasis should be placed on practical laboratory experience, challenge-based learning, industrial placements and collaboration with companies to ensure that graduates possess both technical knowledge and practical competences.

Flexible learning pathways, including lifelong learning programmes, modular courses and micro-credentials, should be expanded to support continuous professional development and facilitate workforce reskilling throughout changing industrial careers. Close dialogue with industry should remain a priority to ensure that educational programmes evolve alongside technological innovation and labour market needs.

Recommendations for Research Organisations and Innovation Centres

Research organisations should strengthen efforts to accelerate the translation of scientific knowledge into industrial applications. Greater emphasis should be placed on applied research, pilot-scale validation, demonstration activities and technology readiness in order to reduce the

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gap between laboratory research and commercial implementation.

Interdisciplinary collaboration should continue to expand across biotechnology, materials science, digital technologies, engineering and environmental sciences. Open innovation, collaborative research and technology transfer mechanisms should be further promoted to maximise the societal and economic impact of publicly funded research while supporting the growth of regional bioeconomy ecosystems.

Recommendations for Policymakers and Public Authorities

Public authorities should continue supporting industrial biotechnology through stable policy frameworks, targeted funding programmes and measures that facilitate innovation and technology transfer. Simplifying regulatory procedures, improving access to pilot infrastructure and supporting demonstration projects will help reduce barriers to industrial adoption, particularly for SMEs.

Policymakers should also encourage stronger collaboration between education, research and industry while promoting regional innovation ecosystems capable of mobilising local biomass resources and industrial capabilities. Continued investment in skills development, lifelong learning and workforce reskilling will be essential to ensure that human capital evolves alongside technological progress. Furthermore, policies promoting circular economy practices, sustainable public procurement and bio-based innovation should continue to create favourable market conditions for biotechnology-based products and manufacturing systems.

A Shared Responsibility for the Bioeconomy Transition

Ultimately, achieving the full potential of industrial biotechnology requires a shared commitment from all stakeholders. Industry, academia, education providers, policymakers and civil society each play complementary roles in accelerating innovation, strengthening knowledge transfer and supporting sustainable industrial transformation. By working collaboratively, these actors can create an integrated innovation ecosystem capable of developing the technologies, skills and business models required to position Europe as a global leader in the circular bioeconomy.

The recommendations presented in this report provide a strategic roadmap for supporting this transition while reinforcing the objectives of the BIOWISE project: fostering collaboration between education and industry, anticipating future skills requirements and promoting the adoption of biotechnology as a driver of sustainable growth, competitiveness and resilience across the European wood, furniture and textile sectors.

9.5 Future Outlook

Industrial biotechnology is expected to become one of the keys enabling technologies underpinning Europe's transition towards a competitive, circular and climate-neutral economy. The technological developments analysed throughout this report demonstrate that biotechnology has evolved far beyond its traditional applications and is now transforming the way materials are produced, natural resources are managed and industrial value chains are organised. Advances in bio-based materials, enzyme technologies, fungal biotechnology, biorefineries and biofabrication are progressively reshaping the wood, furniture and textile sectors, creating opportunities for more sustainable, resource-efficient and resilient manufacturing systems.

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Over the coming decade, the convergence of biotechnology with digital technologies, advanced materials and circular economy principles is expected to accelerate even further. Artificial intelligence, automation, digital twins, advanced process monitoring and data-driven manufacturing will increasingly complement biological production systems, enabling greater process optimisation, improved traceability and enhanced environmental performance. At the same time, growing societal demand for sustainable products, together with increasingly ambitious European environmental policies, will continue to stimulate investment in biotechnology-based innovation across multiple industrial sectors.

However, technological progress alone will not guarantee successful industrial transformation. The widespread adoption of biotechnology will depend on the capacity of companies, research organisations, educational institutions and policymakers to work collaboratively in addressing the technological, regulatory, economic and skills-related challenges identified throughout this report. Strengthening technology transfer, supporting industrial scale-up, improving access to innovation funding and fostering regional bioeconomy ecosystems will remain essential priorities for accelerating market uptake and ensuring that biotechnology solutions achieve their full industrial potential.

Equally important will be the development of a workforce capable of operating within increasingly interdisciplinary industrial environments. Future professionals will require a combination of scientific knowledge, engineering expertise, digital competences, sustainability awareness and innovation capabilities that allow them to integrate biotechnology into modern manufacturing systems. Continuous investment in education, vocational training and lifelong learning will therefore be fundamental for ensuring that Europe's workforce evolves alongside technological innovation and remains capable of supporting the emerging bio-based economy.

The findings of this report demonstrate that the opportunities created by industrial biotechnology extend well beyond technological innovation. They encompass new business models, regional development opportunities, sustainable supply chains, circular manufacturing systems and enhanced international competitiveness. By integrating renewable biological resources with advanced manufacturing and digital technologies, biotechnology provides a pathway towards industrial systems that are simultaneously more productive, environmentally responsible and economically resilient.

Within this context, the BIOWISE project represents an important contribution to Europe's broader transition towards a sustainable bioeconomy. By combining stakeholder consultation, technological analysis and skills assessment, the project establishes a robust evidence base for the development of future-oriented education and training programmes. The BIOWISE elective course will translate these findings into practical learning opportunities that prepare learners to respond to emerging industrial challenges while supporting innovation across the wood, furniture and textile sectors.

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10. Conclusions and Recommendations

The analysis presented in this report demonstrates that industrial biotechnology is becoming an important enabling framework for the sustainable transformation of the European wood, textile, and furniture industries. Its contribution extends across renewable biomaterials, enzyme-assisted manufacturing, microbial and fungal processes, integrated biorefineries, bio-based chemicals, biological recycling, and circular production models. Together, these approaches can reduce dependence on fossil resources and hazardous chemicals, improve energy and material efficiency, lower emissions, and create higher-value products from renewable feedstocks and industrial side streams.

Mycelium composites illustrate one specific pathway within this broader technology portfolio: fungal growth can convert agricultural and lignocellulosic residues into lightweight, biodegradable materials for packaging, insulation, interiors, and selected furniture applications. The report includes two comparable but contextually distinct case studies which demonstrate different development routes, product priorities, and regional innovation settings. These examples confirm the potential of mycelium-based materials while also underlining the need for further scale-up, performance validation, standardisation, and market development.

The report highlights complementary opportunities across the three target sectors. In wood-based value chains, enzyme-assisted processing, lignocellulosic biorefineries, nanocellulose, lignin valorisation, fungal conversion, and bioremediation can improve resource efficiency and expand the range of high-value products. In textiles, enzymatic pretreatment and finishing, microbial colourants, bacterial cellulose, biosynthetic fibres, and biological recycling can reduce water, energy, and chemical use. In furniture, bio-based adhesives and coatings, renewable foams and composites, fungal pigments, and residue valorisation support healthier materials, cleaner production, and circular product design.

The case studies show that these applications span different levels of technological maturity, from established industrial processes to pilot-scale biomaterials and emerging biofabrication platforms. Their wider deployment will depend on reliable performance, competitive production costs, access to demonstration infrastructure, appropriate standards and certification, and stronger cooperation among industry, universities, research organisations, policymakers, investors, and education providers. This coordinated approach is essential for translating biotechnology into economic, environmental, and societal value across the European bioeconomy.

10.1 Key Findings

Industrial biotechnology offers a broad portfolio of pathways for strengthening the competitiveness and sustainability of the European wood, textile, and furniture sectors. The principal opportunities include enzyme-assisted processing, microbial fermentation, fungal biotechnology, integrated biorefineries, lignin and cellulose valorisation, bio-based adhesives and coatings, advanced biomaterials, biological recycling, and bioremediation. Their common value lies in using renewable resources and side streams more efficiently while reducing waste, emissions, fossil inputs, and hazardous substances over the product life cycle.

No single biotechnology application addresses all sectoral needs. Established enzyme-based processes and fermentation technologies offer nearer-term efficiency gains, while advanced biomaterials, biological recycling, and biofabrication provide longer-term opportunities for new

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products and value chains. The linked MYCOPOR and MUSH MycoTechnology cases are retained as complementary examples of mycelium-composite development, alongside the report's wider set of industrial cases covering enzyme-assisted wood processing, medicinal fungi, microbial textile colouration, bio-based coatings, circular fibres, and other biotechnology applications.

Digitalisation is an important complementary driver of biotechnology adoption. Artificial intelligence, machine learning, process automation, hyperspectral imaging, digital twins, and sensor-based monitoring can improve process control, product consistency, traceability, and industrial efficiency across biological manufacturing systems. Wider implementation, however, remains constrained by scale-up risks, production costs, feedstock variability, regulatory complexity, limited standards and certification routes, and shortages of interdisciplinary expertise.

10.2 Strategic Recommendations for Industry

Practical laboratory education should be complemented by industrial placements, project-based learning, pilot-scale demonstrations, and collaboration with companies implementing biotechnology solutions. Curricula should address industrial fermentation, enzymatic technologies, fungal biotechnology, biorefineries, bio-based chemicals and materials, biological recycling, synthetic biology, life-cycle assessment, regulatory and standardisation requirements, and digitally controlled manufacturing. Mycelium cultivation and biofabrication provide useful applied examples within this wider competence framework.

Continuous professional development will also be essential to enable the existing workforce to adapt to rapidly evolving industrial technologies and sustainability requirements.

10.3 Recommendations for Education and Training Providers

The rapid expansion of industrial biotechnology requires a new generation of professionals capable of working across biology, engineering, materials science, sustainability, and digital technologies. Universities, vocational education and training (VET) providers, and lifelong learning institutions should therefore develop interdisciplinary curricula that combine biotechnology with wood science, textile engineering, furniture manufacturing, biomaterials, circular economy, data science, and innovation management.

Practical laboratory education should be complemented by industrial placements, project-based learning, pilot-scale demonstrations, and collaboration with companies actively implementing biotechnology solutions. Emerging topics such as fungal biotechnology, mycelium cultivation, industrial fermentation, synthetic biology, biofabrication, enzymatic technologies, life-cycle assessment, and digital manufacturing should become integral components of future educational programmes.

Continuous professional development will also be essential to enable the existing workforce to adapt to rapidly evolving industrial technologies and sustainability requirements.

10.4 Recommendations for Policymakers

Public policies should continue to recognise industrial biotechnology as a strategic pillar of

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Europe's green and digital transition. Stable regulatory frameworks, long-term research funding, and targeted innovation instruments are needed to accelerate industrial deployment of biotechnology-based solutions.

Support should be provided for pilot plants, demonstration facilities, technology transfer centres, and collaborative innovation platforms connecting academia with industry. Regulatory procedures for novel bio-based products should be streamlined while maintaining high standards for environmental protection and product safety.

Policymakers should also promote sustainable public procurement, bio-based product certification, circular manufacturing, and industrial symbiosis. Dedicated support mechanisms for SMEs—including innovation vouchers, technology transfer programmes, and specialised advisory services—will further strengthen regional bioeconomies and increase industrial competitiveness.

10.5 Future Outlook

Industrial biotechnology is expected to become a major component of sustainable manufacturing over the coming decades. Advances in enzyme and metabolic engineering, precision fermentation, fungal biotechnology, lignocellulosic fractionation, biological recycling, synthetic biology, and data-driven process control will support increasingly efficient production of materials, chemicals, fibres, additives, and functional products from renewable resources.

Future progress is likely to follow several parallel pathways rather than a single dominant technology. Integrated biorefineries can supply cellulose, lignin, platform chemicals, and bioenergy; enzymes can reduce the environmental burden of wood and textile processing; microbial systems can produce pigments, polymers, coatings, and fibres; and fungal technologies can contribute to bioremediation, high-value bioproducts, decorative wood, and biodegradable composites. Mycelium-based materials remain a promising part of this portfolio, particularly for packaging, insulation, interiors, and non-load-bearing components, but further work is required on consistent performance, durability, moisture and fire behaviour, standardisation, and competitive scale-up.

The convergence of biotechnology, materials science, digital manufacturing, and circular economy principles can create resilient industrial ecosystems based on renewable resources and closed-loop value chains. By investing in a balanced portfolio of research, demonstration infrastructure, standards, education, and market-support measures, Europe can accelerate sustainable bio-based manufacturing while contributing to the European Green Deal, the Bioeconomy Strategy, and the transition towards a competitive, circular, and climate-neutral economy.

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