D6.4

Feasibility Study on Value Chain Interconnection

BBTWINS
Agri-Food Value Chain Digitalisation for Resource Efficiency

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1. Introduction

The agri-food sector is undergoing a profound transformation, driven by increasing global demand, climate change challenges, supply chain disruptions, and the pressing need for sustainability. Digitalization has emerged as a critical enabler in addressing these challenges, leveraging technologies such as artificial intelligence (AI), the Internet of Things (IoT), blockchain, and Digital Twin systems. These innovations enhance operational efficiency, improve traceability, and support data-driven decision-making across agricultural value chains. Among these technologies, Digital Twins are revolutionizing the sector by creating real-time virtual representations of physical assets. This capability enables continuous monitoring, predictive analytics, and optimization of complex agricultural processes. While industries such as manufacturing and healthcare have successfully integrated Digital Twins, the agri-food sector is still in the early stages of adoption, facing hurdles such as high implementation costs, data standardization challenges, and the need for sector-specific customization. Overcoming these obstacles is essential to unlocking the full potential of digitalization in agriculture.

The BBTWINS project, funded under the Horizon 2020 Bio-Based Industries Joint Undertaking (BBI JU), seeks to accelerate the adoption of digital technologies in agri-food value chains. By integrating sensorization, data-driven analytics, blockchain traceability, and digital twin applications, BBTWINS provides innovative solutions for two real-world use cases: PORTESA (pig farming) and DIMITRA (peach production). These use cases demonstrate how digital transformation can optimize resource efficiency, enhance product traceability, and improve supply chain resilience. Beyond enhancing efficiency within existing agri-food value chains, the project also explores the interconnection between different bio-based sectors to create new, circular, and resource-efficient value chains. By leveraging digital tools to bridge agriculture, bio-processing, and waste valorization, BBTWINS contributes to the broader bioeconomy transition. This deliverable focuses on the sectoral interconnections that enable the creation of new bio-based value chains, facilitating the efficient utilization of agricultural by-products and waste streams to develop high-value bio-based products.

The digital transformation of the agri-food sector is not just an opportunity but a necessity. By integrating Digital Twin technology, blockchain traceability, and Data/AI-driven analytics, the BBTWINS project paves the way for a more efficient, transparent, and sustainable agricultural future. This deliverable highlights the importance of sectoral interconnections in developing new bio-based value chains, demonstrating how digital innovations can enhance resource efficiency and circularity across industries.

1.1. Executive Summary

This deliverable provides a comprehensive feasibility study on the interconnection of bio-based value chains, with a particular focus on how digital technologies can enable cross-sectoral integration. It expands upon previous BBTWINS outputs by assessing how innovations such as Digital Twins, AI, IoT, and blockchain can not only optimize individual agrifood processes but also foster synergies across agriculture, energy, waste valorization, and bioprocessing sectors.

Drawing from the project's two real-world use cases—PORTESA (meat value chain) and DIMITRA (fruit value chain)—the report illustrates how bio-based by-products like manure, pruning waste, and animal residues can be transformed into high-value outputs such as biogas, hydroxyapatite, polyphenols, keratin, and collagen. It evaluates the technical and economic viability of these transformations, identifying which processes are market-ready and which require further development or policy support.

This expanded analysis includes:

- **A mapping of potential interconnections** between different sectors, highlighting points of integration where waste streams from one value chain become inputs for another.
- **Economic evaluations** of selected bio-based processes, including IRR, NPV, and payback periods, to guide investment strategies.
- **Policy and regulatory analysis**, identifying key EU-level barriers and enablers (e.g., Regulation 1069/2009, RED II, Fertilizing Products Regulation).
- **Strategic recommendations** for scaling digitalization in the bioeconomy, with emphasis on replicability, workforce needs, and the role of regional bio-hubs.

The document is structured to provide actionable insights for multiple stakeholders—industry actors, policymakers, and R&D teams—interested in advancing circular bioeconomy models. It serves as a key reference point within the BBTWINS project for understanding how digitalization supports sectoral coupling, and how such interconnections can unlock new value streams while improving sustainability.

1.2. Structure

This deliverable is structured to provide a comprehensive analysis of sectoral interconnections within bio-based value chains, focusing on the role of digitalization in enhancing resource efficiency, sustainability, and economic viability. The document is divided into five main sections:

1. Bio-Based Value Chains in BBTWINS – Explores the key bio-based innovations introduced by the project, detailing the identified bio-based products, their market potential, and the role of digital technologies in optimizing their production and integration into interconnected value chains.
2. Supply Chain & Market Considerations – Examines the key actors in the bio-based supply chain, the competitive landscape, opportunities for additional income streams, and policy and investment support mechanisms that can facilitate cross-sectoral integration.
3. Cross-Sectoral Interconnections: Big Data & Agrifood – Analyzes the impact of digital technologies such as Digital Twins, AI, IoT, and blockchain on improving decision-making, traceability, and resource efficiency

across interconnected bio-based sectors. Real-world integration cases are presented to illustrate successful implementations.

4. Supporting New Bio-Based Business Models – Discusses how bio-based value chains contribute to the broader bioeconomy, their potential for job creation, and strategies for scaling up digitalized bio-based processes to enhance economic and environmental sustainability.
5. Conclusions and Future Steps – Summarizes the key findings of the deliverable, highlights best practices for enhancing sectoral interconnections, and provides recommendations for future research, policy development, and industrial implementation.

This structured approach ensures that the deliverable presents a logical progression from understanding sectoral challenges to showcasing digital innovations and proposing actionable strategies for integrating bio-based industries into a cohesive and sustainable ecosystem.

1.3. Purpose and Scope

The purpose of this deliverable is to analyze and demonstrate how digital technologies and bio-based value chains can be interconnected across multiple industrial sectors. The BBTWINS project explores the potential for integrating digital twins, blockchain traceability, data-driven analytics, and AI-powered modeling into bio-based industries, fostering synergies between agriculture, energy, and manufacturing. This deliverable specifically focuses on how these cross-sectoral interconnections can enhance efficiency, sustainability, and economic feasibility in bio-based value chains.

The scope of this study includes:

- ✓ Mapping interconnections between agrifood, bioenergy, and biomaterial sectors to assess how digital technologies can optimize resource utilization and value creation.
- ✓ Identifying new bio-based value chains and bio-based materials by analyzing emerging opportunities for transforming agricultural and industrial waste into high-value products.
- ✓ Identifying market opportunities and regulatory challenges associated with integrating bio-based value chains into different industrial ecosystems.
- ✓ Showcasing real-world examples and pilot case studies from BBTWINS and other industry initiatives that highlight the benefits of digitalization in bio-based sectors.

By addressing these key areas, this deliverable aims to provide actionable insights for industry stakeholders, policymakers, and researchers seeking to enhance the integration of bio-based processes with advanced digital tools, ultimately contributing to the transition toward a circular bioeconomy.

1.4. Relationships with other deliverables

This deliverable builds upon and integrates findings from multiple BBTWINS deliverables, particularly those related to feedstock optimization, data management, blockchain traceability, digital twins, and bio-based product development:

- ✓ D1.4 - Characterization of Products and Biomass Processing Chains: Provides a detailed analysis of feedstock properties, including physicochemical and microbiological characterizations of raw materials.
- ✓ D1.5 - Implementation of the Data Lake: Establishes a centralized cloud-based data infrastructure, facilitating seamless data management for all digital tools in the project.
- ✓ D2.4 - Downstream Processes for the BBTWINS Feedstock: Evaluates the purification and transformation of biomass into new bio-based products, such as biogas, collagen, keratin, and polyphenol extracts.
- ✓ D2.5 - Technical Evaluation of Best Methodologies: Assesses and compares the most efficient processing techniques for converting biomass into bio-based materials.
- ✓ D3.2 - Mathematical Modelling of Feedstock for Bio-Based Operations: Develops computational models to optimize feedstock utilization and support decision-making for new bio-based value chains.
- ✓ D4.3 - Deliver a Blockchain Network for Supply Chain Traceability: Implements a blockchain-based traceability system to improve transparency and regulatory compliance across interconnected value chains.
- ✓ D5.1 - Digital Twin and Simulation Framework & D5.2 - Digital Twin Prototype: Define and implement digital twin models to simulate, monitor, and optimize the bio-based value chains identified in this deliverable

By integrating insights from multiple deliverables, this document contributes to enhancing sectoral interconnections in the bio-based industry. It serves as a foundation for scaling up digital and bio-based innovations, ensuring their practical application across different industrial sectors.

2. Bio-based value chains in BBTWINS

2.1. Overview of BBTWINS' Bio-Based Innovations

The BBTWINS project is dedicated to advancing the bio-based economy by leveraging digital twin technologies, machine learning, and AI-driven analytics. The primary focus is on optimizing agricultural and food processing operations through enhanced efficiency and sustainability measures. Two main sectors are addressed within this initiative: the meat production sector (PORTESA value chain) and the fruit processing sector (DIMITRA value chain). Deliverables D2.4 and D2.5 provide comprehensive insights into the methodologies for stabilizing, converting, and purifying bio-based feedstocks derived from meat and fruit production. These processes aim to extract maximum value from residual biomass, thereby reducing waste and promoting a sustainable circular economy.

The core innovations identified in these deliverables encompass several bio-processing techniques designed to enhance value chain sustainability and economic feasibility. These include:

- Anaerobic Digestion for Biogas Production – Utilization of pig manure and wastewater sludge to generate biogas and biomethane.
- Nutrient Recovery from Manure and Sludge – Extraction of phosphorus and nitrogen for use as fertilizers.
- Hydrolysis and Extraction of High-Value Proteins (Keratin & Collagen) – Processing of pig hair and skin into protein hydrolysates.
- Hydroxyapatite Purification from Animal Bones – Recovery of hydroxyapatite from pig bones for biomedical and industrial applications.
- Combustion & Composting of Fruit Residues – Thermal and biological valorization of pruning waste and discarded fruits.
- Extraction of Bioactive Compounds (Polyphenols) from Fruit Waste – Isolation of antioxidants from peach and nectarine processing waste.

Each of these processes contributes significantly to the circular bioeconomy by converting underutilized waste streams into valuable commodities for the energy, agriculture, cosmetics, and biomedical industries.

Biogas Production from Pig Manure & Wastewater

The production of biogas through anaerobic digestion represents a key innovation within BBTWINS. Utilizing a mixture of pig manure, wastewater sludge, and leguminous residues, the estimated yield can reach 19.7 million m^3 of biogas per year. This biogas can be further upgraded into biomethane, which has potential applications in boilers, co-generation systems, and as a transportation fuel. From an economic perspective, the most promising biogas production scenario demonstrates a Net Present Value (NPV) of €24 million, an Internal Rate of Return (IRR) exceeding 15%, and a payback period of approximately 1.2 years, making it a financially viable bio-energy solution.

Nutrient Recovery from Pig Manure

The recovery of phosphorus and nitrogen from pig manure presents an opportunity to create sustainable fertilizers. The extraction process has achieved a phosphorus recovery efficiency of 91%, although nitrogen retention remains a technical challenge. While this method aligns with the principles of a circular economy, economic feasibility remains a concern. High operational costs, coupled with low nutrient concentrations in the raw manure, result in negative cash flows, rendering the process economically unviable under current market conditions.

Hydrolysis and Extraction of Keratin & Collagen from Pig Hair & Skin

The hydrolysis and purification of keratin and collagen from animal by-products present significant industrial potential. Keratin, derived from pig hair, and collagen, extracted from pig skin, are essential components in the cosmetics, biomedical, and food industries.

- Keratin Extraction: The process achieves an impressive yield of 561.8g of keratin hydrolysate per 1kg of pig hair, with a purity level of 94.15%. Economically, this process has strong indicators, with an NPV of €907,940, an IRR of 13.07%, and a payback period of 5.4 years, suggesting that keratin extraction is a viable investment.
- Collagen Extraction: Despite obtaining a yield of 11.6g of hydrolyzed collagen per 1kg of pig skin (96% purity), the economic outlook for collagen extraction is less promising. High operational costs result in negative cash flows, making this process unfeasible under current economic conditions.

Hydroxyapatite Purification from Pig Bones

Hydroxyapatite, a key material in biomedical applications (e.g., bone grafting) and fertilizers, can be efficiently extracted from pig bones through pyrolysis. The optimized method involves pyrolysis at 1200°C, producing hydroxyapatite with 99.7% purity. Economic analysis reveals that this process holds strong investment potential, with an NPV of €1.27 million, an IRR of 65.43%, and a payback period of just 1.5 years. These indicators confirm that hydroxyapatite recovery is a viable and profitable bio-based innovation.

Combustion of Pruning Wastes for Energy

The combustion of peach and nectarine pruning residues provides a renewable biomass fuel alternative for industrial heat generation. This method proves to be highly economically attractive, boasting an NPV of €1.77 million, an IRR of 199.67%, and a payback period of less than one year. Such figures highlight the strong potential of this waste-to-energy solution.

Extraction of Polyphenols from Peach & Nectarine Processing Waste

Polyphenols are valuable bioactive compounds with applications in the nutraceutical and cosmetic industries. The BBTWINS project evaluated two extraction methodologies:

- Ultrasound-Assisted Extraction (UAE) – This approach offers a higher yield and better economic viability, with an NPV of €441,846, an IRR of 17%, and a payback period of 4.7 years.
- Supercritical Fluid Extraction (SFE) – While this method achieves higher purity, it suffers from lower extraction yields and excessive capital and operational costs, making it economically unfeasible.

The bio-based innovations in the BBTWINS project demonstrate strong technical feasibility, with several processes showing excellent economic potential. Biogas production, keratin extraction, hydroxyapatite recovery, and pruning waste combustion stand out as the most promising methodologies, both in terms of financial returns and sustainability impact. However, certain processes, such as phosphorus recovery and collagen extraction, require further optimization or policy incentives to achieve economic feasibility. Through its holistic approach to waste valorization, digitalization, and economic analysis, BBTWINS contributes significantly to the transition toward a sustainable and circular bio-based economy.

2.2. Identified Bio-Based Products and Their Market Potential

The BBTWINS project has identified a range of bio-based products derived from meat and fruit processing waste streams. The transformation of these waste materials into valuable bio-based products aligns with global sustainability goals and circular economy principles. Understanding the market potential of these products is crucial for assessing their economic viability and guiding strategic investment decisions. Recent market analyses suggest that bio-based industries, particularly those linked to renewable energy, agriculture, cosmetics, and biomedical applications, are experiencing strong growth. The increasing demand for sustainable alternatives to fossil-based products, coupled with government incentives for renewable energy and sustainable agriculture, further enhances the prospects of these bio-based innovations.

The table below summarizes the identified bio-based products, their sources, key applications, and projected market potential based on recent industry data:

Table 1: Identified bio-based products from the examined BBTWINS use cases [1–3]

Bio-Based Product	Source Material	Applications	Market Potential
Biogas/Biomethane	Pig manure, wastewater sludge, leguminous residues	Renewable energy for heating, electricity, and transportation	Global biogas market projected to reach **$87.86 billion by 2030**, with a CAGR of **4.3%**
Organic Fertilizers	Recovered phosphorus and nitrogen from pig manure	Sustainable agriculture as soil amendments	Expected to grow to **$15.7 billion by 2030**, with a CAGR of **4.3%**
Keratin Hydrolysates	Pig hair	Cosmetics (hair and skin care products), biomedical applications (wound healing)	Increasing demand in personal care and biomedical sectors; positive market outlook.
Collagen Hydrolysates	Pig skin	Nutraceuticals, food supplements, cosmetics	Projected to be valued at **$7.5 billion by 2027**, with a CAGR of **5.9%**
Hydroxyapatite	Pig bones	Biomedical applications (bone grafts, dental implants), fertilizers	Expected to reach **$3.3 billion by 2028**, with a CAGR of **5.8%**
Biochar	Pruning wastes from fruit trees	Soil conditioner, carbon sequestration, water treatment	Projected to grow to **$5.91 billion by 2033**, with a CAGR of **12%**
Polyphenol Extracts	Peach and nectarine processing waste	Dietary supplements, functional foods, cosmetics	Expected to reach **$2.9 billion by 2026**, with a CAGR of **7.2%**

Biogas/Biomethane

Biogas derived from pig manure, wastewater sludge, and leguminous residues plays a crucial role in the transition toward renewable energy sources. The market for biogas is expected to grow significantly, driven by policies promoting sustainable energy and carbon neutrality. With an estimated market value of $87.86 billion by 2030, biogas production presents a promising avenue for the bioeconomy. The European Union and North America remain leading regions due to strong regulatory frameworks supporting biogas integration into national grids.

Organic Fertilizers

The recovery of phosphorus and nitrogen from manure for use as organic fertilizers aligns with the increasing shift toward sustainable agriculture. The global market for organic fertilizers is projected to reach $15.7 billion by 2030, fueled by the rising demand for organic food and eco-friendly soil management practices. However, economic feasibility remains a challenge due to processing costs and the competitive pricing of synthetic fertilizers.

Keratin and Collagen Hydrolysates

Keratin and collagen hydrolysates, derived from pig hair and skin, respectively, have significant industrial applications. While keratin is highly valued in the cosmetics industry for hair and skin treatments, collagen is widely used in nutraceuticals and biomedical applications. The collagen market is projected to reach $7.5 billion by 2027, growing at a CAGR of 5.9%, demonstrating strong demand in health and wellness industries. However, the economic feasibility of collagen extraction depends on production efficiency and market pricing strategies.

Hydroxyapatite

Hydroxyapatite, a key material for bone grafting and dental applications, is experiencing increasing demand due to the growth of the medical implant industry. The market for hydroxyapatite is expected to reach $3.3 billion by 2028, with biomedical applications driving its expansion. The primary challenge in commercialization is maintaining high purity standards while ensuring cost-effective processing.

Biochar

Biochar, produced from fruit pruning waste, has multiple applications in soil enhancement and carbon sequestration. The biochar market is anticipated to grow significantly, reaching $5.91 billion by 2033, with a CAGR of 12%. The demand is fueled by carbon credit markets and the need for sustainable soil amendments. Policy support and advancements in biochar production technology will be key enablers of market growth.

Polyphenol Extracts

Polyphenols extracted from fruit processing waste have gained attention for their antioxidant properties, particularly in the health and wellness sectors. The global polyphenol market is projected to be valued at $2.9 billion by 2026, with a CAGR of 7.2%. The increasing consumer demand for functional foods and natural dietary supplements supports this growth. However, the high cost of extraction technologies such as Supercritical Fluid Extraction (SFE) presents a barrier to economic scalability. The bio-based products identified within the BBTWINS project offer promising market potential, with several products demonstrating strong economic viability. The most lucrative opportunities exist in biogas production, collagen extraction, hydroxyapatite recovery, and biochar production due to their established and expanding markets. However, the success of these bio-based products will depend on overcoming technical and economic challenges, optimizing production costs, and leveraging policy incentives.

Future research should focus on improving processing efficiencies, developing cost-effective purification techniques, and fostering collaborations with industries that can integrate these bio-based products into commercial applications. By addressing these aspects, the BBTWINS project can contribute to a robust and sustainable bioeconomy while enhancing resource efficiency across agricultural and industrial sectors.

2.3. Market & Regulatory Barriers to Value Chain Development

The successful development and commercialization of bio-based value chains depend not only on technological feasibility and market potential but also on overcoming key market and regulatory barriers. While bio-based industries present promising opportunities for sustainability and economic growth, multiple challenges hinder their large-scale adoption and competitiveness in existing markets. The primary barriers can be categorized into economic constraints, regulatory frameworks, technological limitations, market competition, and policy gaps. This section provides an in-depth analysis of these barriers and their impact on the BBTWINS bio-based products.

Key Market Barriers

1. High Production Costs and Economic Viability

One of the most significant barriers to bio-based product development is the high cost of production and purification processes. Compared to conventional fossil-based or synthetic alternatives, bio-based solutions often require specialized extraction, conversion, and stabilization techniques, leading to increased capital and operational expenses. For example:

- Biogas and Biomethane: While biogas has strong market potential, upgrading biogas to biomethane for grid injection requires costly gas purification infrastructure and regulatory compliance with gas quality standards.
- Hydroxyapatite from Pig Bones: Achieving high purity for medical-grade hydroxyapatite requires expensive pyrolysis and post-processing steps.
- Polyphenol Extraction: Technologies such as Supercritical Fluid Extraction (SFE) have high investment costs, making them economically unviable compared to synthetic alternatives.

To address these economic challenges, scaling production, optimizing processes, and accessing financial incentives will be crucial.

2. Market Acceptance and Competition with Conventional Products

Despite the sustainability benefits of bio-based products, market competition with well-established synthetic alternatives poses a challenge. Consumers and industries often favor conventional materials due to lower costs, established supply chains, and consistent quality.

- Organic Fertilizers vs. Synthetic Fertilizers: Farmers often prefer synthetic fertilizers due to predictable nutrient compositions, longer shelf life, and cost-effectiveness.
- Biochar vs. Traditional Soil Amendments: Biochar competes with widely available composts, synthetic fertilizers, and traditional soil amendments.
- Bioplastics and Bio-based Materials: Adoption remains slow due to higher production costs and concerns over performance compared to petroleum-based materials.

Effective market awareness campaigns, incentives for bio-based purchasing, and stronger sustainability regulations will be necessary to drive consumer and industry adoption.

3. Supply Chain and Logistics Challenges

Many bio-based value chains depend on agricultural and industrial waste streams, requiring well-developed logistics, collection, and processing networks. However, fragmented supply chains and seasonal biomass availability create hurdles for consistent production.

- Biogas Feedstock Availability: The availability of manure and agricultural residues fluctuates seasonally, affecting continuous biogas production.
- Pruning Waste for Biochar: Collection and processing require regional coordination with farmers and investments in biomass densification and transport infrastructure.
- Collagen and Keratin from Animal By-Products: Processing requires specialized slaughterhouse partnerships, which may not always align with industrial demand.

Developing regional bio-based hubs and investment in infrastructure will be essential to overcoming supply chain inefficiencies.

Regulatory Barriers

4. Strict EU Animal By-Product Regulations (Regulation 1069/2009)

Animal-derived bio-based products, such as keratin, collagen, and hydroxyapatite, are subject to Regulation 1069/2009, which imposes stringent requirements on processing, sterilization, and traceability.

- Keratin and Collagen Extraction: Must meet strict hygiene and sterilization protocols before being approved for cosmetic or food applications.
- Hydroxyapatite for Medical Use: Requires compliance with European Medicines Agency (EMA) standards for biocompatibility and purity.

These regulatory hurdles increase compliance costs and delay commercialization, requiring companies to invest in certification and regulatory approvals.

5. EU Fertilizing Product Regulations (2019/1009)

The EU Fertilizing Product Regulation (2019/1009) governs organic fertilizers and soil amendments, including biochar and phosphorus recovery products.

- Biochar Classification: Biochar must meet stringent heavy metal and contaminant limits to qualify as an approved soil amendment.
- Phosphorus recovered from Manure: Fertilizer products derived from manure must comply with nutrient balance requirements, limiting their widespread agricultural use.

These regulatory requirements increase testing and compliance costs, making it difficult for small-scale bio-based companies to compete with established fertilizer manufacturers.

6. Renewable Energy Directive (RED II) and Gas Grid Injection Standards

While biogas and biomethane hold strong potential, their integration into national energy systems faces regulatory and infrastructure challenges under the Renewable Energy Directive (RED II) and gas grid injection standards.

- Biomethane Grid Injection: Requires compliance with gas purity, calorific value, and sustainability certification, which adds financial and operational burdens.
- Subsidy and Incentive Variability: Many biogas projects depend on government incentives, feed-in tariffs, and carbon credit schemes, which vary across EU member states, creating uncertainty in investment returns.

To encourage biogas adoption, policy harmonization and long-term subsidy frameworks are needed.

Policy Recommendations and Investment Support

To overcome these market and regulatory barriers, targeted policy measures and investment support are necessary. Key recommendations include:

- Financial Incentives for Bio-Based Startups: EU and national governments should expand grant programs, low-interest loans, and tax benefits for bio-based industries.
- Standardized EU Regulations for Bio-Based Products: Streamlining approval processes for biochar, hydroxyapatite, and organic fertilizers will help accelerate commercialization.
- Infrastructure Investment for Biomass Processing: Developing bio-based industrial parks and regional processing hubs will improve supply chain efficiency.
- Consumer Awareness and Green Procurement Policies: Governments and industries should promote bio-based product adoption through green public procurement and eco-labeling initiatives.

The development of bio-based value chains faces economic, regulatory, logistical, and market challenges that must be addressed to ensure long-term viability. High production costs, regulatory complexities, and supply chain limitations remain key hurdles. However, policy support, technological advancements, and industry collaboration can help mitigate these barriers and accelerate the transition toward a sustainable bioeconomy. By addressing these challenges through targeted investments, streamlined regulations, and market-driven policies, BBTWINS and similar initiatives can drive the large-scale adoption of bio-based products, contributing to both economic growth and environmental sustainability.

3. Supply Chain & Market Considerations

3.1. Key Actors in the Bio-Based Supply Chain

The development of bio-based value chains relies on a complex network of stakeholders that coordinate across multiple stages, from raw material collection to the final commercialization of bio-based products. These stakeholders include feedstock suppliers, processing industries, technology providers, logistics and distribution networks, policymakers, and end-market consumers. The seamless integration of these actors is essential to achieving sustainability and economic viability in bio-based sectors. At the initial stage of the supply chain, feedstock suppliers provide the raw materials necessary for bio-based production. In the case of the BBTWINS project, this involves agricultural producers and meat and fruit processing industries. The PORTESA value chain, focused on the meat industry, supplies pig manure, wastewater sludge, bones, skins, and hair, while the DIMITRA value chain processes fruit waste, including pruning residues and discarded fruits (BBTWINS, 2023). The availability, quality, and seasonal fluctuations of feedstock influence the stability and cost-efficiency of the supply chain, making strategic sourcing and storage solutions critical. Additionally, regulatory constraints such as EU Animal By-Product Regulations (1069/2009) affect the transportation and processing of these raw materials.

Once collected, feedstock moves to processing industries, where raw biomass is converted into marketable bio-based products. This transformation occurs through anaerobic digestion, hydrolysis, pyrolysis, extraction, and chemical purification. The success of bio-based processing depends on technological advancements, cost-effectiveness, and environmental compliance. In BBTWINS, biogas plants utilize pig manure for methane production, hydroxyapatite is extracted from bones for biomedical applications, and ultrasound-assisted extraction (UAE) is employed to recover high-value polyphenols from fruit waste. The efficiency of these processes is crucial for maintaining competitive pricing and securing industrial partnerships. Another critical group in the supply chain is technology providers, who supply bioreactors, digital monitoring systems, AI-driven analytics, and blockchain-based traceability solutions. Emerging innovations, such as digital twins and machine learning algorithms, enhance process optimization and resource efficiency, reducing costs and waste generation. As the bioeconomy evolves, the role of technology providers will continue to expand, especially in integrating automated process control and predictive maintenance solutions.

The logistics and distribution sector plays a vital role in ensuring the movement of both raw materials and finished products. Biomass logistics pose unique challenges, particularly due to high moisture content, low bulk density, and perishability. For instance, transporting pig manure for biogas production requires specialized containment systems, while fruit residues must be dried or stabilized before processing. Solutions such as regional bio-hubs and decentralized processing plants help mitigate transportation inefficiencies and reduce costs [4].

At the regulatory and policy level, government bodies, financial institutions, and research organizations provide the framework necessary for the sustainable expansion of bio-based value chains. Funding mechanisms such as Horizon 2020 and the Bio-Based Industries Joint Undertaking (BBI JU) provide grants and financial incentives to bio-based startups, reducing initial capital investment risks (EU BBI JU, 2023). Without policy backing and market incentives, many bio-based industries struggle to compete against fossil-based incumbents.

Ultimately, the bio-based supply chain is highly interdependent, requiring strong collaboration among stakeholders to overcome logistical, economic, and technological challenges. As regulatory frameworks evolve and market demand increases, enhanced coordination, investment in technology, and streamlined logistics will be key to unlocking the full potential of bio-based industries.

3.2. Competitive Landscape: Who Are the Players?

The bio-based sector operates within a competitive and evolving landscape, where established industries, emerging bio-tech firms, and regulatory bodies shape market dynamics. While fossil-based and synthetic products still dominate many industrial applications, the growing emphasis on decarbonization and sustainability has fueled interest in bio-based alternatives. Competition within the bioeconomy is largely driven by cost efficiency, regulatory compliance, technological innovation, and consumer acceptance.

In the biogas sector, large energy corporations such as ENGIE, Veolia, and Nature Energy have developed extensive anaerobic digestion infrastructures to convert livestock manure, wastewater sludge, and organic waste into biomethane. The European biogas market is projected to reach €87.86 billion by 2030, with Germany, France, and Italy leading in biomethane production capacity [2]. The success of biogas initiatives depends on feedstock availability, government incentives, and infrastructure for gas grid injection [5]. In the organic fertilizer industry, companies like Yara, Nutrien, and Biolan dominate, supplying synthetic and organic fertilizers to agricultural markets. The recovered phosphorus and nitrogen fertilizers produced through BBTWINS nutrient recovery technologies face cost disadvantages compared to conventional fertilizers. However, increasing EU restrictions on synthetic fertilizers and the Fertilizing Product Regulation (2019/1009) create market opportunities for sustainable alternatives [6].

In specialty biochemicals, companies such as Evonik, Croda, and BASF compete in keratin and collagen extraction, supplying the cosmetics, food supplement, and biomedical industries. BBTWINS' keratin hydrolysate extraction from pig hair shows strong economic potential, with an NPV of €907,940 and IRR of 13.07%, while collagen extraction remains less viable due to high costs. Competitive positioning in this market depends on product purity, production scalability, and integration with existing supply chains. The biochar market, which utilizes fruit pruning residues for carbon sequestration and soil conditioning, is growing, with companies like AirTerra, Carbon Gold, and Swiss Biochar leading innovation. The global biochar market is projected to reach €5.91 billion by 2033, with EU policies supporting its use as a carbon-negative agricultural input [1].

Overall, the bio-based industry is gaining competitiveness, but success depends on reducing costs, improving product standardization, and securing policy incentives to compete with traditional materials.

3.3. Challenges & Opportunities for Additional Income Streams

The bio-based sector presents both economic barriers and new revenue opportunities, requiring strategic approaches to maximize profitability. While bio-based solutions align with circular economy principles, they face high processing costs, market competition, and supply chain inefficiencies. However, opportunities for additional income streams exist through by-product valorization, carbon credit schemes, policy-driven incentives, and market diversification.

Challenges in Generating Additional Revenue

One of the primary economic challenges in bio-based value chains is high operational costs, which often make bio-based alternatives less competitive than fossil-based or synthetic counterparts. Many bio-based products require energy-intensive extraction, stabilization, and purification processes, significantly impacting profit margins. For example, supercritical fluid extraction (SFE) of polyphenols provides high-purity bioactive compounds but is capital-intensive, making it less economically viable compared to solvent-based extraction methods. Similarly, collagen extraction from pig skin currently struggles with negative cash flows, as processing costs outweigh market returns. Additionally, market competition with conventional products presents a major hurdle. Despite their sustainability advantages, bio-based solutions must compete with well-established synthetic alternatives that benefit from lower production costs and existing supply chains. For instance, synthetic fertilizers outperform organic fertilizers in terms of cost-effectiveness and nutrient concentration, making adoption among farmers slower. Similarly, biochar from fruit pruning residues competes with commercial soil amendments, requiring stronger market incentives for widespread use [4]. Supply chain inefficiencies further hinder revenue generation. Unlike fossil-based industries, which operate on highly optimized logistics networks, bio-based industries face feedstock collection challenges, seasonal fluctuations, and transportation costs. For example, biomass transportation for biogas production is expensive due to high moisture content, making regional bio-refineries necessary to reduce logistics expenses and stabilize input supply [5].

Opportunities for Additional Income Streams

Despite these challenges, several revenue-enhancing opportunities exist within the bio-based industry. One of the most effective strategies is by-product valorization, where multiple revenue streams are generated from a single feedstock source. For instance, in BBTWINS' biogas production, anaerobic digestion generates both biomethane and digestate, with the latter being sold as an organic fertilizer, enhancing overall project profitability. Similarly, hydroxyapatite from pig bones can serve both the biomedical and fertilizer industries, diversifying market applications (BBTWINS D2.4, 2023). Another significant opportunity lies in carbon credit trading and emissions reduction incentives. Under the EU Emissions Trading System (ETS) and voluntary carbon markets, bio-based industries can monetize greenhouse gas (GHG) reductions by selling carbon offsets. For example, biogas and biomethane production qualify for carbon credit sales, as methane capture and its conversion into energy displace fossil fuels. The EU carbon market currently values CO_2 reductions at approximately €85 per metric ton, providing a new revenue stream for biomethane producers [7].

Moreover, market diversification into high-value sectors creates new income streams. Bio-based products can be applied across renewable energy, agriculture, pharmaceuticals, nutraceuticals, and cosmetics. For example, keratin hydrolysates from animal by-products have applications in cosmetics (hair and skin care), biomedical (wound healing, tissue engineering), and dietary supplements. Similarly, polyphenols extracted from fruit waste are in demand in functional food and cosmetic formulations, expanding the potential consumer base. Additionally, public-private partnerships (PPP) and EU policy incentives provide funding for bio-based start-ups and pilot projects, helping reduce financial risks associated with new revenue models. The EU Innovation Fund, Horizon Europe, and the Bio-Based Industries Joint Undertaking (BBI JU) allocate billions in funding to biomass processing, waste valorization, and industrial-scale production of bio-based alternatives, providing financial stability for market entrants.

The following SWOT analysis deepens in the key factors affecting additional income generation.

Strengths (Internal Advantages)

- ✓ Circular Economy Benefits – Bio-based industries align with sustainability goals by utilizing waste streams (e.g., pig manure, fruit residues) and converting them into multiple high-value products, increasing revenue potential.
- ✓ Diverse Market Applications – Bio-based products such as keratin, collagen, polyphenols, and hydroxyapatite can be applied in cosmetics, nutraceuticals, agriculture, and biomedical sectors, creating multiple revenue streams.
- ✓ Regulatory Push for Sustainability – EU and global sustainability regulations promote biogas, biomethane, organic fertilizers, and bio-based materials, stimulating market demand through carbon reduction policies.
- ✓ Carbon Credit Potential – Biogas and biomethane projects can sell carbon credits, with CO_2 reduction valued at ~€85 per metric ton, providing additional financial incentives for GHG reduction efforts.

Weaknesses (Internal Disadvantages)

- ✓ High Processing Costs – Energy-intensive processes (e.g., polyphenol extraction, collagen hydrolysis, biomethane upgrading) reduce profitability, making bio-based alternatives less competitive than fossil-based counterparts.
- ✓ Supply Chain Inefficiencies – Biomass feedstock collection, seasonal fluctuations, and high transportation costs create logistical challenges for large-scale bio-based production.
- ✓ Market Acceptance & Consumer Preferences – Bio-based alternatives must compete with established synthetic products, requiring stronger policy incentives and marketing strategies to drive adoption.
- ✓ Regulatory Compliance Costs – EU regulations on animal by-products, biomethane injection, and organic fertilizers impose strict processing and certification requirements, increasing operational expenses.

Opportunities (External Market Potential)

- ✓ By-Product Valorization – Multiple co-products from bio-based processing (biomethane + digestate, polyphenols + dietary supplements, keratin + collagen) increase revenue streams and profitability.

- ✓ Carbon Trading & Emission Reductions – Bio-based industries can monetize carbon reductions through ETS markets, providing new income sources for biogas, biochar, and biomethane production.
- ✓ Expanding Circular Economy Markets – Growing demand for renewable materials, organic fertilizers, and biodegradable products increases investment opportunities in the bioeconomy.
- ✓ Public & Private Sector Investment Growth – EU funding programs (e.g., BBI JU, Horizon Europe, Innovation Fund) offer billions in grants and low-interest loans for bio-based projects.

Threats (External Market Risks)

- ✓ Volatile Carbon Credit Prices – Carbon credit values fluctuate, creating uncertainty in revenue projections for bio-based industries dependent on ETS schemes.
- ✓ Fossil-Based & Synthetic Competition – Oil-based and synthetic alternatives remain cheaper due to economies of scale, challenging bio-based market penetration.
- ✓ Regulatory Uncertainty & Policy Gaps – Inconsistent regulations across EU member states affect biomethane subsidies, fertilizer classifications, and biochar approvals, leading to investment risks.
- ✓ Limited Consumer Awareness & Adoption Rates – Despite sustainability benefits, bio-based products require education campaigns and stronger branding strategies to compete with mainstream alternatives.

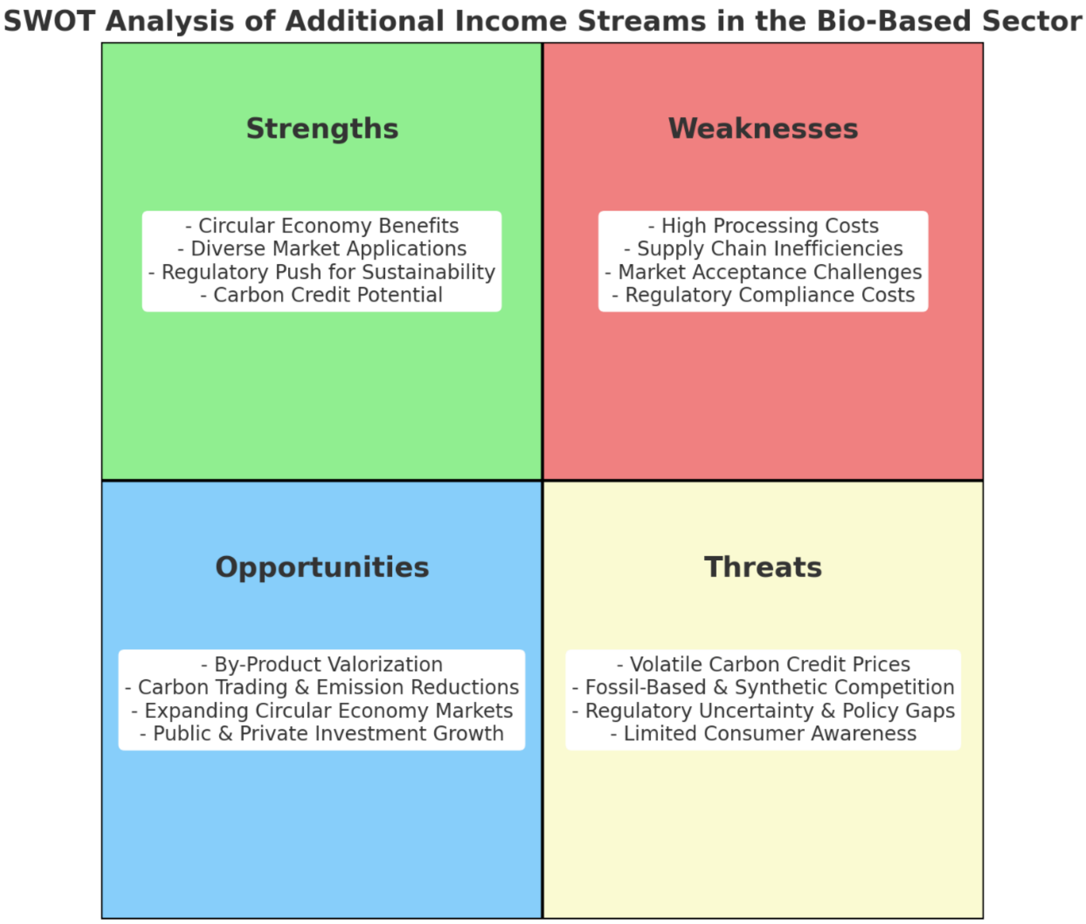

Figure 1: SWOT analysis of key factors affecting additional income generation

3.4. Policy & Investment Support for Bio-Based Sectors

The growth of bio-based industries depends heavily on policy frameworks, financial incentives, and investment support mechanisms that drive innovation, infrastructure development, and market adoption. Governments and international organizations provide funding through research grants, tax incentives, and infrastructure investments, reducing financial risks and fostering a competitive bio-based economy. At the European level, the EU Green Deal, the Circular Economy Action Plan, and the Renewable Energy Directive promote bio-based solutions as key drivers of climate neutrality and sustainable industrial transformation. The Fertilizing Product Regulation (2019/1009) facilitates the commercialization of organic fertilizers and biochar, while EU waste directives encourage the valorization of residual biomass into high-value products.

In the energy sector, RED II provides subsidies and feed-in tariffs for biomethane production, making biogas plants economically viable. However, challenges remain regarding gas grid injection regulations, cross-border certification, and varying incentives across EU member states. Standardizing biomethane subsidy schemes will be essential for ensuring long-term investment stability [8]. Additionally, EU animal by-product regulations (1069/2009) impose stringent sterilization and traceability requirements on keratin, collagen, and hydroxyapatite processing, increasing compliance costs. Policy reforms to streamline approval processes could enhance the commercialization of these bio-based products.

Key Investment & Funding Programs for Bio-Based Projects

The European Union provides significant funding for bio-based initiatives through programs such as Horizon Europe, the Innovation Fund, and the Bio-Based Industries Joint Undertaking (BBI JU). These financial instruments aim to de-risk investments, fund pilot projects, and accelerate commercialization.

- ✓ Horizon Europe (2021–2027) – The EU's flagship R&D program allocates €95.5 billion, with a strong focus on bioeconomy research, industrial decarbonization, and sustainable processing technologies. Specific calls under Cluster 6 (Food, Bioeconomy, Natural Resources, Agriculture, and Environment) fund projects related to biogas upgrading, biochar production, and biochemical extraction technologies.
- ✓ The Bio-Based Industries Joint Undertaking (BBI JU) – With a budget of €3.7 billion, this public-private partnership supports industrial-scale bio-refineries and circular economy projects. Successful BBI JU projects have demonstrated the financial viability of bio-based feedstock conversion into high-value chemicals and materials (EU BBI JU, 2023).
- ✓ The EU Innovation Fund – Focused on low-carbon technologies and industrial decarbonization, this fund provides €10 billion for carbon capture, waste-to-energy conversion, and bio-based material innovation. Bio-based companies can secure grants covering up to 60% of capital and operational costs, reducing the financial burden of scaling up new technologies.
- ✓ The LIFE Programme – With €5.4 billion allocated between 2021–2027, LIFE supports circular economy and waste valorization initiatives, including biomethane recovery, nutrient recycling, and biochar applications.

To accelerate bio-based industry growth, policy reforms should focus on standardizing subsidy frameworks, streamlining regulatory approvals, and expanding investment in bio-processing infrastructure. Additionally, increased financial support for digitalization and automation in bio-based industries could enhance efficiency and market competitiveness. Strategic investments in regional bio-refineries, cross-border carbon markets, and sustainable logistics networks will be key to unlocking the full economic potential of the bioeconomy. As global demand for circular bio-based solutions grows, leveraging EU policy frameworks, funding instruments, and private-sector partnerships will be essential for ensuring a scalable, profitable, and sustainable bio-based future.

4. Cross-Sectoral Interconnections: Big Data & Agrifood

4.1. Role of Digital Technologies in Agrifood

The agrifood industry is undergoing a fundamental transformation driven by digital technologies that enhance efficiency, traceability, sustainability, and economic viability. With global challenges such as climate change, food security, and resource depletion, digital innovations offer a data-driven approach to optimize agricultural productivity, improve waste management, and create a transparent supply chain. Key technologies including Artificial Intelligence (AI), Internet of Things (IoT), blockchain, and Digital Twins have become essential in modern agrifood systems, enabling precision in farming, processing, logistics, and distribution.

AI-driven solutions play a crucial role in predictive analytics, helping farmers and food processors make data-informed decisions. Machine learning algorithms can analyze weather patterns, crop health, and soil conditions to determine the optimal time for planting, watering, and harvesting. In livestock farming, AI-based monitoring systems track animal behavior, weight gain, and potential disease outbreaks, allowing early intervention to minimize losses. AI is also instrumental in food processing plants, where it enhances quality control through automated visual inspection systems, identifying defects in meat, fruits, and packaged products, reducing food waste, and ensuring high product standards.

The Internet of Things (IoT) further strengthens agrifood value chains by enabling real-time monitoring of agricultural and food production environments. IoT sensors measure soil moisture levels, temperature, humidity, and nutrient composition, providing farmers with precise data for irrigation and fertilization. This reduces water consumption and improves yield quality. In food processing, IoT devices track cold chain logistics, ensuring that perishable products maintain optimal storage temperatures throughout the supply chain. Smart sensors embedded in processing equipment detect machine wear and tear, enabling predictive maintenance that minimizes downtime and operational costs.

A major challenge in agrifood is supply chain transparency, particularly in tracing product origins and ensuring compliance with safety and sustainability regulations. Blockchain technology addresses this challenge by providing an immutable, decentralized ledger that records every stage of production, processing, and distribution. This improves food safety by enabling rapid recalls of contaminated products, reduces fraud in organic and fair-trade certifications, and builds consumer trust by allowing end-users to verify product origins via QR codes or mobile applications. The BBTWINS project integrates Digital Twin technology with these innovations, offering a virtual simulation environment that replicates the entire biomass processing chain, from raw material sourcing to final product optimization. The digital twin approach allows stakeholders to test different processing scenarios, evaluate economic and environmental impacts, and optimize production processes before implementation, reducing waste and increasing efficiency. Through the integration of AI, IoT, blockchain, and Digital Twins, the agrifood industry is not only enhancing productivity but also ensuring a sustainable and resilient future.

4.2. BBTWINS Digital Twin Platform

The BBTWINS Digital Twin Platform is an advanced digital infrastructure designed to integrate real-time data analytics, AI-powered optimization, and blockchain-based traceability across the agrifood supply chain. By creating a dynamic digital replica of biomass processing operations, the platform enables simulation-driven decision-making, predictive maintenance, and improved resource utilization. The platform is built on a cloud-based Data Lake architecture, hosted on AWS, ensuring scalability, real-time processing, and secure data management.

The Digital Twin Platform is structured to support two major value chains within BBTWINS:

- ✓ Meat Processing (PORTESA Value Chain): The platform integrates feed production, livestock monitoring, slaughterhouse operations, waste valorization, and biogas production. It provides real-time data on feed efficiency, animal health, and slaughter yields, helping producers optimize processing capacity and by-product utilization. Through AI-driven analytics, the system identifies waste-to-energy opportunities, ensuring that organic waste from meat processing is efficiently converted into biogas, hydroxyapatite, and organic fertilizers.
- ✓ Fruit Processing (DIMITRA Value Chain): The digital twin monitors fruit sorting, cold storage efficiency, secondary product recovery, and supply chain logistics. AI algorithms analyze harvest timing, storage conditions, and processing efficiency, minimizing post-harvest losses. The platform also simulates alternative by-product valorization methods, such as polyphenol extraction and biochar production from pruning waste, allowing producers to identify the most profitable and sustainable processing strategies.

The BBTWINS Digital Twin is powered by the NORLEAN NOA platform, a high-performance simulation engine that enables real-time visualization of biomass flow, energy consumption, and economic returns. The system integrates data from IoT sensors, AI-based predictive models, and blockchain traceability records, providing comprehensive oversight of the bio-based production lifecycle. With the ability to predict bottlenecks, reduce operational costs, and optimize processing efficiency, the Digital Twin Platform represents a cutting-edge solution for improving sustainability in agrifood value chains.

4.3. Blockchain for Supply Chain Traceability

Blockchain technology is revolutionizing agrifood supply chains by providing unparalleled transparency, security, and compliance verification. The BBTWINS blockchain platform, developed using Hyperledger Fabric, enables decentralized tracking of biomass processing and product distribution, ensuring that all transactions and data points are tamper-proof and verifiable.

The blockchain framework consists of three key layers:

- ✓ Data Collection Layer – IoT-enabled sensors and ERP systems automatically record production parameters, feedstock sourcing data, and transport details, ensuring real-time accuracy.
- ✓ Verification & Smart Contracts Layer – Blockchain-based smart contracts automate regulatory compliance, ensuring that only certified, traceable biomass enters the supply chain.
- ✓ Consumer Access Layer – End-users, retailers, and regulators can trace product origins, quality control measures, and sustainability certifications, improving transparency and trust in bio-based products.

For the meat processing sector, blockchain ensures compliance with EU Animal By-Product Regulations (1069/2009) by securely recording processing conditions, nutrient recovery efficiency, and transportation protocols. This minimizes fraud risks, improves waste management, and strengthens food safety standards. In the fruit processing sector, blockchain captures pesticide usage records, cold storage conditions, and processing workflows, ensuring full traceability from orchard to consumer. The integration of blockchain with Digital Twin simulations enhances predictive risk management. By combining historical blockchain records with real-time simulation models, the system can identify potential supply chain disruptions, ensuring proactive intervention to reduce economic losses and enhance regulatory compliance. The BBTWINS blockchain solution sets a new benchmark for agrifood traceability, ensuring end-to-end product authentication, fraud prevention, and enhanced market confidence.

4.4. Real-World Integration Cases

The integration of Digital Twin and blockchain technologies is transforming the agrifood sector by improving efficiency, transparency, traceability, and sustainability. These technologies are being implemented in precision agriculture, livestock management, food traceability, and biogas production, significantly enhancing resource optimization and regulatory compliance. Below, we expand on real-world applications, providing additional case studies that illustrate how these innovations are being applied in various food and biomass supply chains.

1. Digital Twins in Precision Agriculture

Digital Twin technology is increasingly being used to create virtual models of farms, allowing real-time monitoring, predictive analytics, and process optimization. By simulating crop growth, soil conditions, and weather patterns, farmers can make data-driven decisions to enhance yields and resource efficiency. For instance, a recent study published in Nature highlights how Digital Twins can revolutionize agrifood production systems and supply chains, particularly by reducing greenhouse gas emissions, minimizing food waste, and improving nutrient efficiency [9].

Similarly, John Deere has integrated AI-driven Digital Twins into its smart farming equipment, allowing farmers to optimize irrigation schedules, fertilizer applications, and harvesting times [10]. In Europe, the Fraunhofer Institute has developed a Digital Twin-based decision support system for greenhouse and open-field farming, helping farmers adjust nutrient distribution, irrigation, and temperature control based on real-time environmental data.

2. Blockchain for Livestock and Poultry Management

In the livestock industry, blockchain technology enhances traceability, food safety, and animal welfare monitoring. By recording data on breeding, feeding practices, vaccinations, and movement tracking, blockchain ensures compliance with safety standards and reduces fraud risks. A prime example is Cargill's blockchain traceability system for poultry farming, which enables farm-to-table transparency by allowing consumers to scan QR codes on chicken packaging to view detailed records on the farm of origin, welfare conditions, feed used, and antibiotic usage. Similarly, in Australia, the Meat & Livestock Australia (MLA) initiative employs blockchain-based verification for grass-fed beef, ensuring organic certification compliance and export market trust [11]. Additionally, the EU Horizon 2020-funded BEEFCHAIN project integrates blockchain and IoT sensors to track cattle movement, reduce disease outbreaks, and ensure ethical sourcing in the European beef supply chain [12].

3. Blockchain and Digital Twins in Food Traceability

The combination of blockchain with Digital Twin technology enhances food traceability, fraud prevention, and supply chain efficiency. By creating verifiable digital records of food products, these technologies reduce counterfeiting risks, improve recall efficiency, and ensure compliance with sustainability certifications. One of the most prominent implementations is the IBM Food Trust blockchain, used by Nestlé, Carrefour, and Walmart to track every stage of food production, processing, and distribution [4,13]. The system enables real-time product recalls, reduces food fraud, and provides consumers with QR-code-enabled transparency on food origins and safety records. Carrefour reports that IBM Food Trust has reduced product recall time from weeks to seconds, significantly improving response time in contamination cases. Similarly, AgriDigital's blockchain platform for grain supply chains automates grain sales, storage monitoring, and payments using smart contracts, reducing financial risks and fraud for farmers and traders. In Japan, Fujitsu's blockchain-enabled food traceability system ensures sushi supply chain integrity by tracking fish sourcing, freezing methods, and transport conditions, allowing consumers to verify sustainability certifications [14].

4. Digital Twins for Biogas and Biomass Optimization

Digital Twins are also being applied in renewable energy production, particularly in biogas and biomass valorization. These systems enable real-time monitoring of feedstock quality, process efficiency, and methane yield predictions, reducing operational costs and improving sustainability. For example, the European Biogas Association (EBA) has deployed AI-enhanced Digital Twin models to simulate anaerobic digestion processes, allowing biogas plant operators to optimize feedstock blending and predict energy output [5]. Similarly, the BBTWINS project integrates Digital Twin simulations for biogas production from meat processing waste, enabling predictive analytics to determine methane generation potential, digestate nutrient content, and grid injection feasibility. In Denmark, Nature Energy, one of Europe’s largest biogas producers, employs real-time Digital Twin models to optimize its biogas upgrading processes, increasing efficiency and ensuring compliance with Renewable Energy Directive (RED II) targets.

5. Blockchain and Digital Twins in Hemp and Specialty Crops

Blockchain and Digital Twins are also being explored in specialty agricultural supply chains, where traceability and compliance with strict regulations are essential. A case study on the industrial hemp supply chain demonstrates how Digital Twin models integrated with blockchain improve regulatory compliance, process learning, and risk management by providing real-time tracking of biomass composition, storage conditions, and shipment verifications [4,6,9]. Similarly, blockchain-powered coffee traceability platforms, such as those implemented by Starbucks and IBM, allow customers to verify the origin, processing methods, and fair-trade certifications of their coffee beans. The growing adoption of Digital Twin and blockchain technologies in agrifood, biomass valorization, and bio-based industries demonstrates their potential to improve efficiency, sustainability, and regulatory compliance. From precision agriculture and livestock traceability to biogas optimization and hemp supply chain management, these technologies are reshaping the food and bio-based economy.

While many companies and industries implement these technologies at different stages of the agrifood value chain, BBTWINS is unique in integrating all these innovations into a single digital platform. By leveraging Digital Twin simulations, blockchain traceability, AI-powered analytics, and IoT-driven process monitoring, BBTWINS creates an end-to-end digital tool that covers every step of the agrifood value chain. Unlike fragmented solutions that focus on individual processes such as farming, processing, logistics, or traceability, BBTWINS seamlessly connects all these elements, providing a holistic approach that enhances efficiency, decision-making, and waste minimization. The BBTWINS platform does not merely adopt existing technologies—it optimizes and synchronizes them to ensure that each stage of the value chain benefits from real-time data integration, predictive insights, and automated compliance mechanisms. This comprehensive digital infrastructure sets a new benchmark for agrifood digital transformation, positioning bio-based industries for a more sustainable, transparent, and economically viable future. As agrifood companies increase their digital transformation efforts, blockchain-enabled transparency and Digital Twin predictive analytics will become essential tools for achieving a more resilient, circular, and sustainable food system. BBTWINS serves as a pioneering model for future bioeconomy initiatives, demonstrating how a fully integrated digital approach can drive innovation, investment, and long-term environmental benefits.

5. Supporting New Bio-Based Business Models

5.1. How Bio-Based Value Chains Contribute to the Bioeconomy

The bioeconomy represents a fundamental shift from fossil-based to renewable and bio-based resources, aiming to create more sustainable industrial and consumer applications. Bio-based value chains contribute significantly to this transformation by promoting resource efficiency, reducing dependency on non-renewable materials, and fostering innovation across various sectors, including agriculture, energy, and biotechnology. A key advantage of bio-based value chains is their ability to close material loops, turning organic waste into valuable commodities such as biofuels, bioplastics, biofertilizers, and biochemical compounds. By leveraging agricultural and food industry residues, bio-based processes ensure a higher utilization rate of biomass, thereby minimizing waste and reducing greenhouse gas (GHG) emissions. The BBTWINS project exemplifies this by converting meat processing by-products (e.g., pig manure, bones, skins) into biogas, hydroxyapatite, and collagen hydrolysates, while fruit residues are transformed into biochar and polyphenols.

Another crucial contribution of bio-based value chains is their impact on the circular economy. Instead of relying on a linear model of production and disposal, bio-based systems integrate recovery and recycling strategies to maximize value extraction. For instance, the anaerobic digestion of livestock waste not only generates biogas but also produces digestate, which can be further processed into organic fertilizers. Similarly, the extraction of high-value biomolecules such as polyphenols from fruit waste aligns with sustainable production models that prioritize resource efficiency and minimal environmental footprint. Furthermore, the bioeconomy fosters industrial symbiosis, where waste from one process serves as input for another, creating interconnected value chains that enhance overall sustainability. For example, biochar derived from fruit processing waste can be utilized as a soil amendment to improve agricultural productivity, while recovered phosphorus and nitrogen from manure can replace synthetic fertilizers, reducing the environmental impact of conventional farming practices. The market potential for such bio-based products is growing, with estimates indicating that the global biochar market will reach $5.91 billion by 2033, with a compound annual growth rate (CAGR) of 12%.

In addition to environmental benefits, bio-based value chains create economic opportunities by stimulating new markets and attracting investment in green technologies. The European Union (EU) has placed significant emphasis on supporting bio-based industries through funding mechanisms such as the Bio-Based Industries Joint Undertaking (BBI JU) and the EU Innovation Fund, which collectively allocate billions of euros to projects that advance sustainable bio-based solutions. Despite these benefits, challenges remain in scaling bio-based solutions to compete with established fossil-based industries. High production costs, regulatory hurdles, and consumer acceptance issues continue to affect market penetration. However, with continued policy support, technological innovation, and strategic investment, bio-based value chains can play a crucial role in driving the transition to a more resilient and sustainable economy.

5.2. Expected Job Creation in the EU Bio-Based Sectors

The expansion of the bioeconomy has significant implications for job creation, as it fosters employment across various sectors, from agriculture and biotechnology to manufacturing and logistics. The European bio-based industry is expected to generate thousands of new jobs, particularly in rural areas where bio-based value chains can leverage agricultural residues and organic waste for processing.

One of the primary drivers of employment in the bioeconomy is the development of new industrial bioprocessing facilities. These facilities require skilled workers in fields such as biochemical engineering, biomass processing, and industrial automation. The BBTWINS project, for instance, involves advanced technologies such as Digital Twins, AI-driven process optimization, and blockchain traceability, creating demand for a highly skilled workforce that can operate and maintain these digitalized bio-based platforms. Moreover, the bio-based sector creates indirect employment opportunities in research and development (R&D), regulatory compliance, and logistics. As companies invest in innovative bio-based solutions, they require expertise in material science, life cycle assessment, and market development to ensure that their products meet industry standards and achieve commercial viability. EU-funded initiatives such as Horizon Europe and the Circular Bioeconomy Investment Platform further support job growth by providing financial incentives for research institutions and startups to develop new bio-based technologies. Agriculture is another key beneficiary of bio-based job creation, as the demand for sustainable raw materials increases. Farmers and cooperatives play a critical role in supplying biomass feedstocks for bio-based industries, creating additional income streams for rural communities. The production of dedicated energy crops, sustainable forestry practices, and waste management services for biogas plants are expected to drive further employment in the primary sector. Policy frameworks such as the EU Green Deal and the Renewable Energy Directive (RED II) also contribute to job creation by setting sustainability targets that encourage investment in renewable energy and bio-based manufacturing. The transition to a low-carbon economy will require a workforce capable of implementing bio-based alternatives across multiple industries, reinforcing the need for vocational training programs and educational initiatives that equip workers with the necessary skills.

Despite these positive trends, workforce transformation remains a challenge, as traditional industries undergo structural changes. Ensuring a smooth transition will require reskilling and upskilling programs to help workers from fossil-based sectors transition into bio-based roles. Collaboration between industry, academia, and policymakers will be essential to creating a robust talent pipeline that supports the long-term growth of the bioeconomy. Overall, the bio-based sector presents a significant opportunity for job creation in Europe, with potential employment gains spanning high-tech industries, agriculture, and green manufacturing. As the bioeconomy continues to expand, strategic investments in education, innovation, and infrastructure will be key to maximizing its economic and social benefits.

Projected Job Creation in Key Bio-Based Sectors

The following sectors are expected to contribute the most to new job creation in the European bioeconomy:

1.Bioprocessing (120,000 new jobs)

- ✓ Growth in biorefineries and biochemical production plants requires highly skilled workers, including process engineers, industrial biotechnologists, and operations specialists.
- ✓ The EU Bioeconomy Strategy projects that biorefineries could generate over 1 million jobs by 2030, with bioprocessing alone accounting for ~12% of this growth.

2.Research & Development (85,000 new jobs)

- ✓ As the EU expands investment in biotechnology, AI-powered industrial processes, and material sciences, R&D will play a key role in advancing bio-based solutions.
- ✓ EU-funded projects under Horizon Europe and the BBI JU are expected to drive significant employment in research, data analytics, and life cycle assessment (LCA) studies.

3.Agriculture & Feedstock Supply (150,000 new jobs)

- ✓ Farmers and cooperatives will benefit from the growing demand for bio-feedstocks, including sustainable forestry products, energy crops, and agricultural residues.
- ✓ According to the EU Rural Bioeconomy Report, sustainable farming and biomass supply chains could create over 1 million jobs by 2030, with agriculture representing ~15% of this growth.

4.Manufacturing & Logistics (95,000 new jobs)

- ✓ The expansion of bio-based industries requires logistics for biomass collection, transport infrastructure, and bio-based product distribution.
- ✓ The circular economy sector is projected to generate 500,000+ jobs by 2035, with logistics and green manufacturing contributing ~95,000 new jobs in the near term.

5.Renewable Energy & Biogas (110,000 new jobs)

- ✓ The EU Renewable Energy Directive (RED II) is boosting investment in biogas and biomethane production, requiring skilled workers for anaerobic digestion plants and energy grid integration.
- ✓ The European Biogas Association estimates that biogas production could generate over 200,000 jobs by 2035, with ~110,000 new jobs expected by 2030.

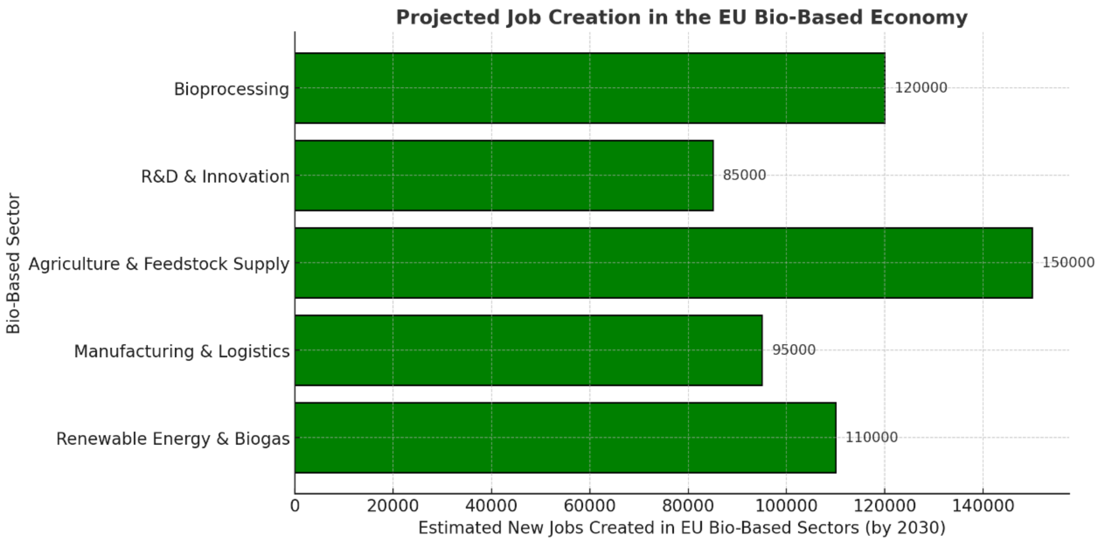

Figure 2: Expected Job creation in EU-bio-Based Economy

6. Conclusions and future steps

The BBTWINS project has demonstrated the feasibility and benefits of interconnecting bio-based value chains through digitalization, data-driven decision-making, and process optimization. By integrating Digital Twins, blockchain traceability, AI analytics, and sensor-driven monitoring, the project has illustrated how synergies between the agrifood, bioenergy, and biomaterial industries can enhance sustainability, economic viability, and resource efficiency. One of the most significant findings of this study is the role of sectoral interconnections in fostering a circular bioeconomy. By integrating agriculture, food processing, and bio-based industries, BBTWINS has shown how waste streams can be transformed into high-value bio-based products, reducing environmental impact and improving economic outcomes. The development of Digital Twin technology has played a pivotal role in this transformation, enabling real-time process optimization, predictive analytics, and data-driven decision support for bio-based production. In addition, the implementation of blockchain technology has enhanced transparency and regulatory compliance, ensuring traceability of raw materials, intermediate products, and final outputs across the entire value chain.

The project has also identified several promising bio-based innovations, including biogas, hydroxyapatite, polyphenol extracts, keratin, and collagen, with strong market potential in various industries such as renewable energy, pharmaceuticals, and cosmetics. Economic assessments indicate that some of these processes, such as biogas production, hydroxyapatite recovery, and biochar valorization, are financially viable, while others, like collagen extraction, require further optimization to become economically sustainable. Despite these advancements, challenges remain particularly in relation to regulatory constraints, economic feasibility, and supply chain integration. Strict EU regulations on animal by-products, fertilizer classifications, and gas grid injection standards pose barriers to the commercialization of some bio-based products. Additionally, the high operational and processing costs of certain bio-based materials necessitate improvements in process efficiency and the implementation of policy incentives to enhance market competitiveness. Moving forward, several key steps should be taken to scale up and expand the impact of digitalized bio-based value chains. The Digital Twin Platform, which has already been successfully applied in meat and fruit processing, should be extended to other bio-based industries, including forestry, aquaculture, and bioplastics. Further integration of AI-driven analytics and machine learning algorithms will enhance predictive capabilities, enabling real-time adjustments to production processes and further improving efficiency. The blockchain-based traceability system developed within BBTWINS should also be expanded beyond its initial scope to cover additional bio-based sectors, ensuring transparent and verifiable sourcing of biochemical feedstocks, sustainable fertilizers, and biomaterials.

Beyond technological improvements, it is crucial to enhance market integration and support new business models. Encouraging public-private partnerships will attract investment in commercial-scale bio-based production facilities, while closer collaboration with key industries such as pharmaceuticals, energy, and cosmetics will facilitate the co-development of bio-based products tailored to specific market needs. At the same time, regulatory challenges must be addressed through harmonized EU policies and certification processes, which would simplify market entry for new bio-based innovations. Additional incentives, such as tax reductions, grants, and carbon credit schemes, should be introduced to support the adoption of bio-based technologies and offset initial investment costs. Equally important is the promotion of cross-sector collaboration and knowledge transfer. Developing training programs and digital skill-building initiatives will equip industry professionals with the necessary expertise to work with advanced digital tools in bio-based industries. Additionally, fostering data-sharing frameworks among different sectors—such as agrifood, bioenergy, and biotech—will further improve transparency and facilitate the integration of circular economy principles into industrial practices.

Overall, the BBTWINS project has laid a strong foundation for the interconnection of bio-based value chains, demonstrating how digitalization can enhance resource efficiency, improve sustainability, and create new economic opportunities. To fully realize this potential, future efforts must focus on scaling up technological solutions, strengthening industry collaboration, and fostering supportive policy frameworks. By doing so, bio-based industries will be able to achieve full-scale market integration, contributing to a more sustainable, resilient, and circular bioeconomy.

References

[1] Global Biogas Market Size & Outlook, 2023-2030 n.d. https://www.grandviewresearch.com/horizon/outlook/biogas-market-size/global?utm_source=chatgpt.com.

[2] No Title n.d. https://www.grandviewresearch.com/.

[3] Biochar Market n.d. https://www.marketdataforecast.com/market-reports/biochar-market.

[4] Food and Agriculture Organization of the United Nations. The State of Food and Agriculture - Revealing the true cost of food to transform agrifood systems. 2023.

[5] Report S. European Biogas Association, European Biogas Association Statistical Report 2023, Brussels, December 2023 2023.

[6] Chen, Chi-Yun and Long AM. Introduction to Big Data and Analytics: How IBM Food Trust Uses Big Data in Food Supply Chain 2021.

[7] Marcu A, Elkerbout M, Wijnand S, Alberola E, Caneill J-Y, Matteo Mazzoni S, et al. 2022 State of the EU ETS Report. Eur Roundtable Clim Chang Sustain Transit 2022:5–6.

[8] Bacovsky D, Rossi A, Chair DB. Iea Bioenergy Annual Report 2023 2023.

[9] Tzachor A, Richards CE, Jeen S. Transforming agrifood production systems and supply chains with digital twins. Npj Sci Food 2022;6:1–5. https://doi.org/10.1038/s41538-022-00162-2.

[10] No Title n.d. https://www.deere.com/en/technology-products/precision-ag-technology/.

[11] Select Committee on Financial Technology and Regulatory Technology. Final report 2021;364:1–60.

[12] BovINE Beef Innovation Network Europe n.d. https://www.bovine-eu.net/.

[13] Group C. nutrition and product quality 2022.

[14] Fujitsu Integrated Report 2023 n.d.