D6.5

A Use Case Driven Analysis on Biomass Feedstock Valorisation

BBTWINS
Agri-Food Value Chain Digitalisation for Resource Efficiency

Circular Bio-based Europe
Joint Undertaking

Bio-based Industries Consortium

Horizon 2020
European Union Funding for Research & Innovation

PROJECT	BBTWINS
PROJECT NUMBER	101023334
PROJECT TITLE	Digital twins for the optimisation of agrifood value chain processes and the supply of quality biomass for bio-processing
PROGRAM	H2020-BBI-JTI-2020
START DATE	1 JUN 2021
DURATION	48 months
DELIVERABLE NUMBER	D6.5
DELIVERABLE TITLE	A Use Case Driven Analysis on Biomass Feedstock Valorisation
SCHEDULE DATE & MONTH	31 May 2025
ACTUAL SUB. DATE & MONTH	28 May 2025
LEAD BENEFICARY NAME	Centre for Waste Valorisation (CVR)
TYPE OF DELIVERABLE	Report
DISSEMINATION LEVEL	PU

LEAD BENEFICIARY NAME	Centre for Waste Valorisation (CVR)
Address	University of Minho, Guimarães, Portugal
Phone number	+351253510020
E-mail address	aribeiro@cvresiduos.pt
Project website	www.bbtwins.eu

This project has received funding from the Bio-based Industries Joint Undertaking under the European Union's Horizon 2020 Research and Innovation Programme under grant agreement No 101023334.

Table of Contents

List of figures

List of tables

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 revolutionising the sector by creating real-time virtual representations of physical assets. This capability enables continuous monitoring, predictive analytics, and optimisation 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 standardisation challenges, and the need for sector-specific customisation. 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 optimise 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 valorisation, BBTWINS contributes to the broader bioeconomy transition.

This deliverable explores the sectoral connections that facilitate the creation of new bio-based value chains, focusing on converting agricultural by-products and waste materials into valuable bio-based products. At the core of this strategy is the biorefinery concept, which allows for the integrated processing of biomass to obtain various products, such as bioenergy, biochemicals, fertilisers, and materials, resource-efficiently. By adhering to the principles of a circular economy, these linked value chains encourage the reuse and enhancement of organic waste, decrease reliance on fossil-based resources, and lessen environmental impacts. This systems-oriented approach improves resource efficiency and encourages collaboration across sectors, including agriculture, food processing, energy, and bio-based industries, facilitating a sustainable and economically feasible shift towards a bioeconomy.

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 identified all the variables for implementing and developing a new bio-based value chain, focusing on the market, technical and legal barriers and potential financial returns.

1.1. Executive Summary

This deliverable provides a comprehensive feasibility study about the development of a new bio-based value chain by examining its existing and potential market sizes and the features of emerging market segments and anticipated demand for bio-based products. Barriers related to the market, regulations, certification needs, policy limitations, and issues concerning consumer acceptance were identified, and the criteria for setting up supply chains to create additional revenue streams for various stakeholders were outlined. This process involved pinpointing key players in the chain (such as producers, processors, and distributors), their market shares, competitive edges, and their ability to expand bio-based solutions. Considerations included factors like feedstock availability, technological readiness, and logistics infrastructure.

The economic viability of the proposed solutions was evaluated using crucial investment metrics such as cost structures, market prices, payback periods, net present value (NPV), and internal rate of return (IRR). A market and competitor analysis was performed across various sectors, regions, and countries to identify the most favourable environments for integrating the proposed technologies, thus optimising value chains from technical, economic, environmental, and social viewpoints.

Consequently, this study established the foundation for at least one new bio-based value chain and one innovative cross-sector connection, aiding in advancing a more circular, integrated, and sustainable bioeconomy.

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:

- Characterisation of actual and potential market sizes;
- Identification of prospective segments and their features;
- Identification of market and regulatory barriers;
- Description of requirements and stakeholders in establishing sustainable supply chains;
- Economic feasibility indicators (e.g., cost drivers, pricing, payback period considerations);
- Analysis of competitors and bio-based markets across European regions.

This analysis characterises both actual and potential market sizes for bio-based products, identifying growth opportunities in sectors such as biofertilizers, bioproducts, and bioenergy. It identifies prospective market segments and their defining features, with particular attention to emerging demand in sustainable agriculture, organic production, and green industries. The study outlines key market and regulatory barriers, including fragmented legislation, high certification costs, and logistical challenges in biomass sourcing and transport.

It describes the technical, logistical, and organisational requirements for establishing sustainable supply chains, while mapping relevant stakeholders, such as producers, processors, technology providers, and end-users, along with their roles, market share, and competitive advantages. The analysis also includes broad economic feasibility indicators, considering cost structures, pricing dynamics, payback period estimates, and return on investment.

Finally, it provides a comparative market and competitor analysis across European regions, highlighting policy support, infrastructure maturity, and biomass availability differences. These insights support the strategic planning and integration of bio-based solutions across diverse European regional contexts.

1.2. Structure

This deliverable is structured to provide a comprehensive analysis of all the variables for implementing and developing a new bio-based value chain, focusing on the role of digitalisation in enhancing resource efficiency, sustainability, and economic viability. The document is divided into six main sections:

1. BBTWINS Bio-Based Value Chains – Identification of the project's significant bio-based innovations, outlining the recognised bio-based products, their market viability, and the market and regulatory barriers imposed on the new bio-based value chains.
2. Sustainable Supply Chain, Stakeholders & Opportunities – Analysis of the key actors in the bio-based supply chain, the leading companies and competition in the bio-based value chains and the challenges and opportunities for additional income streams.
3. Market and Competitor Analysis – detailed market and competitor analysis across various European regions to understand demand, technological readiness, and investment potential. The analysis maps key players in bioenergy, fertilisers, and bio-based materials, evaluating their innovation capacity, market share, and integration of digital tools.
4. Economic Feasibility of the Proposed Solutions – Identification of key financial indicators such as cost structures, payback periods, and return on investment.
5. Analyses
   Real-world integration cases are presented to illustrate successful implementations.
6. Cross-Sectoral Interconnections with BBTWINS Bio-Based Value Chain – Discusses how the new BBTWINS bio-based value chains contribute to the broader bioeconomy and analyses the impact of digital technologies such as Digital Twins, AI, IoT, and blockchain on improving decision-making, traceability, and resource efficiency
7. Conclusions and Future Steps – Summarises the key findings of the deliverable and provides recommendations for future research, policy development, and industrial implementation.

This structured approach ensures that the deliverable presents a logical sequence between the innovations developed in the project and their potential application on an industrial scale, their technical and economic viability, and the barriers and main stakeholders in the current market.

1.3. Purpose and Scope

This deliverable aims to identify all the variables for implementing and developing a new bio-based value chain. This analysis characterises both actual and potential market sizes for bio-based products, identifying growth opportunities in sectors such as biofertilizers, bio-based products, and bioenergy. It identifies prospective market segments and their defining features, with particular attention to emerging demand in sustainable agriculture, organic production, and green industries. The study outlines key market and regulatory barriers, including fragmented legislation, high certification costs, and logistical challenges in biomass sourcing and transport.

It describes the technical, logistical, and organisational requirements for establishing sustainable supply chains, while mapping relevant stakeholders, such as producers, processors, technology providers, and end-users, along with their roles, market share, and competitive advantages. The analysis also includes broad economic feasibility indicators, considering cost structures, pricing dynamics, payback period estimates, and return on investment.

Finally, it provides a comparative market and competitor analysis across European regions, highlighting differences in policy support, infrastructure maturity, and biomass availability. These insights support the strategic planning and integration of bio-based solutions across diverse regional contexts in Europe.

The scope of this study includes:

- ✓ Identifying new bio-based value chains and bio-based materials by analysing emerging opportunities for transforming agricultural and industrial waste into high-value products.
- ✓ Identifying market opportunities, challenges and barriers for commercialising these new bio-based products.
- ✓ Identifying the actual supply chain - main stakeholders and companies, and the potential incomes for the future.
- ✓ Identifying the techno-economic analyses for developing these new bio-based products and their integration into value chains.
- ✓ Mapping interconnections between agrifood, bioenergy, and biomaterial sectors to assess how digital technologies can optimise resource utilisation and value creation.

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 optimisation, data management, blockchain traceability, digital twins, and bio-based product development:

- ✓ D1.4 - Characterisation of Products and Biomass Processing Chains.
- ✓ D2.4 - Downstream Processes for the BBTWINS Feedstock.
- ✓ D2.5 - Technical Evaluation of Best Methodologies.
- ✓ D6.1 - BBTWIN's Use Case Specifications/Descriptions.
- ✓ D6.2 - Use Case Implementation analysis.
- ✓ D6.3 - Replication Plan.
- ✓ D6.4 - Feasibility Study on Value Chain Interconnection.

2. BBTWINS Bio-Based Value Chain

2.1. 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 optimizing agricultural and food processing operations through enhanced efficiency and sustainability measures. This initiative addresses two main sectors: 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 stabilising, converting, and purifying bio-based feedstocks derived from meat and fruit production.

A diagram was developed to comprehend D2.4 and D2.5 derivable content better, summarising the actions or steps needed for the WP2 - Feedstock Optimisation for Bio-based Operations. It can be noticed that the proposed workflow of WP2 is divided into three significant steps: Stabilisation Step (D2.2), Conversion Step (D2.3) and Downstream Step (D2.4). However, it is essential to note that the conversion and purification steps overlap in some proposed technologies.

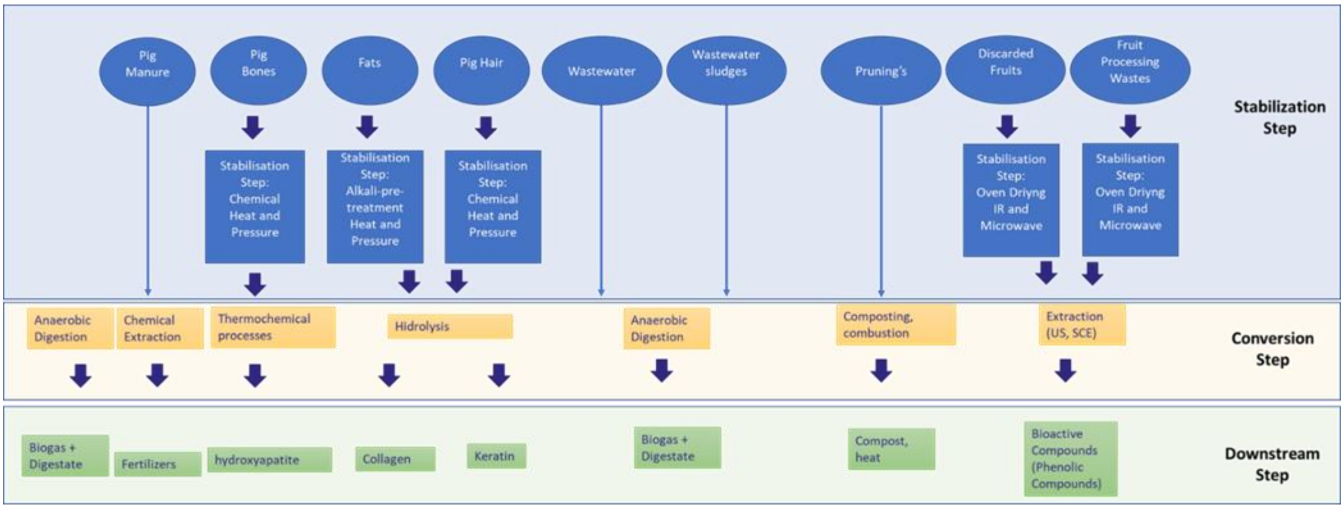

Figure 1. Feedstock optimisation for Bio-based operations diagram.

Considering the work performed previously, it was selected for further valorisation of the principal wastes produced throughout the value chain of meat production: Pig Manure, Pig Bones, Fats, Skins, Pig Hair, Wastewater, Wastewater sludges, and other animal subproducts type III. According to the defined diagram of valorisation, these wastes will be converted into Biomethane, Fertilisers (phosphorus and digestate), Hydroxyapatite, and protein hydrolysates (Keratin and Collagen). Regarding the fruit use case, the following wastes were selected for valorisation: Pruning wastes, Peach and Nectarine fruits discarded or unsuitable for human consumption, and Peach and Nectarine fruit processing waste. These processes aimed 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 – Utilisation of pig manure and wastewater sludge to generate biogas and biomethane.
- Nutrient Recovery from Manure and Sludge – Extraction of phosphorus and nitrogen for fertiliser use.
- Hydrolysis and Extraction of High-Value Proteins (Keratin & Collagen) – Processing 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 valorisation of pruning waste and discarded fruits.
- Extraction of Bioactive Compounds (Polyphenols) from Fruit Waste – Isolation of antioxidants from peach and nectarine processing waste.

Each process contributes significantly to the circular bioeconomy by converting underutilised 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. Anaerobic digestion (AD) appears promising, allowing the simultaneous recovery of energy (in the form of biogas) in line with the circular economy concept. Energy recovery from renewable materials is a sustainable waste management practice that is beneficial to the environment by reducing the use of fossil fuels, decreasing greenhouse gas emissions, and ensuring energy demand [1]. AD has the further advantage of simultaneous materials recovery in the form of digestate. The digested liquid by-products are rich in bioavailable nutrients, especially N, P and K. The digestate is estimated to contain more bioavailable nitrogen (in the form of NH4–N) than the feedstock undergoing AD [2]. These characteristics make the digestate suitable for agricultural use as a plant fertiliser.

AD is a process that converts organic matter (e.g., animal manure, agricultural residue, municipal waste, etc.) into a gaseous mixture, mainly composed of methane and carbon dioxide, through the concerted action of a close-knit community of bacteria [3]. Nevertheless, AD of single substrates (mono-digestion) presents some drawbacks linked to substrate properties. For instance, animal manure has low organic loads and high nitrogen (N) concentrations, which may inhibit methanogens. Both pig manure and sludge are high-water-content organic wastes. Improper pig manure or sludge treatment will cause severe environmental pollution, such as deleterious gas emissions, water/soil contamination, and pathogen spread [4]. When considering energy recovery, land utilisation and properties of waste, anaerobic digestion is identified as a sustainable option to treat pig manure or sludge [5]. Anaerobic digestion could be carried out at a specific temperature range (psychrophilic, mesophilic, thermophilic and hyper thermophilic), but most anaerobic digesters are operated in the mesophilic and thermophilic range because it can maintain a balance between energy and efficiency [6].

Pig manure and sludge are typical solid wastes which are easy to collect. Pig farms and sewage treatment plants are generally located in the suburbs. A close distance is favourable for synergistic treatment. Pig manure has high micronutrients, buffering capacity and biodegradability, which subserves the growth of anaerobic microbes. However, high volatile solids (VS) and total solids (TS) (greater than 20%) also lead to superabundant organic acids and ammonia, which seriously inhibit methanogenesis [7]. The characteristics of thickened sewage sludge showed low VS, TS, carbon/nitrogen (C/N) ratio and hydrolysis rate, which brings about low biogas yield [8]. However, sewage sludge is rich in nitrogen, so there is no need to add dewatering conditioners, which is beneficial to land utilisation [9].

Some properties of pig manure and sludge are complementary. By mixing pig manure and sludge, the anaerobic digester has a strong buffer capacity, nutrient balance for microorganisms, high volumetric load rate, suitable operational pH, dilution of toxic compounds and improvement of microbial diversity [10]. Co-digestion is an effective method to alleviate the disadvantages of mono-digestion, which could enhance digestion performance [11]. Compared to mono-digestion of sludge, co-digestion of pig manure and sludge at mesophilic temperatures could remarkably increase the methane yield (over 50%) at an adequate mixing ratio [12].

Another interesting prospect in swine by-products of anaerobic digestion is the co-digestion with other agri-food wastes. Co-digesting corn stalk (CS) with pig manure (PM) showed higher methane production than mono-digestion [13], and it was found that manure could provide buffering capacity and a wide range of nutrients. Much of these inefficient digestion problems can be improved by adding a co-substrate in what has recently become called anaerobic co-digestion [14]. The addition of CS to PM enhanced biogas production in both mesophilic (39 °C) and thermophilic (55 °C) anaerobic digestion [15]. More than 50% of the carbon in CS was converted to gas. Wu et al. studied three crop residues (oat straw, wheat straw, and corn stalks) in anaerobic co-digestion with PM, among which corn stalks performed the best with an increase in daily maximum biogas volume by 11.4-fold compared to the control (PM only) at mesophilic conditions [16].

Utilising 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, cogeneration 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

Pig manure has a lower nitrogen to phosphorus (N: P) ratio (<4:1) than most crops (8:1), so applying it at nitrogen-optimal rates leads to phosphorus buildup in soil. This excess phosphorus can leach into water bodies, causing eutrophication. While transporting manure to P-deficient areas helps, it is costly. Sustainable P recovery technologies are needed due to the scarcity of mineral phosphorus sources [17, 18].

Various methods exist for phosphorus recovery from manure, including physical separation, biological treatment, adsorption, and chemical precipitation (e.g., struvite formation or using aluminium/iron salts) [19-27]. One promising method is the “quick wash” process, which extracts and recovers phosphorus using acids and lime, producing:

1. Washed solids with improved N:P ratios,
2. Concentrated P product suitable for transport and use as a fertiliser,
3. Liquid effluent for nearby use or recycling.

Unlike other methods, quick wash preserves organic C and N and operates at ambient temperature. Lime precipitation is especially cost-effective, achieving >90% P removal while producing a fertiliser-grade product. It also inactivates pathogens, making the phosphorus microbiologically safe and enabling water reuse in swine facilities [28, 29].

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 and 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

Hydrolysis and extraction technologies were used to purify valuable compounds from category III animal by-products (bones, skins, hair, and fats) from the Cartesa slaughterhouse facility. These processes aim to extract proteins such as keratin and collagen using chemical and enzymatic hydrolysis.

Collagen, the most abundant mammalian protein (>30%), and keratin, which makes up to 90% of skin derivatives like wool and feathers, are particularly interesting. Their extraction supports large-scale production of materials for applications in medicine, cosmetics, pharmaceuticals, bioremediation, biodegradable materials, fertilisers, and animal feed. Future research focuses on refining physicochemical and enzymatic methods for producing these proteins and their hydrolysates for industrial use [30].

- 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 hydrolysed 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

Ceramics are a class of biomaterials used in biomedical devices. Ceramics are widely used as implant materials due to their ability to be fabricated into various shapes and their high compressive strength, variable porosity, and bioactive properties in the body [31]. The high similarity in the chemical composition of some ceramics, such as calcium phosphate, with human bone minerals makes them suitable for use as orthopaedic implants (human skeleton, bones, and joints), and dental materials [31]. These materials show excellent bioactivity, biocompatibility, and osteoconduction characteristics [32, 33].

Hydroxyapatite, HAP ($Ca_{10}(PO_4)_6(OH)_2$), is thermodynamically stable in its crystalline state in body fluid and has a very similar composition to bone minerals [34]. HAP can integrate with bone without causing any local or systemic toxicity, inflammation or foreign body response [35]. For these reasons, HAP has been widely used for biomedical applications, particularly in orthopaedics, odontology, and as the coating material for metallic implants [36]. Regarding the extraction of HAP from bones, most methods used the calcination method, which is either the sole process or a combination of calcination with other methods. The calcination process involves heating the bone in a furnace at different temperatures of up to 1400 ºC to completely remove the organic matter and kill the pathogens which may be present.

The optimised 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

Among all the renewable energy sources, biomass waste can significantly contribute as an alternative to fossil fuels. Energy from biomass accounts for 14% of the total energy consumption in the world [37, 38]. Biomass is expected to contribute to around two-thirds of the renewable energy share in 2020, according to projections of the European Commission. Biomass waste includes different kinds of feedstock, including agriculture, forestry, animal husbandry, and municipal solid waste. Agricultural biomass represents an attractive and suitable feedstock for energy conversion, particularly in rural areas. This feedstock is obtained from residues of crop cultivation and wastes from agro-industrial food processing.

Despite its huge potential as biomass, pruning residues can be deemed a neglected source, poorly utilised until now for bioenergy purposes [39]. There are many reasons for this, including variability in space, time and typology of pruning; the reluctance of farmers to introduce innovations; and the lack of an efficient and cost-effective supply chain. Of course, exploitation will become an effective opportunity only when the biomass can be delivered to the end user at a reasonable price [40, 41].

The combustion of peach and nectarine pruning residues provides a renewable biomass fuel alternative for industrial heat generation. This method is 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.

Composting of Discarded Peach and Nectarine Fruits

Composting is an environmentally friendly and cost-effective substitute for processing and converting organic waste into organic fertiliser [42]. It is a biological process in which the polymeric waste materials contained in organic waste are degraded by the accelerated growth of fungi and bacteria [43]. It is a highly complex mechanism involving various processes (microbiological, physicochemical and thermodynamic), all of which seem to be interrelated [44]. The products of the composting process are carbon dioxide and stable carbon forms that lead to the decomposition and mineralization of organic matter and the production of humic substances. During composting, microorganisms release heat and energy as they decompose the material. The heat generated increases the compost pile's temperature, ensuring the inactivation of pathogenic microorganisms. For this reason, measuring the pile's temperature is crucial in evaluating the composting process [45]. The performance of the composting process is influenced by factors such as temperature, pH, moisture content, C/N ratio, particle size, nutrient content and oxygen supply [46].

Results showed that the compost complies with all the parameters required for Class I as specified in DL 103/2015 and, therefore, can be used as a fertiliser material. Results also indicate that the proposed composting process has a slightly negative cash flow (-583,60 €/year). Although the initial assessment of the composting process's economic viability was negative, optimising several parameters could make it economically viable in the future.

Extraction of Polyphenols from Peach & Nectarine Processing Waste

Ultrasounds Assisted Extraction (UAE) and Supercritical Fluid Extraction (SFE) were performed to extract and purify bioactive compounds. In general, fruit peels present a good source of cellulose, hemicellulose, and phenolic compounds with the potential to be used as raw material to generate new products. The uses could include preparing animal feed, organic fertilisers, cosmetics, and pharmaceutical applications due to their bioactive components such as phenols, peptides, and terpenes, providing antioxidant, therapeutic, and nutritional properties [47]. The seed is a raw material fraction that is wasted chiefly in processing fruits and vegetables. This by-product is generated in the pulping stage, where only the pulp is extracted. For example, peach seeds contain almost 30% of proteins and 60% of fibres. The pomace represents the mixture of seed residues, skin, fibre, and pulp of the fruit or vegetable, generated in large quantities in the straining and pulping stage. The pomace of peaches and nectarines is characterised by containing a significant amount of fibre (between 40 and 60%) and bioactive compounds. Polyphenols are valuable bioactive compounds with applications in the nutraceutical and cosmetic industries [47, 48]. 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. With were obtained an extraction ratio of 153,5 g of extract/kg of dry peach waste with a concentration of 2400 mg GAE/kg of dry peach was obtained using Ultrasound-Assisted Extraction (UAE);
- Supercritical Fluid Extraction (SFE) – Results of SFE extraction showed lower extraction yield (12,5% at maximum) than the conventional Soxhlet extraction (43,4% at maximum). However, the results also proved that SFE is more selective for TPC extraction than conventional Soxhlet extraction. The extract with higher purity was achieved in the sample stabilised in an Oven at 300 bar (20,1 mg GAE/g extract). Regarding the mass balance of TPC, the sample stabilised in the oven at 500 bar achieved the highest result, with a concentration of 1663.2 mg GAE/Kg of peach waste. While this method achieves higher purity, it suffers from lower extraction yields and excessive capital and operational costs, making it economically unfeasible.

In summary, it can be concluded that the bio-based advancements showcased in the BBTWINS project reveal notable technical viability, with numerous processes exhibiting significant economic potential. The production of biogas, the extraction of keratin, the recovery of hydroxyapatite, and the combustion of pruning waste are highlighted as the most promising methods regarding financial returns and sustainability influence. Nevertheless, processes like phosphorus recovery and collagen extraction need additional optimisation or policy support to reach economic viability. BBTWINS plays a crucial role in fostering the shift towards a sustainable and circular bio-based economy through its comprehensive approach to waste valorisation, digital transformation, and economic assessment.

2.2. Identified Bio-Based Products and Their Market Potential

The BBTWINS project has pinpointed several bio-based products originating from waste streams in meat and fruit processing. Converting these waste materials into valuable bio-based products aligns with global sustainability objectives and principles of a circular economy. Evaluating the market potential of these products is essential for determining their economic viability and informing strategic investment choices. Recent market studies indicate that bio-based sectors, especially those related to renewable energy, agriculture, cosmetics, and biomedical uses, are showing robust growth. The rising demand for sustainable alternatives to fossil-fuel-based products, along with government support for renewable energy and sustainable farming, further boosts the potential of these bio-based innovations.

Biogas Production from Pig Manure & Wastewater

Biogas generated from agricultural waste is an expanding aspect of Europe’s renewable energy landscape – Europe currently leads globally in biogas production, with policy forecasts suggesting that biomass (including manure) could contribute up to 50% of the EU's renewable energy by 2030 [49]. If a small portion of the EU's 23 billion m³ of biomethane potential is tapped, it could significantly reduce natural gas imports. The demand for organic fertilisers and soil enhancers is also rising, driven by sustainable farming practices and EU policies promoting nutrient recycling. Nutrient products recovered from manure can address the need for phosphorus fertilisers in Europe, which predominantly relies on imports [50]. (Significantly, phosphate rock is now recognised as a Critical Raw Material in the EU, increasing the urgency to identify local sources.) The anticipated demand for recycled fertilisers depends on their price competitiveness and farmers’ willingness to adopt them; interest in manure-based nutrients has surged in response to the high costs of mineral fertilisers in recent years. Furthermore, regulations restricting land application (such as the Nitrates Directive) create a demand for off-farm manure management, effectively driving the market for treatment options. In conclusion, as long as manure-derived products comply with quality standards and regulatory frameworks, there is a robust prospective demand in energy sectors (for green gas/electricity) and agri-food sectors (for organic nutrients) [51].

Nutrient Recovery from Pig Manure

Harvesting phosphorus and nitrogen from manure to produce organic fertilisers aligns with the increasing trend towards sustainable farming. The market for organic fertilisers is expected to grow to $15.7 billion by 2030, driven by a growing demand for organic food and sustainable soil management techniques. However, economic feasibility is a concern due to the expenses associated with processing and the competitiveness of prices for synthetic fertilisers [52, 53].

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

The keratin market for cosmetic and detergent applications is still in its early stages. The KERASOL project estimates that the global keratin market reached approximately 10,740 tonnes in 2018, with a projected growth of 45% over the next decade. This suggests an increasing demand, spurred by the cosmetics industry and potentially by textile uses as well. Within this market, functional (bioactive) keratin represents a niche area—if keratin derived from pig hair can be produced without alterations, it holds a competitive advantage since many existing products lose their functionality due to harsh processing methods. Cosmetic brands are in search of ingredients that are animal-derived yet sustainably sourced and upcycled; pig hair keratin could satisfy this requirement if positioned effectively (though the trend towards veganism in cosmetics might limit demand) [54]. Another avenue being explored is using keratin in detergents (such as additives in laundry formulas to protect fabrics), with companies like Royal Triumph (KERASOL) investigating this segment. The demand in this area will rely on both performance and cost effectiveness compared to alternatives.

In contrast, the market for collagen and gelatine is more established. Europe's collagen and gelatine market is significant (the European collagen segment alone was valued at approximately €3.6 billion in 2023). There has recently been a surge in collagen peptide supplements powered by consumer interest in “beauty from within” and sports nutrition. The potential market segments for products derived from pig skin are: mainstream food and pharmaceutical gelatine (high demand, commodity pricing) and speciality collagen peptides targeting health and cosmetics (lower demand, premium pricing).

Projected demand for collagen is relatively constant and expected to increase with population growth and income. Global collagen demand is anticipated to grow at about 5% per year. As long as the pig slaughter rate remains high, the supply of raw pigskin will not be a limiting factor [55]. The current demand for keratin derived from hair is modest but may increase if new products prove to be effective. The hair care industry is vast, and a functional keratin additive that can be promoted as "from upcycled pig bristles" (although this phrasing may be framed in a more appealing way) could gain traction with certain brands. Additionally, there appears to be emerging demand in agriculture for keratin-based fertilizer products as the organic farming sector expands—farmers are looking for non-synthetic nutrient sources; keratin hydrolysate could provide nitrogen and enhance soil quality, though this market is still in its early stages.

Hydroxyapatite Purification from Pig Bones

Europe has a vast supply of bones—consider that if the EU generates around 20 million tonnes of meat, a notable portion of that weight is composed of bone. The potential for bone-based fertilisers is associated with the fertiliser market size. The annual phosphorus fertilizer consumption in the EU (measured in terms of P_2O_5) amounts to several million tonnes.

Recycled inputs like bone char could realistically fulfil part of that demand. For instance, research suggested that processing approximately 1.8 billion tonnes of manure (including bedding, etc.) could yield about 18 million tonnes of P_2O_5—bones could similarly provide a significant source of phosphorus. The demand for organic fertilisers is continuously increasing, and prices for phosphate fertilisers soared by more than 300% from 2021 to 2023, underscoring the necessity for alternative sources. Farmers, particularly those involved in organic farming (which cannot use synthetic superphosphates unless derived from natural origins), represent a specific demand for bone meal and bone char. These products are currently marketed within the gardening and agricultural sectors, although most bone meal today is a by-product of the rendering industry instead of being produced through focused “biorefinery” processes. The market for bone char as a phosphate alternative could be substantial if policies provide support, given that the EU is susceptible to supply shocks related to phosphate rock, importing around 85% of its phosphate. Demand could increase if regulations permit a broader application of bone char as a fertiliser (the new EU Fertilising Products Regulation has included specific ash and char materials). Early adopters might consist of farmers in areas with insufficient soil phosphorus or those practising organic cultivation.

The anticipated demand for bone-derived hydroxyapatite in medical applications is significantly lower (on a scale similar to the medical device industry) but is still notable: potentially only a few tonnes globally each year yet priced at thousands of euros per tonne. Hydroxyapatite, a critical material for bone grafts and dental applications, is experiencing increasing demand due to the growth of the medical implant industry. It is projected that the hydroxyapatite market will reach $3.3 billion by 2028, driven by applications in biomedicine. The main challenge for commercialisation is achieving high purity levels while also ensuring economically feasible processing [56].

Combustion of Pruning Wastes for Energy

The main consumer market for pruning biomass is the bioenergy sector. The EU exhibits a significant appetite for biomass for energy purposes, especially for heating applications. Wood chips and pellets are well-established commodities – Europe has an extensive pellet market, primarily supplied by forestry byproducts, though orchard wood can also be converted into pellets if it meets certain criteria. With rising energy prices and ambitious renewable energy goals, the demand for biomass fuels remains robust. For example, Italy promotes the use of agricultural residues in biomass power plants by providing green certificates. The potential availability in the EU is estimated at 40 million tons of agricultural pruning annually, highlighting an ample resource pool. If utilised effectively, this could substantially contribute to renewable energy: research in a Mediterranean region indicated that pruning could greatly enhance local energy supplies without encroaching on food production or forest resources.

Nevertheless, the current lack of demand is an obstacle, meaning that local biomass plants or consumers do not always accept pruning. This situation is evolving, as an increasing number of small-scale boilers and community heating initiatives are becoming operational. Additionally, in some EU nations, agricultural biomass power contributes to advanced bioenergy quotas, which may boost demand.

If pellets or briquettes are produced, they can integrate into the current residential or industrial heating market. The products must comply with specific quality standards (such as ash content and energy content). While fruit wood generally has a slightly higher ash content than pine, it is typically considered acceptable.

An increasing demand for biochar is starting to surface. Although it is not yet a mainstream market, as carbon sequestration credits gain recognition, the sale of biochar could become lucrative (some companies are already marketing biochar at premium prices for gardening purposes or agronomic research). Biochar created from fruit pruning waste has multiple applications in enhancing soil quality and sequestering carbon. The biochar market is anticipated to expand significantly, reaching a value of $5.91 billion by 2033, with a compound annual growth rate (CAGR) of 12%. Carbon credit initiatives and the desire for sustainable soil additives drive this anticipated growth. Supportive policies and advancements in biochar production methods will be critical for facilitating market growth.

Extraction of Polyphenols from Peach & Nectarine Processing Waste

There is a significant demand for natural antioxidants, colourants, and extracts. For instance, the market for polyphenol extracts, such as grape seed extract and olive leaf extract, is growing due to trends in health supplements. Fruit waste could provide these extracts; for example, grape pomace extract is already marketed as a nutritional supplement (proanthocyanidin) and a natural food colourant. As consumers turn away from synthetic additives, ingredients derived from fruits are becoming more appealing. Potential market segments include manufacturers of dietary supplements, producers of functional foods, and cosmetic companies searching for natural components. Demand for specific compounds often exceeds supply because extracting them from primary sources can be costly; utilising waste can cost-effectively enhance supply.

Polyphenols extracted from fruit processing waste are receiving growing attention for their antioxidant properties, particularly in the health and wellness industries. The global polyphenol market is projected to reach $2.9 billion by 2026, with a compound annual growth rate (CAGR) of 7.2%. The rising consumer interest in functional foods and natural dietary supplements fuels this expansion. However, the high expenses associated with extraction technologies, such as Supercritical Fluid Extraction (SFE), pose a challenge to scalable economic viability.

The biobased products emphasised reveal considerable market potential, with numerous items demonstrating economic viability. The most lucrative is biogas production, collagen extraction, hydroxyapatite recovery, and biochar production, all backed by established and expanding markets. Nevertheless, their prosperity will hinge on overcoming technical and economic hurdles, optimising production costs, and leveraging policy incentives.

Future research should enhance processing efficiencies, create cost-effective purification techniques, and promote partnerships with industries that can integrate these biobased products into commercial uses. By tackling these areas, the BBTWINS project has the potential to aid in developing a strong and sustainable bioeconomy while improving resource utilization in both agricultural and industrial fields. The table below summarises the identified bio-based products, their sources, main uses, and expected market potential according to the recent industry data.

Table 1. Identified bio-based products from the examined BBTWINS use cases [62–64].

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 P & N 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 growth to $5.91 billion by 2033, with 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%**

2.3. Market & Regulatory Barriers to Value Chain Development

The successful establishment and commercialisation of bio-based value chains depend on technological viability and market opportunities and on addressing significant market and regulatory hurdles. Although bio-based industries offer encouraging prospects for sustainability and economic development, several challenges impede their large-scale implementation and competitiveness in current markets. The main obstacles can be grouped into economic limitations, regulatory structures, technological constraints, market rivalry, and policy deficiencies. This section presents an in-depth analysis of these barriers and their impact on the BBTWINS bio-based products.

Key Market Barriers

Biogas Production from Pig Manure & Wastewater

Although there is significant potential, various obstacles hinder the complete development of the market. Major challenges include:

- Logistics and Dilution: Pig manure contains a high-water content (up to around 95%), leading to inefficient transportation. The cost of hauling slurry is substantial (transportation can make up about 60% of manure processing expenses), which creates difficulties for value chains unless processing occurs on-site or nearby. Small, modular, or mobile treatment units, such as the modular biorefinery units, are being created to tackle this issue [57, 58].

- Low Energy Density: The low yield of biogas per volume (especially for pig slurry with reduced solid content) often necessitates the use of co-substrates (like crop residues or food waste) for biogas plants to be financially viable. This technical challenge can be a hurdle in areas lacking easily accessible co-feedstocks [57, 58].

- Market Perception and Quality Standards: Farmers may be reluctant to apply fertilisers derived from waste if there are uncertainties regarding their nutrient content or stability. Establishing trust in new manure-based products (through standards and certifications such as the EU Fertilising Products Regulation) is essential. Likewise, injecting biomethane into the energy grid necessitates compliance with quality standards and obtaining grid access—administrative challenges that small projects often find hard to navigate [57, 58].

- Economic Scale: Numerous pig farms in Europe are of medium size; on their own, they find it difficult to justify the capital expenditure for biogas or advanced treatment facilities. Aggregating manure from multiple farms or utilising cooperative models is necessary, although organising this is not always straightforward. Additionally, competition from traditional waste management methods (like less expensive lagoon storage and raw spreading) diminishes incentives, particularly in regions where environmental regulations are not strictly enforced [57, 58].

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

Again, despite significant potential, several obstacles hinder the complete development of the market. These challenges include:

- Technical Challenges: Pig hairs, being tough and heavily cross-linked keratin (with disulfide bonds), pose challenges for extraction. Traditional techniques often lead to compromised protein quality. Newer methods like subcritical water hydrolysis or reductive chemistry are under development, but scaling these processes for industrial use presents difficulties. If yield is minimal or the methods are costly, the resulting products might not be financially feasible. The same applies to skin: producing medical-grade collagen requires precise processing to avert contamination and maintain functional integrity, which can drive up costs [54, 55].

- Market Acceptance & Competition: Persuading industries to adopt pig hair keratin or pigskin collagen may encounter some resistance. For example, the cosmetics sector might be apprehensive due to consumer attitudes ("animal-derived" ingredients can raise concerns for some buyers unless marketed as sustainable upcycling). Additionally, there is rivalry from alternative keratin sources: poultry feathers (which produce a larger volume of waste) are rich in keratin and are being investigated for similar applications, while discarded sheep wool is another option. Pig hair could be overlooked if these alternatives are cheaper or more practical. In the collagen space, fish collagen/gelatine has found a niche as an eco-friendly choice and caters to markets avoiding pork due to cultural factors; bovine hide gelatine is also a competitor (though pigskin gelatine typically has slightly different characteristics and cost structure). While synthetic or plant-based collagen is not truly available (as collagen is fundamentally animal-sourced, although some biotech firms are attempting to create recombinant human collagen using microbes – a possible future rival for specific high-end applications) [54, 55].

- Scale and Supply Chain Logistics: Efficiently gathering pig hair can prove challenging. During slaughter, hair is frequently singed off or removed with scalding water. Separating and purifying it for further processing demands investment in equipment at the abattoir. Not all facilities may find this worthwhile unless a buyer is secured. This could restrict feedstock supply for a keratin biorefinery [54, 55].

Hydroxyapatite Purification from Pig Bones

- Perception and Acceptance: Some farmers may be reluctant to use animal-based fertilisers if they or their buyers favour vegan or vegetarian production inputs (though this is a minor concern, primarily within certain consumer-driven standards). On the other hand, organic farmers largely welcome bone meal, as it is one of the few permitted high-phosphorus fertilisers. Public perception issues may surface if, for instance, bone char is utilised in the treatment of drinking water (some individuals might be opposed to the idea of animal bones being present in their water filtration, despite the final water having no remnants of it). Such psychological barriers underscore the importance of education and transparency [59].

- Competing Uses and Economic Viability: If bone waste is currently allocated for a particular purpose (such as meat and bone meal for energy), transferring it to a different application must be economically viable[59].

- Technical Challenges: Transforming bones for various products requires specific processing conditions. Methods such as calcination/pyrolysis are effective, but managing the process to achieve the correct form of phosphorus is crucial. Another technical consideration is grinding – bone char must be milled into a fine powder for incorporation into fertiliser blends or pellets, necessitating durable milling equipment (as bones can be abrasive to machines).
- Hydroxyapatite from Pig Bones: Achieving high purity for medical-grade hydroxyapatite requires expensive pyrolysis and post-processing steps [59].

Extraction of Polyphenols from Peach & Nectarine Processing Waste

- Seasonality and Supply Chain: The fruit waste often varies by season. Maintaining a continuous operation for a biorefinery year-round can be difficult. It may be necessary to preserve raw materials (through methods like drying or ensiling), which incurs additional costs. A study conducted in Spain on peach juice by-products found that drying the waste in an oven to a moisture content of less than 15% effectively allowed for storage while preserving polyphenols. However, implementing such measures throughout the industry presents logistical and financial challenges. Moreover, fruit waste tends to be wet and bulky, making it challenging to transport over long distances. Therefore, biorefineries should ideally be situated close to processing facilities or farms, as transportation costs and spoilage could otherwise become significant issues [60, 61].

- Market Competition and Price: Numerous potential products derived from fruit waste already face competition from established alternatives.

- Fragmentation of Waste Streams: Generally, a biorefinery operates most efficiently with a consistent type of biomass. An integrated facility might process a primary type or require separate processing lines for different waste types. This fragmentation suggests the potential necessity for multiple smaller biorefineries, which could result in a loss of economies of scale. Alternatively, a facility could manage a blend of various fruit wastes, but the processing design must account for that (for instance, mixing wastes for anaerobic digestion is acceptable, but for the extraction of specific compounds, mixing is not ideal).

- Technical hurdles: Certain biorefinery concepts still pose significant technical challenges. For example, isolating multiple products from a singular feedstock demands complex multi-step processes. Each step (extraction, filtration, fermentation, etc.) adds complexity and cost. Ensuring that these processes work cohesively is not straightforward. Achieving "pilot-scale success" does not always guarantee that the process is feasible on an industrial scale without further optimisation.

Combustion of Pruning Wastes for Energy

- Logistics & Collection: Prunings are spread across numerous small orchards, making efficient collection challenging. Although mechanised options such as tractor-mounted shredders that blow chips into a trailer are available, many farmers still find it simpler to pile and burn them. The costs associated with collection can undermine the economics if transport distances are lengthy or if specific equipment purchases are necessary. Optimising logistics is essential – synchronising pruning activities with biomass collection timelines, potentially involving contractors specialising in this, like firms travelling from farm to farm to collect pruning.

- Fragmented Ownership: Numerous farmers own small portions of biomass, making it challenging to organise them (for instance, into cooperatives to deliver to a plant). If one or two large fruit corporations operate (with their own orchards or contract farmers), central management could simplify coordination. This is practical in certain EU regions, such as large olive estate areas or vineyard companies, whereas in others (like small family orchards), it is more challenging.

- Market Access: Energy plants typically have predetermined suppliers (primarily from forestry). Demonstrating that agricultural residues can be just as effective may be necessary – operators may express concerns regarding higher ash content or silica from the soil. Additionally, pruning's are only available after the pruning season; thus, ensuring a consistent supply throughout the year necessitates storage (dry storage might be required to prevent decay). This adds a further dimension of complexity and expense (entailing the need for covered storage or silos).

Regulatory Barriers

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 processing, sterilisation, and traceability requirements.

- Keratin and Collagen Extraction: Must meet strict hygiene and sterilisation protocols before being approved for cosmetic or food applications. As Category 3 ABP, pig hair and skin can be used for specific applications, but processing facilities must obtain approval and adhere to hygiene regulations. For example, transforming hair into a cosmetic component necessitates processing in line with chemical regulations (REACH) and safety standards for cosmetics. Any use in food (such as collagen) must comply with food-grade requirements. Navigating these regulatory challenges can be expensive for newcomers. However, an established gelatine sector offers a framework for adherence.
- Hydroxyapatite for Medical Use: Requires compliance with European Medicines Agency (EMA) standards for biocompatibility and purity. Bone char typically complies with these standards (and has the benefit of being very low in contaminants compared to rock phosphate), but manufacturers must prove consistency and safety (including inactivation of prions through high-temperature processing, with pyrolysis at 850°C being adequate).

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

EU Fertilising Product Regulations (2019/1009)

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

- Compost 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. While these regulations promote manure processing, they can also complicate the process; for instance, ammonia stripping and fertiliser production from manure must adhere to the regulations governing fertiliser products and animal by-products. Any applications of manure-derived products as feed must follow strict health and safety regulations. Supportive policies are essential: incentives or feed-in tariffs for manure biogas have varied inconsistently across nations. In some instances, insufficient long-term support for small farm digesters has hindered their adoption.

Regulatory Approval for Food/Cosmetic Use

When extracting substances from "waste" for use in food or cosmetics, it is essential to demonstrate that these extracts comply with safety regulations (free from contaminants and consistent in quality). Particular fruit wastes (like peels) may contain pesticide residues. The methods used must ensure that the final extracts are safe and any toxins are eliminated or remain within permissible limits. If developing a new food ingredient derived from waste, one may need to obtain novel food approval in the EU, particularly if the ingredient does not have a history of usage. This approval process can be protracted. For cosmetic applications, ingredients must be documented and proven to be non-harmful (most fruit extracts are generally recognized as safe, but the specific extraction solvent must be deemed acceptable – for example, the use of harsh solvents could leave unacceptable residues unless purified).

Regulatory Issues for using peach pruning as solid fuel

Due to pollution concerns, the open burning of agricultural waste is increasingly constrained or outlawed in Europe. This trend is pushing the search for alternatives (farmers can no longer legally burn in many places or face restrictions). However, there is a regulatory distinction: if pruning's are classified as a "product" (fuel), their transport and usage are relatively straightforward. If labelled as "waste," they could be subject to waste transport regulations, but generally, plant residues at the source farm are not regarded as waste if utilised as fuel. The EU waste directives include exemptions for biomass used for energy on the farm or in the vicinity. Furthermore, sustainability criteria for biomass (under the Renewable Energy Directive) necessitate evidence that it is a residue and that its harvesting does not adversely affect soil health, among other factors. Some might contend that leaving pruning's contributes to soil organic matter, implying that their removal could negatively impact soil carbon levels or lead to erosion; hence, guidelines for leaving some behind or compensating with other organic amendments might be relevant. These regulatory requirements increase testing and compliance costs, making it difficult for small-scale bio-based companies to compete with established fertiliser manufacturers.

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 harmonisation and long-term subsidy frameworks are needed.

3. Sustainable Supply Chain, Stakeholders & Opportunities

3.1. Key Stakeholders in the Bio-Based Supply Chain

The establishment of bio-based value chains depends on a complicated network of stakeholders that collaborate across various phases, from gathering raw materials to commercialising bio-based products. These stakeholders encompass feedstock suppliers, processing industries, technology providers, logistics and distribution networks, policymakers, and end-market consumers. Effectively integrating these participants is crucial for achieving sustainability and economic viability within bio-based sectors. At the beginning of the supply chain, feedstock suppliers deliver the raw materials essential for bio-based production. For the BBTWINS project, this includes agricultural producers as well as the meat and fruit processing industries. The PORTESA value chain, which centres on the meat sector, provides pig manure, wastewater sludge, bones, skins, and hair, whereas the DIMITRA value chain focuses on processing fruit waste, such as pruning residues and discarded fruits (BBTWINS, 2023). The stability and cost-effectiveness of the supply chain are influenced by the availability, quality, and seasonal variations of feedstock, underscoring the importance of strategic sourcing and storage solutions. Furthermore, regulatory limitations like the EU Animal By-Product Regulations (1069/2009) impact the transportation and processing of these raw materials.

The logistics and distribution industry is essential for facilitating the transportation of raw materials and finished goods. Biomass logistics present specific challenges, especially considering factors like high moisture levels, low bulk density, and perishability. For example, the transportation of pig manure for biogas production necessitates specialised containment systems, while fruit by-products must undergo drying or stabilisation before processing. Approaches such as regional bio-hubs and decentralized processing facilities help address transportation inefficiencies and lower costs. On the regulatory and policy front, government agencies, financial institutions, and research organisations establish the framework needed for the sustainable growth of bio-based value chains. Financial support mechanisms like Horizon 2020 and the Bio-Based Industries Joint Undertaking (BBI JU) offer grants and incentives to bio-based startups, diminishing the risk associated with initial capital investments (EU BBI JU, 2023). Without the support of policies and market incentives, numerous bio-based industries find it challenging to compete with established fossil-based players [65].

Ultimately, the bio-based supply chain is deeply interconnected, necessitating robust collaboration among various stakeholders to tackle logistical, economic, and technological obstacles. As regulatory frameworks develop and market demand grows, improved coordination, investment in technology, and optimised logistics will be crucial for realising the full potential of bio-based industries.

Below are presented the main stakeholders for each technology and each value chain.

Biogas Production from Pig Manure & Wastewater

Creating a sustainable manure-to-value chain requires collaboration among various stakeholders:

- **Primary producers (pig farmers):** They provide the manure and have the potential to earn extra income from its valorisation. Farmers can take on different roles, from merely supplying manure to actively investing in biogas plants or treatment facilities. Their competitive edge lies in feedstock availability at no cost (as manure is considered waste). Farmer cooperatives can enhance their scale and bargaining power by collectively managing a biogas facility.

- **Technology providers and processors:** Enterprises that supply anaerobic digesters, nutrient recovery systems, dryers, pyrolysis units, and more play a crucial role. They are responsible for constructing, operating, or maintaining the biorefinery units. Innovative small and medium-sized enterprises (SMEs) and engineering companies thrive in this sector by offering modular systems tailored for agricultural use. Their skills and efficiency influence the capital expenditure (CAPEX) and operational expenditure (OPEX) profiles.

- **Off-takers and buyers:** This category encompasses energy utilities (purchasing biogas or electricity), fertiliser blenders/distributors (marketing recovered nutrients), or industrial users (if any chemicals or fibres are created). For energy, gas grid operators or power companies might acquire biomethane or electricity through feed-in agreements. For fertilisers, agricultural input firms could integrate recovered nitrogen and phosphorus into their product offerings, or farmers might utilise the products themselves, completing the nutrient loop.

- **Regulators and certifiers:** Although they are not directly part of the chain, government agencies exert significant influence through subsidies (such as renewable energy incentives and carbon credits) and by establishing regulatory frameworks (such as permitting plants and product approval). Alignment with policy objectives (e.g., national biogas targets and nutrient recycling ambitions) can provide a competitive edge through support programs.

- **Supporting stakeholders:** This group includes financial backers (banks or funds investing in bioeconomy ventures), research institutions (optimising technologies and evaluating sustainability), and consulting services for farmers. Additionally, local communities are interested, as effective manure processing can mitigate odour and pollution, thus enhancing the social acceptance of intensive pig farming.

In a well-structured supply chain, pig farmers would generate revenue (or savings) from selling manure or associated products instead of incurring costs for waste disposal. Processors and technology firms benefit from managing the facilities and selling the outputs. Buyers procure a nearby renewable energy or fertiliser source, often at competitive prices and with "green" accolades. For example, the MANUREFINERY initiative anticipates launching seven innovative value chains in livestock areas and envisions generating €350 million in new annual income for primary producers if an expansion occurs. Notably, these models strive for mutually beneficial outcomes: minimising environmental impact while broadening farm revenue.

Nutrient Recovery from Pig Manure

- **Pig farmers and livestock producers** are fundamental to the process, as they create the manure that requires management. They are motivated to lower waste disposal expenses, enhance nutrient utilization on their farms, and adhere to environmental regulations. Enhanced manure management also aids in achieving their sustainability objectives and improving their public reputation.

- **Manure processing facilities and technology developers** are vital in creating and implementing nutrient recovery systems. These systems include chemical, biological, and physical treatment techniques like the Quick Wash process or struvite precipitation. They provide the technical knowledge and infrastructure necessary to transform raw manure into valuable fertiliser products.

- **Fertiliser companies** are significant stakeholders as potential consumers of the recovered nutrients. Given the worldwide scarcity and increasing costs of mineral phosphorus, these businesses are more interested in sustainable alternative nutrient sources that can be incorporated into commercial fertiliser offerings.

- **Crop farmers and the broader agricultural sector** are the end-users of the reclaimed fertilisers. They gain from manure-derived products that feature improved nitrogen-to-phosphorus ratios, which better meet crop nutritional requirements, enhance soil fertility, and reduce environmental impacts.

- **Environmental regulatory bodies** are crucial in establishing and enforcing nutrient management and water quality regulations. They facilitate the adoption of nutrient recovery technologies by mandating or encouraging practices that prevent runoff, leaching, and the eutrophication of water bodies.

- **Researchers and academic institutions** assist by advancing and refining recovery technologies, evaluating their environmental and economic effects, and ensuring scientific integrity. Their efforts promote ongoing innovation and evidence-driven policymaking.

- **Governments and lawmakers** affect the entire system through funding initiatives, policy formulation, and regulatory frameworks. They can promote investment in nutrient recovery through grants, tax incentives, or environmental requirements.

- **Non-governmental organisations (NGOs) and environmental advocates** facilitate the implementation of sustainable manure management techniques. They raise awareness, advocate for stronger regulations, and often collaborate on pilot initiatives to showcase best practices.

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

In the process of valorising pig hair and skin, the supply chain would involve the following:

- **Slaughterhouses and meat processors represent the origin of the raw hair and skin materials.** Currently, they incur costs for disposing of hair (or incinerating it on-site for heating purposes). With a new chain, abattoirs could gather bristles and hooves in designated bins for a keratin processor, potentially receiving modest payments instead of paying for waste disposal. For skin, large processors already separate skins for gelatine production or pork rind manufacturing; any shift to a new application will require coordination. Slaughterhouses play a crucial role as stakeholders, and their willingness to engage (providing space for collection and modifying procedures to keep hair free from chemical contamination) will influence supply reliability.

- **Rendering or processing companies may either adopt new processes or emerge as specialised entities**. A rendering company currently handling animal by-products (such as bones and fat) could introduce a keratin extraction line or a collagen refinement line. Royal Triumph Solutions (Spain) is an example of a small to medium-sized enterprise that was involved in this area through the KERASOL project. Established gelatine producers are also essential stakeholders; they may see new uses for collagen as either competition or complementary opportunities. Some may choose to invest in creating higher-value collagen peptides or medical-grade collagen derived from pig skin, rather than simply producing bulk gelatine.

- **End-product manufacturers** include cosmetics companies (for keratin), detergent producers, supplement and pharmaceutical firms (for collagen peptides and capsules), and food industries (for gelatine). These entities drive market demand and may establish partnerships or supply agreements. For example, a cosmetics brand could contract a keratin supplier to provide a specific grade of soluble keratin intended for a shampoo product line. Their needs (including purity, functionality, and regulatory approval for the ingredient) essentially define the specifications for the output from the biorefinery.

- **Regulatory bodies and standards organisations** ensure that any products derived from these waste materials comply with safety regulations (for example, EFSA oversees food additives like gelatine, while the European Chemicals Agency pertains to chemical substances in cosmetics). Achieving approved status (such as being listed among permitted cosmetic ingredients or receiving novel food approval for a new collagen peptide product) is a vital process.

- **Market facilitators include marketing experts** to highlight the sustainability aspect (upcycling and circular economy) of these ingredients, which can enhance their value. Additionally, R&D partners must continually improve extraction efficiency and product quality (for example, universities researching non-denaturing keratin extraction as mentioned in academic literature).

An eco-friendly supply chain would convert materials that were previously considered waste needing disposal into a valuable product stream. For instance, rather than burning bristles (which causes pollution and produces no valuable product), those bristles could be utilised as a cosmetic ingredient, generating revenue while minimising pollution. This approach also alleviates landfill pressure (keratin and collagen waste are biodegradable but decompose very slowly; hair disposed of in landfills can persist for extended periods due to its keratin strength). The main goal is to ensure that every stakeholder benefits: slaughterhouses can manage waste disposal more cost-effectively (or profitably), processors can earn by selling ingredients, and end-users receive a story and functionality that may justify a higher price.

Hydroxyapatite Purification from Pig Bones

Key participants in a pig bone-based value chain consist of:

- **Slaughterhouses and Cutting Plants:** These facilities produce raw bones. Presently, they usually send bones to rendering plants. In a revised value chain setup, they could instead direct bones to a bone processing facility (if distinct from rendering). They would require storage (chilled or frozen to avoid spoilage) and logistical transport solutions. They would have a motive to supply if they receive a better return for bones than rendering provides (which often merely covers costs). Large abattoirs (particularly beef) produce several tonnes of bones daily and might even perform initial on-site processing (like crushing or steaming) to decrease transport volume.

- **Rendering / Processing Industry:** Renderers currently play a crucial role in bone management – they sterilise and crush bones into meat and bone meal (MBM) and extract fats. They could transition to generating specific products such as bone char or hydroxyapatite, due to their access to feedstock and some existing infrastructure (e.g., boilers and cookers that might be repurposed as pyrolysis units). In fact, some innovative facilities integrate combustion/char of by-products. New specialised firms (3R BioPhosphate technology) could collaborate with or license technology to renderers.

- **Environmental Agencies & Policymakers:** They indirectly affect the supply chain by establishing management regulations. Furthermore, waste regulations can promote shifting bones from a "waste" classification to a "product" classification, for example, by acknowledging bone char as a product.

- **Innovators in Material Science:** For applications beyond fertilizers (such as hydroxyapatite for medical purposes or catalysts), relevant stakeholders include research laboratories and high-tech companies. They connect raw bone processing to manufacturing biomedical devices or industrial catalysts, ensuring that the material fulfils necessary specifications (purity, particle size, phase composition).

Combustion of Pruning Wastes for Energy

- **Agricultural Producers/Orchard Owners:** They must permit or engage in collecting pruning. This helps them avoid burning (which can be labour-intensive and is now often prohibited) and potentially earn some revenue or save on biomass. Some orchardists might invest in their chippers or boilers to utilise pruning directly. Their willingness is essential; if the process becomes too cumbersome without adequate benefits, they will not participate. Uprunning discovered that showing potential additional income or clear local advantages was necessary to incentivise farmers.

- **Biomass Collection Contractors:** In areas where this has become popular, a service company frequently arises that specialises in the collection of pruning. They may offer to prune and gather for a fee or in exchange for the biomass itself. These contractors possess the necessary equipment (pruners, balers, chippers, trucks) and then provide the biomass to the end users (such as power plants or pellet producers). Their business model depends on having enough quantity and a reliable buyer.

- **Energy Generators:** These can range from small-scale (individual farm boilers) to larger operations (biomass power plants, heating facilities). Larger plants may require consistent fuel specifications (moisture content, size) and volumes and might blend pruning biomass with other fuel types. For instance, a 5 MW biomass facility could utilise several thousand tonnes of pruning mixed with other wood materials. District heating providers could incorporate local pruning, promoting them as locally sourced renewable energy.

- **Machinery Manufacturers:** Companies that create equipment such as pruner attachments, chippers, and balers specifically designed for orchard wood are stakeholders—success in this niche broadens their market. Some businesses in the EU have indeed created prototypes like pruning balers that compress small pruning into round bales for more manageable handling.

- **Local Governments/Cooperatives:** Occasionally, local authorities or agricultural cooperatives can enhance coordination and invest in shared equipment. They might also organize awareness initiatives or collective projects. For example, a cooperative could operate a shared biomass heating system that uses the pruning from its members, thereby establishing a closed loop where farmers receive heat and a portion of the savings.

Extraction of Polyphenols from Peach & Nectarine Processing Waste

- **Food/Fruit Processing Companies:** These companies generate by-products. Numerous juice manufacturers or canneries are currently responsible for either paying for waste disposal or utilizing some of it in low-value applications. They may show interest if offered a value chain that transforms their waste into revenue or at least provides free disposal options. Some large processors have already invested in partial valorisation (for instance, a juice processing plant may have a feed mill that produces citrus pellets from peels). They can serve as partners by supplying raw materials and may even invest in on-site extraction facilities if it is advantageous.

- **Biorefinery Operators/Companies:** This group can include either new startups or divisions within established corporations. For instance, a major jam manufacturer could establish a separate unit to convert its waste into new products (vertical integration), or a startup might set up operations near several factories to consolidate their waste. They are responsible for the conversion processes – extracting compounds, fermenting substances into fuels, etc. An example of this is PeelPioneers in the Netherlands, which collects orange peels from supermarkets and juicing facilities and produces citrus oil, fibre, and animal feed ingredients; they effectively function as a biorefinery for citrus peels. Such entities must coordinate with waste producers to ensure a consistent supply and with end-users for product sale agreements.

- **Buyers of the Outputs:** This category is quite broad, including ingredient suppliers, dietary supplement producers, cosmetic manufacturers, energy purchasers, chemical firms, and farmers (for fertilisers or feed). Establishing stable markets may necessitate offtake contracts – for example, a chemical company might contract to purchase all the limonene oil produced by a peel biorefinery, providing financial assurance. Likewise, a polyphenols manufacturer may collaborate to process extracted pectin into commercial-grade products.

- **Research and Development Bodies:** As numerous fruit waste processing methods are evolving, partnerships with academic institutions or research organisations are common to enhance technology (such as optimising enzyme application to maximise fermentable sugars from pomace or creating new applications like microbial enzyme production using fruit waste as a substrate).

- **Policy and Waste Management Sector:** Fruit waste typically falls under regulations concerning biodegradable waste. If governments impose stricter restrictions on the landfilling of organic waste (as is being implemented by the EU), processors will require solutions for their waste – this indirectly bolsters the supply chain by making waste accessible (and perhaps at a negative cost: companies might pay biorefineries to accept it, akin to a tipping fee). Additionally, if local governments collect fruit and vegetable waste (for example, from wholesale markets), they could supply a public or private biorefinery facility.

The development of bio-based value chains relies on a complex network of stakeholders coordinating across multiple stages, from raw material collection to the final commercialisation 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. The BBTWINS project involves agricultural producers and the 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 utilise 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 due to high moisture content, low bulk density, and perishability. For instance, transporting pig manure for biogas production requires specialised containment systems, while fruit residues must be dried or stabilised before processing. Solutions like regional bio-hubs and decentralised processing plants help mitigate transportation inefficiencies and reduce costs [65].

At the regulatory and policy level, government bodies, financial institutions, and research organisations 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). Many bio-based industries struggle to compete against fossil-based incumbents without policy backing and market incentives.

The bio-based supply chain is highly interdependent, requiring strong stakeholder collaboration 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. Main Companies and Competition in the Bio-Based Value Chain

In the field of biogas, major energy firms such as ENGIE, Veolia, and Nature Energy have established comprehensive anaerobic digestion systems to transform livestock manure, wastewater sludge, and organic waste into biomethane. The European biogas market is expected to achieve €87.86 billion by 2030, with Germany, France, and Italy at the forefront of biomethane production capacity [63]. The effectiveness of biogas projects relies on feedstock availability, governmental incentives, and the infrastructure needed for gas grid integration [66, 67].

Companies including Yara, Nutrien, and Biolan are major players in organic fertiliser, offering synthetic and organic fertilisers to agricultural markets. The nutrient recovery technologies from BBTWINS, which produce recovered phosphorus and nitrogen fertilisers, encounter cost disadvantages when compared to conventional fertilisers. Nonetheless, the tightening EU regulations on synthetic fertilisers and the Fertilising Product Regulation (2019/1009) present market opportunities for sustainable alternatives. In the realm of speciality biochemicals, firms such as Evonik, Croda, and BASF extract keratin and collagen, serving the cosmetics, food supplement, and biomedical sectors. BBTWINS' process of extracting keratin hydrolysate from pig hair demonstrates significant economic potential, with a net present value of €907,940 and an internal rate of return of 13.07%, while collagen extraction is less feasible due to high costs. Competitive positioning within this sector hinges on product purity, scalability of production, and the ability to integrate with existing supply chains.

The biochar market employs fruit pruning waste for carbon sequestration and soil amendment, with innovators like AirTerra, Carbon Gold, and Swiss Biochar leading the way. The global biochar market is anticipated to reach €5.91 billion by 2033, supported by EU policies that advocate for its use as a carbon-negative agricultural input. In summary, the bio-based industry is becoming more competitive, yet its success relies on reducing costs, enhancing product standardisation, and obtaining policy incentives to rival traditional materials [62].

3.3. Challenges & Opportunities for Additional Income Streams

The bio-based sector presents both economic barriers and new revenue opportunities, requiring strategic approaches to maximise 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 valorisation, carbon credit schemes, policy-driven incentives, and market diversification [62-69]. Below are described the main opportunities for each technology and bio-based product:

Biogas and Biomethane Production via Anaerobic Digestion

Producing biogas and biomethane from agri-food waste, including pig manure and sludge, not only addresses environmental issues but also creates substantial revenue opportunities. In various European nations, renewable energy feed-in tariffs and green certificate schemes provide attractive payments for biomethane introduced into the grid. Moreover, digestate, the solid and liquid byproduct of this process, can be processed and marketed as organic fertiliser, especially in areas where sustainable agricultural inputs are in high demand. Additional revenue can be generated through participation in voluntary carbon markets, where methane capture and reducing fossil fuel use result in tradable carbon credits.

Recovery of Nutrients from Manure and Sludge

Technologies that extract nitrogen and phosphorus from manure and sludge can produce bio-based fertilisers like struvite and ammonium sulphate. These products can be used in both conventional and organic farming. Customised nutrient blends tailored to the specific soil requirements of the region can command higher prices, particularly under EU guidelines that promote circular nutrient usage. Moreover, local production diminishes dependency on imported synthetic fertilisers, strengthening regional resilience. The intellectual property linked to unique recovery methods can also generate licensing income or form the foundation for technology collaborations.

Protein Recovery from Pig Hair and Skin

Extracting high-value proteins such as keratin and collagen from pig hair and skin presents opportunities in various industries. Hydrolysed collagen is a sought-after component for anti-ageing and skin-repair products in the cosmetics and personal care sector. In agriculture, amino-acid-rich protein powders can be utilised as feed additives for aquaculture and livestock. Additionally, these proteins can be integrated into biodegradable materials like biofilms and adhesives, capitalising on the expanding bio-based materials market. By-products such as lipids and aqueous fractions from the processing may be further utilised through energy recovery or included in lower-value product formulations.

Hydroxyapatite Sourced from Pig Bones

Hydroxyapatite obtained from pig bones has valuable uses in the medical, nutraceutical, and materials industries. Medical-grade hydroxyapatite is employed in bone grafts and prosthetics due to its compatibility with biological systems. Calcium supplements derived from natural bone sources are increasingly preferred over synthetic options in the nutraceutical sector. The material can also be utilised as a pigment in ceramics and coatings. Partnering with pharmaceutical or biomaterials companies could establish revenue streams through co-development of technologies or contracts for raw material supplies.

Fruit Processing Waste Polyphenol Extraction

Recovering polyphenols from fruit waste, such as peach and nectarine skins, offers multiple possibilities in the functional food, supplement, and cosmetics industries. These antioxidant compounds are highly sought after for their health benefits and can be marketed as active ingredients in dietary supplements or included in skincare products. Additionally, polyphenols possess natural preservative qualities that can be utilised in sustainable food packaging. Sales to ingredient formulators or incorporation into proprietary product lines can further diversify revenue streams.

Valorisation of Peach Pruning Waste (Combustion, Composting, Biochar)

Peach pruning waste, typically viewed as a disposal issue, can be converted into several valuable products. The combustion of biomass can provide heating for local applications, such as in greenhouses or small-scale district heating systems. Composting produces organic fertilisers that are well-suited for vineyards and orchards, while pyrolysis can create biochar, a soil improvement agent recognised for its carbon sequestration capabilities. Emerging carbon farming initiatives may enable the monetisation of biochar through confirmed carbon credits, establishing a sustainable income source linked to environmental performance.

4. Market and Competitor Analysis

4.1. Biogas Production from Pig Manure & Wastewater

The utilisation of pig manure in Europe can be analysed alongside other regions and alternative applications. Within the EU, Germany and Italy have been at the forefront of agricultural biogas production; thousands of biogas plants mix manure with other biomass, benefiting from feed-in tariffs. Denmark is a pioneer in centralised biogas, aiming to utilise 50% of its manure for biogas, supported by substantial subsidies and climate initiatives. In this landscape, manure competes with energy crops (such as maize silage) as a source for biogas. Although crops yield greater biogas per ton, utilising waste manure is more environmentally friendly and is now promoted by policy (with certain countries offering incentive payments for biogas produced from manure). Conversely, in many parts of the world (for instance, certain areas in Asia), untreated manure is primarily viewed as a problem, leading to pollution – the EU's movement towards biogas and nutrient recovery may allow European technologies and firms to share their expertise with those markets.

In Europe, the biorefinery process for manure encounters competition from traditional waste management: in the short term, the cost of doing nothing (such as lagoon storage or spreading on fields) is low. However, increasing regulations and societal pressure (concerning odours and water quality) are making these options less feasible – for example, regions with high pig populations (such as the Netherlands, Brittany in France, and Catalonia in Spain) have had to implement manure quotas and promote processing. Another competitor is the production of chemical fertilizers: any nutrient product derived from manure must compete with mined phosphate or synthetic nitrogen from the Haber-Bosch process in terms of cost and performance. However, manure has an advantage here as it completes nutrient loops and generally has a smaller carbon footprint; moreover, fertilisers produced from manure often retain organic matter that is beneficial for soil health, which is absent in mineral fertilisers. Despite this, the nutrient content tends to be lower and releases more slowly, indicating that the market for these products may initially be limited to local or specialized segments.

From a technological integration standpoint, the value chains of pig manure can be enhanced by merging with other waste streams – for instance, co-digesting manure with fruit or food waste can significantly increase biogas production (since manure supplies buffering agents and nutrients, while high-energy waste contributes fermentable carbon). Indeed, research has demonstrated that integrating fruit waste with swine manure has improved nutrient and protein recovery. Such interactions result in better economic and technical performance.

On a social level, systematically managing manure can enhance the reputation of livestock farming as a component of a circular bioeconomy instead of being perceived as a wasteful industry. Life Cycle Assessments (LCAs) consistently show that processing manure through biogas digesters decreases greenhouse gas emissions (by capturing methane that would otherwise escape) and alleviates nutrient pollution, assuming the digestate is properly managed. For instance, capturing methane from manure and using it results in more emissions reductions than the processes emit, thus supporting climate objectives. One consideration is that if manure is currently applied to land, extracting it for processing may require fields to have compensatory fertilization; therefore, recycling the nutrients in a different format is essential for genuinely closing the loop.

In conclusion, European pig manure biorefineries possess significant potential to establish value chains for energy and fertilisers, leading to positive environmental outcomes. The actual implementation hinges on overcoming economic and logistical challenges, but continuous innovation and favourable EU policies (supporting renewable energy and nutrient recycling) are steering the perception of manure from a “waste” to a valuable resource for sustainable value generation.

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

In different settings, various keratinous by-products are being utilised – for example, poultry feathers (amounting to millions of tonnes worldwide) are frequently transformed into feather meal for animal feed (a simpler value chain with moderate worth) or are being investigated for keratin film production. Some Asian businesses have started extracting keratin from feathers for use in shampoos.

Pig hair presents competition in this area; one potential advantage of pig hair is that it generally comes from a single source (abattoir) and is cleaner than feathers (which often carry blood and faecal matter from chicken processing), although pig bristles do have bits of attached skin and require cleaning. Regionally, perspectives differ: in countries like China, pig bristles are traditionally used (e.g., for high-quality calligraphy brushes or bristle brushes) – this represents a developed, although niche market. In Europe, synthetic fibres have largely supplanted these traditional uses, so an innovative application like keratin extraction might encounter less established competition and receive more support as an environmentally friendly solution. Regarding pig skin, the main competition comes from other gelatine producers and alternative sources (bovine and fish).

Europe’s regulations post-BSE complicated bovine sourcing in the late 1990s, benefiting pig skin use. Currently, fish gelatine poses only a minor competitive threat (with particular appeal in halal/kosher and “pescatarian” markets) but tends to be more expensive and not a complete substitute for pig or bovine gelatine in various uses. From a social standpoint, cultural factors must be considered – some consumers avoid porcine products, so certain markets (such as the Middle East) may reject ingredients derived from pigs (which explains the existence of halal gelatine made from fish or bovine sources). This somewhat restricts the global market for pig-based value chains, though they are generally acceptable in Europe and America.

The integration and optimisation of technology: Valorising pig hair and skin can be integrated with existing rendering and processing facilities. For instance, a slaughterhouse could direct skins to a collagen plant while simultaneously utilising the remaining grease or bones for other processes, achieving near-zero waste. Integration may also entail combining processes: a biogas unit could digest some of the residues from collagen extraction to generate energy for the facility (some gelatine factories utilise their waste for energy). From a technical optimisation viewpoint, enhancing extraction yields (e.g., through enzyme cocktails to break down hair more completely into soluble keratin – current yields might only be around 60%, leaving some residue) is crucial. Developing continuous processes (as opposed to batch) could also boost efficiency for large quantities.

Environmentally speaking, repurposing these wastes significantly lessens pollution. Disposing of hair and hooves in landfills is a concern due to their slow decomposition and potential leaching (and landfills must be reduced according to EU law). While incinerating them recovers energy, it releases CO_2 and may generate odours; transforming them into products conserves some carbon and prevents emissions from producing equivalent synthetic items. Life-cycle assessments would likely yield favourable results: for instance, a kilogram of keratin obtained from waste versus producing it through chemical synthesis (if that were even feasible) or not extracting it at all – the upcycled product conserves resources and curtails emissions. From a social perspective, utilising all parts of the animal aligns with the ethical treatment of livestock; it can be portrayed as a sign of respect for the animal, ensuring that nothing is wasted, which may enhance public perception of the meat industry's sustainability initiatives.

4.3. Hydroxyapatite Purification from Pig Bones

In various regions or industries, some nations like the USA continue to permit the use of meat and bone meal (MBM) in animal feed for non-ruminants, giving bones value as a protein source. In Europe, however, such use is restricted, highlighting the necessity for alternative applications. Bone waste can be likened to fish bone waste generated in the fish processing industry, where similar techniques for extracting gelatine or producing fertiliser can be utilised, although fish bones typically have a smaller volume. Another analogy involves the extraction of phosphate from sewage sludge, which is a significant focus in Europe, encompassing technologies that retrieve phosphorus from incinerated sewage sludge ash or directly from sludge. Bone char competes with struvite, a crystallised form of phosphate derived from wastewater, and fertilisers based on sewage sludge ash as recycled phosphorus sources. Each alternative has its advantages and disadvantages: bone char features very low heavy metal content and is easily applicable on farms; struvite is highly pure and beneficial for specific crops but only provides phosphorus and some nitrogen; while fertilisers from sludge ash may require acid treatment. From a competitive standpoint, bone char may have an advantage as a natural product that contains multiple nutrients.

From a technical viewpoint, the valorisation of bones can enhance other waste management strategies. For instance, if a biogas facility processes slaughterhouse byproducts (such as blood and fat), it may still require a separate method for bones – incorporating a bone char unit could enable the biogas facility to handle all outputs on-site. Alternatively, a gelatine production facility could partner with a power plant that burns residual bone solids to generate energy for gelatine extraction (some already implement similar strategies with skin offcuts).

Social and environmental factors support the use of bone waste as being largely beneficial for the environment, as it diminishes the need for landfilling (which was previously more common but is now increasingly avoided) and helps conserve phosphorus, a finite resource crucial for food production. Disposing of bones in landfills not only squanders space but also misses the opportunity to recycle valuable nutrients and materials. From a climate standpoint, converting bones into biochar effectively captures some carbon (via the char portion) and prevents emissions that could arise from decomposition or open incineration without energy recovery. The advantages of the circular economy are considerable, as this exemplifies transforming waste into valuable resources, enhancing resource efficiency, and lessening dependence on virgin mining.

From a social perspective, the direct effects on consumers may be minimal (unlike the concerns raised regarding the use of animal proteins in feed). Fertilisers made from animal bones might even be perceived as more “natural” than their chemical counterparts. However, it is essential to ensure transparency in the supply chain to prevent any food safety issues; experiences from BSE demonstrate the necessity of strict regulation and communication when reintegrating animal by-products into food or feed systems. If used as fertiliser, the risk remains low (as it involves soil application rather than direct entry into the food processing chain, and high-temperature processing can eliminate any pathogens).

Regarding other regions, countries with significant meat production industries (such as Brazil, the USA, and Australia) also face challenges related to bone waste. Some have found productive uses for it (for example, Australia exports meat and bone meal as fertiliser). Europe's sophisticated regulatory framework and its emphasis on sustainability may position it favourably in developing advanced uses (like certified organic fertilisers or biomedical applications). This could potentially evolve into an export sector, with bone char fertilizer or technology being sent to areas experiencing phosphate deficiencies or high meat production levels.

4.4. Combustion of Pruning Wastes for Energy

The alternative to utilising pruning typically involves traditional energy sources like fossil fuels or other forms of biomass. For instance, inexpensive coal or gas diminishes the motivation to engage with pruning unless incentives like carbon pricing or renewable energy targets exist. Another alternative is forest biomass; sawdust and forestry waste are often easier to gather in certain areas and have established markets. A power plant may prefer the predictability of forestry chips unless encouraged to also utilize agricultural biomass. Additionally, there's competition for land use: leaving pruning to serve as mulch provides alternative benefits (although it is not a market competitor, it holds value for farmers regarding nutrient enrichment and organic matter). If removing pruning necessitates increased fertilizer application or impacts long-term yields, this is a trade-off to evaluate. Some agronomists suggest returning some biomass to uphold soil carbon levels. However, research indicates that properly removing above-ground pruning has a negligible effect on yield, and any lost nutrients (primarily potassium found in wood ash) can be replenished through ash or other methods. In contrast, orchard pruning are frequently burned or mulched in regions like the USA or Australia. The EU is leading the effort to exploit them for energy purposes. When comparing sectors, one might look at the utilization of straw in grain farming—straw can either be left in the fields or harvested for various uses, such as bedding or bioenergy. Straw has a more developed market (e.g., power plants in Denmark utilize straw). Prunings are akin but tend to be denser and less uniform, which complicates handling somewhat.

Peach pruning waste can be seamlessly incorporated into current farming operations. For example, a farmer may integrate a pruning harvester into their annual schedule and use the resulting chips to heat buildings on-site or to dry fruit and nuts. This on-site integration is efficient, reducing transportation needs and providing direct benefits. On a larger scale, incorporating orchard pruning into regional energy strategies, such as combining them with other residues like olive pits, which are a significant bioenergy resource in olive oil production, can help ensure a consistent biomass supply for a regional bioenergy facility. It is crucial to keep moisture levels low; one optimization method involves allowing pruning to dry in the field post-cutting (sun drying) for several weeks before collection, which enhances combustion quality and decreases weight.

Environmental evaluations show that utilising pruning for energy yields net greenhouse gas savings, particularly when replacing coal-based power. However, if replacing a relatively clean grid (such as one that predominantly uses renewable electricity), the benefits are diminished, yet still significant. Direct emissions from burning in an uncontrolled environment are avoided, including CO_2, particulate matter, and black carbon that contribute to local pollution. Thus, from a social and environmental viewpoint, halting the open burning of pruning offers immediate air quality improvements for local communities by reducing smoke, a known health hazard. Many regions in Europe face severe air quality issues at times, partially due to agricultural burning; reducing this is a compelling reason for promoting these value chains.

The community's acceptance of converting pruning into energy is generally favourable—turning waste into useful energy is considered practical. The challenges encountered are more practical and economic than perceptual. In fact, some communities take pride in local renewable energy initiatives that utilize what was once considered waste. The successful flagship cases all share a story of local innovators overcoming initial doubts to demonstrate feasibility, prompting gradual adoption of the practice by others.

4.5. Extraction of Polyphenols from Peach & Nectarine Processing Waste

Some nations have traditional applications for particular fruit byproducts. For instance, Brazil, the leading producer of orange juice, utilizes citrus waste to create citrus pulp pellets for livestock feed and also extracts d-limonene oil – a well-established process. In Italy, a significant portion of the grape marc is sent to distilleries to manufacture grappa (a type of brandy) and tartaric acid – another classic value chain operating as a biorefinery. These examples illustrate that with favourable conditions (such as a high volume of a single type of waste and a clear product like alcohol or animal feed), industries can thrive. Europe can draw comparisons to regions that are less developed: for instance, in numerous developing nations, fruit waste is often discarded, presenting an opportunity if technology and scale can be adapted.

When comparing across sectors, fruit waste faces similar challenges to other forms of biowaste, including vegetable waste and non-food biomass. The movement toward “zero waste” and a circular economy is beneficial – companies seek to avoid the perception of squandering valuable resources. Furthermore, compared to lignocellulosic waste (such as wood or straw), fruit wastes are easier to process biologically due to their lower lignin content and more accessible sugars. This results in technologies designed for their conversion often yielding better results or requiring less extensive pretreatment. However, their elevated moisture content and propensity to decay quickly necessitate prompt action, whereas straw can remain stored for several months.

In terms of technical integration, a biorefinery focusing on fruit waste may combine several processes: one study proposed a generic strategy where fruit byproducts are initially ground and then dried to approximately 5% moisture using energy derived from biogas produced on-site, followed by sequential extraction and fermentation processes. Integrating energy (by utilising some of the waste to power the drying or extraction processes) is vital for reducing external energy requirements. For example, using biogas generated from part of the waste to fuel the evaporators needed for pectin extraction is one such integration. Another form of integration involves reusing water or solvents between different processing stages to minimise waste.

From a societal viewpoint, the valorisation of fruit waste presents largely positive outcomes: it decreases disposal issues (thus reducing smells and pest problems at dumps) and often generates employment in rural or processing areas where these new operations are established. Moreover, it resonates with consumers who are increasingly drawn to sustainable products – the notion that their jams or juices are produced in facilities that also develop valuable products from leftover materials serves as a strong marketing point (some companies already highlight their waste-upcycling initiatives as part of their corporate responsibility efforts).

Regarding environmental implications, converting fruit waste reduces methane emissions that would otherwise be released if it decomposed in landfills (landfilled fruit waste generates methane, a potent greenhouse gas). There is a dual greenhouse gas benefit by transforming it into ethanol or biogas, which can replace fossil fuels. Additionally, the nutrients found in fruit (such as potassium and nitrogen) can be reintroduced to the soil through the digestate or compost, effectively closing nutrient loops. If extraction solvents are utilised, it is essential to ensure they are eco-friendly (like water, ethanol, or supercritical CO_2) rather than harmful chlorinated solvents to maintain an environmentally sustainable process. Many research initiatives are prioritising green extraction methods for this reason.

5. Economic Feasibility of the Proposed Solutions

Techno-economic analysis, or techno-economic assessment, often abbreviated as TEA, is a method for analysing the economic performance of industrial processes. TEA is conducted through a methodology consisting of a series of holistic analyses that must be completed consecutively (process design, process modelling, equipment sizing, capital cost estimation, operating cost estimation, and cash flow analysis). The complexity of the problems demands a wide coverage of economic indicators (e.g., plant operation, plant design, transport, market behaviour, etc.).

Based on the TEA result, a process can be evaluated based on specified parameters and assumptions for many purposes. It has been conducted conventionally over the past two decades for various purposes, ranging from the evaluation of economic factors, i.e., net present value (NPV), payback period (PBP), internal rate of return (IRR), return of investment (ROI), discounted cash flow rate of return (DFROR), capital cost, general costs, profit or revenue, economic potential, overall economic feasibility, process factors, i.e., energy saving percentage, process parameter optimization, efficiency of operation, and environmental factor.

The TEA for each technology under study was determined by analysing the Net Present Value (NPV), Internal Rate of Return (IRR) and Payback Period.

- **Net Present Value (NPV)**

Net Present Value (NPV) is a financial metric used to evaluate the profitability of an investment or project by calculating the difference between the present value of cash inflows and the present value of cash outflows over a period of time. It considers the time value of money, which reflects the principle that a certain amount of money today is worth more than the same amount in the future due to its potential earning capacity. Usually, the NPV discounts future cash flows to their present value using a specified discount rate, typically the cost of capital or required rate of return. A positive NPV indicates that the projected earnings (in present value terms) exceed the anticipated costs, suggesting that the investment is likely to be profitable.

NPV is calculated using the following equation:

$NPV=\sum t=1nRt-Ct(1+r)t-C0$NPV=∑t=1n(1+r)tRt−Ct−C0 (Equation 1)

Where:

- RtRt = Revenue in year tt
- CtCt = Cost in year tt
- rr = Discount rate (10%)

- $C0$C0 = Initial investment
- nn = Project lifespan (10 years)

- **Internal Rate of Return (IRR)**

The Internal Rate of Return (IRR) is a financial metric used in capital budgeting to assess the profitability of potential investments or projects. It is defined as the discount rate that makes the net present value (NPV) of all cash flows (both inflows and outflows) from a particular project equal to zero. In other words, IRR is the rate of return at which the present value of a project's cash inflows equals the present value of its cash outflows. It is often used to compare the desirability of different investments or projects. Generally, the higher the IRR, the more attractive the investment. In other words, if the IRR exceeds the required rate of return (hurdle rate), the investment is considered acceptable. If it is lower, the investment is typically rejected.

IRR is calculated using the following equation:

0=∑t=1nRt−Ct(1+IRR)t−C00=∑t=1n(1+IRR)tRt−Ct−C0 (Equation 2)

- **Payback Period**

The Payback Period is a financial metric used to determine the amount of time it takes for an investment to generate cash flow sufficient to recover the initial investment. It is a simple and straightforward method of evaluating a project's risk and liquidity.

Payback Period = Annual Cash Flow / Initial Investment (Equation 3)

It is important to note that the TEA was not carried out when a methodology or technology presented negative cash flows. If positive cash flows were obtained, the TEA analysis was performed. Below are presented the results of the TEA for each technology:

- **Biogas Production Study:** The scenarios using waste streams from Portesa (100 000 tons), Cartesa (212 tons) and 50 000 tons of Mixed grass and leguminous wastes and using waste streams from Portesa (100 000 tons), Cartesa (212 tons) and 20 000 tons of Mixed grass and leguminous wastes presented a remarkably high economic feasibility. Scenarios showed high economic feasibility with positive EBITDA, NPV, and IRR. The optimal scenario combining pig manure with mixed grass and leguminous wastes had a payback period of 1.2 years and produced 427,6269 m^3 of biomethane annually.

- **Chemical Extraction Study of Phosphorous and Nitrogen:** Economically unviable due to negative cash flows despite high recovery rates. The operational costs outweighed the potential profits from the recovered elements. The results obtained clearly indicate that a phosphorus and nitrogen recovery unit using the proposed chemical extraction method is not financially viable, as the cash flow obtained in both cases was negative.

- **Hydrolysis and Extraction of Keratin Hydrolysates:** The TEA results indicate that a unit processing and valorising 10 tons of pig hair per year for the production of keratin hydrolysate has an NPV of 907,940 €, an

IRR of 13.07%, and a Payback period of 5.41 years. All of these indicators suggest a highly potential project to explore in the future.

- **Hydrolysis and Extraction of Collagen Hydrolysates:** Economically unviable with negative cash flows in all scenarios due to high-fat content in raw materials, affecting the efficiency of conversion and purification processes. Results proved that economic viability was not achieved in any of the evaluated scenarios, as the calculated cash flow was negative for both. In fact, the results from the valorisation of 10 tons of pig skin had a negative cash flow of 453 743,88 €.

- **Extraction and purification of Hydroxyapatite from Pig Bones with Pyrolysis:** TEA results indicate that a unit processing and valorising 10 tons of pig bones per year for the production of hydroxyapatite has an NPV of 1 274 819,00 €, an IRR of 65.43%, and a Payback period of 1,5 years over a timeline of 10 years with a discount rate of 10%. All of these indicators suggest a highly potential project to explore in the future.

- **Combustion of Pruning Wastes:** TEA results indicate that a unit processing and valorising 10 tons of pig bones per year for the production of hydroxyapatite has an NPV of 1 77 220,00 €, an IRR of 199.67%, and a Payback period of less than 1 year over a timeline of 10 years with a discount rate of 10%. Once again, all of these indicators suggest a highly potential project to explore in the future.

- **Composting of Discarded Peach and Nectarine Fruits:** Results indicate that the proposed composting process currently has a slight negative cash flow (-583,60 €/year). Although the initial assessment of the composting process's economic viability was negative, optimizing several parameters could make it economically viable in the future.

- **Ultrasound Extraction of Polyphenols from Peach and Nectarine Processing Waste:** TEA results indicate that a unit of processing and valorising 10 tons of peach processing waste per year for the production of polyphenol extract with Ultrasound-Assisted Extraction (UAE) technology has an NPV of 441 846,00 €, an IRR of 17.00%, and a Payback period of 4,7 years over a timeline of 10 years with a discount rate of 10%. All of these indicators suggest a highly potential project to explore in the future

- **Supercritical Extraction of Polyphenols from Peach and Nectarine Processing Waste:** TEA results indicate that a unit of processing and valorising 10 tons of peach processing waste per year for the production of polyphenol extract with SFE technology has an NPV of 195 319,00 €, an IRR of -5,87%, and a Payback period higher than 10 years with a discount rate of 10%.

Therefore, the Best Technologies for the valorisation of meat and fruit processing waste, both from the technical and economic perspectives, are: Biogas Production; Hydrolysis and Extraction of Keratin Hydrolysates; Extraction and purification of Hydroxyapatite with Pyrolysis; Combustion of Pruning Wastes; Extraction of Polyphenols from Peach and Nectarine Processing Waste using Ultrasound-Assisted Extraction. However, it is essential to highlight that this assessment study analysed the technical and economic perspectives of the technologies under study. To fully comprehend all possible gains, it is imperative to consider the potential environmental benefits.

6. Cross-Sectoral Interconnections with BBTWINS Bio-Based Value Chain

Bio-based value chains form a fundamental component of the bioeconomy, facilitating the environmentally responsible production and utilising biological resources to meet industrial and societal demands. These value chains transform renewable biological materials—such as crops, animal by-products, forestry residues, and organic waste—into diverse products, including food, feed, bioenergy, biochemicals, biomaterials, and fertilisers.

To begin with, bio-based value chains promote resource efficiency and circularity. By leveraging waste streams and by-products from the agricultural, forestry, and food sectors, they decrease reliance on fossil fuels and lessen environmental impact. This fosters a circular bioeconomy, where materials are reused and recycled to prolong their lifespan and diminish waste. Moreover, they boost rural development and generate green job opportunities. Creating bio-refineries and processing facilities in farming areas stimulates economic activity, supports local enterprises, and promotes employment in rural communities. This strengthens local economies while encouraging sustainable growth.

Additionally, bio-based products can act as substitutes for fossil-based alternatives across various applications, including plastics, textiles, chemicals, and fuels. This replacement diminishes greenhouse gas emissions and aids in climate change mitigation by decreasing the carbon footprint associated with industrial manufacturing. Furthermore, bio-based value chains encourage innovation through the emergence of new technologies and materials. Progress in biotechnology, green chemistry, and process engineering allows for the production of high-value items from biological resources, bolstering the competitiveness of the bioeconomy sector. Lastly, these value chains align with sustainability, energy transition, and food security policy objectives. Decreasing dependency on imported raw materials and enhancing self-sufficiency in vital sectors contribute to more resilient and sustainable economic frameworks.

The BBTWINS project illustrates this by transforming meat processing by-products (such as pig manure, bones, and skins) into biogas, hydroxyapatite, and collagen hydrolysates, while converting fruit residues into biochar and polyphenols.

In addition to their environmental advantages, bio-based value chains generate economic prospects by stimulating new markets and drawing investment in green technologies. The European Union (EU) has prioritised support for bio-based industries through funding initiatives like the Bio-Based Industries Joint Undertaking (BBI JU) and the EU Innovation Fund, which dedicate billions of euros to projects promoting sustainable bio-based solutions together. Despite these advantages, challenges persist in scaling bio-based approaches to compete with established fossil fuel industries effectively. High production expenses, regulatory obstacles, and issues regarding consumer acceptance continue to impact market integration. Nevertheless, with ongoing policy backing, technological advancements, and targeted investment, bio-based value chains can significantly contribute to the transition toward a more resilient and sustainable economy.

The new value chains associated with the BBTWINS project can be individualised by each technology and product formed, or through the connection and interconnectivity between the different technologies and products formed.

The energy produced by the anaerobic digestion and combustion technologies will be the anchor vectors for supplying renewable energy to the technological processes.

Another critical factor is the formation of fertilisers (anaerobic digestion, chemical extraction and composting), which will make it possible to close the nutritional cycle and the circular economy of the whole process.

From a technical point of view, this value chain will lead to the formation of value-added bio-based products, such as keratin and collagen hydrolysates, hydroxyapatite and polyphenols. The figure below represents this potential bio-based value chain.

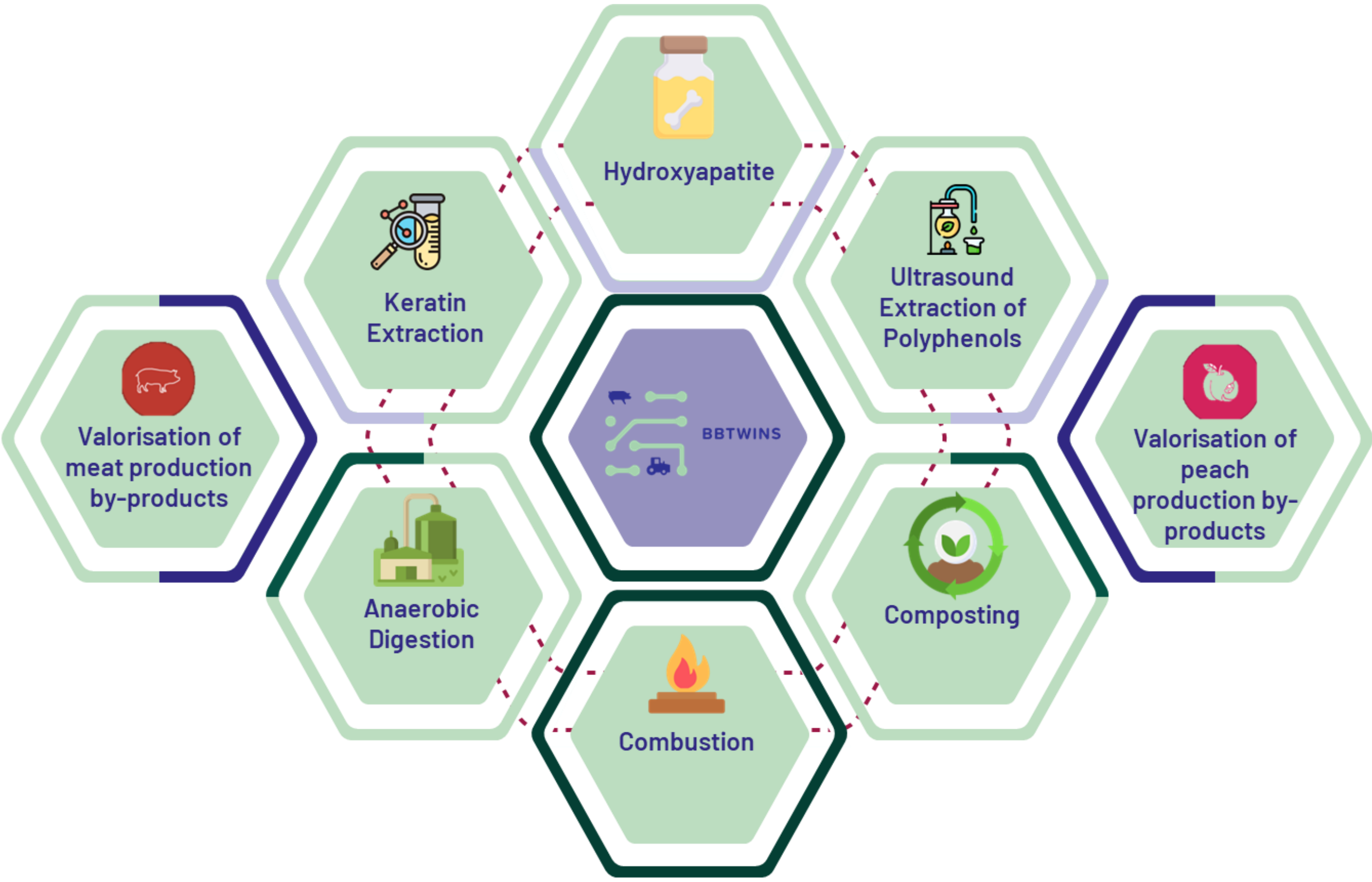

Figure 2. Proposed BBTWINS Bio-Based Value Chain

Another critical aspect is interconnectivity with other technological sectors. The agrifood industry is being transformed by digital technologies such as AI, IoT, blockchain, and Digital Twins, which enhance efficiency, traceability, sustainability, and economic resilience. These tools optimize farming, processing, logistics, and distribution through real-time data, predictive analytics, and automation. AI supports crop and livestock management decision-making, while IoT devices monitor environmental conditions, enabling precision agriculture and improved food safety. Blockchain ensures transparency by securely recording supply chain data, reducing fraud, and building consumer trust [70-75]. Digital Twins simulate the entire biomass processing chain, allowing the optimisation of resources and reducing waste.

The BBTWINS Digital Twin Platform integrates these technologies across two value chains: meat processing (PORTESA) and fruit processing (DIMITRA). It uses cloud-based infrastructure and AI analytics to monitor operations, simulate waste-to-energy solutions, and improve by-product valorisation (e.g., biogas, polyphenol extraction). Powered by the NORLEAN NOA engine, it provides real-time visualisation of biomass flow and economic performance.

Blockchain within BBTWINS ensures traceability by recording each step from raw material sourcing to the final product. It includes layers for data collection (via IoT), verification (smart contracts), and consumer access (QR code verification). This enhances compliance, safety, and sustainability in meat and fruit processing.

Real-world applications include:

- Digital Twins in precision farming, biogas optimisation, and speciality crops [65-67].
- Blockchain for traceability in livestock, poultry, sushi, and coffee supply chains [74, 75].

Companies like John Deere, IBM, and Cargill show how these technologies improve transparency and efficiency globally. The BBTWINS platform fully integrates these tools into one system, providing a comprehensive solution for digital transformation in the bio-based economy. It sets a new standard for circular, resilient, and sustainable agrifood value chains innovation and strategic investment. Bio-based value chains can be crucial in driving the transition to a more resilient and sustainable economy.

7. Conclusions and Future Steps

In the agri-food sector, materials previously deemed useless are now recognised as valuable resources for creating new value-added processes, driving Europe towards a circular bioeconomy. This report delivered a thorough feasibility analysis for establishing a new bio-based value chain by evaluating current and potential market sizes and identifying characteristics of emerging market segments and expected demand for bio-based products. Challenges related to the market, regulations, certification requirements, policy constraints, and consumer acceptance were highlighted, and criteria for developing supply chains to generate additional revenue streams for diverse stakeholders were specified. This endeavour involved identifying key participants in the chain, such as producers, processors, and distributors, along with their market shares and capacity to promote bio-based solutions. Factors considered included feedstock availability, technological readiness, and logistics infrastructure. The project has uncovered several promising bio-based innovations, including biogas, hydroxyapatite, polyphenol extracts, keratin, and collagen, which show significant market potential in multiple industries, such as renewable energy, pharmaceuticals, and cosmetics.

The economic feasibility of the suggested solutions was assessed using key investment metrics, including cost structures, market prices, payback periods, net present value (NPV), and internal rate of return (IRR). A comprehensive market and competitor analysis was conducted across various sectors, regions, and countries to pinpoint the most advantageous environments for incorporating the proposed technologies, thereby enhancing value chains from technical, economic, environmental, and social perspectives. As a result, this study laid the groundwork for at least one new bio-based value chain and one innovative cross-sector collaboration, supporting the development of a more circular, integrated, and sustainable bioeconomy.

Several common themes arise from the analysis:

- **Market Potential vs. Realisation Gap:** While the projected market sizes for these valorised products can reach vast figures (for example, billions of cubic meters of biogas from manure, hundreds of thousands of tonnes of keratin or collagen, and millions of tonnes of hydroxyapatite derived from bones), actual current usage remains relatively low in many instances. This disparity points to an opportunity that calls for further innovation, investment, and supportive regulations.

- **Integrated Value Chains and Multi-Output Models**: The most significant economic and environmental benefits often arise from integrated strategies that prioritise the extraction of high-value compounds, and the utilisation of residues for energy or fertiliser. This cascading approach ensures almost complete resource utilisation (for example, extracting polyphenols from peach waste and subsequently composting or producing biogas, or generating both bio-based products and bioenergy from slaughterhouse by-products). Biorefineries should be adaptable in their design to maximise outputs according to market needs and feedstock characteristics.

- **Stakeholder Collaboration:** Establishing these novel value chains requires collaboration among various stakeholders, including farmers, waste producers, technology providers, and end users. Case studies demonstrate that cooperative models can distribute both risk and reward (for instance, joint collection of pruning for district heating or collaboration between a slaughterhouse and a biotech company to produce keratin) [76]. Involving stakeholders early in the process, particularly those at the feedstock source, is vital for ensuring a reliable supply and gaining social acceptance. Furthermore, shifting perceptions towards seeing these wastes as valuable products rather than mere waste needing management is essential.

- **Economic Viability and Policy Support**: Economic evaluation indicates that most of the suggested technologies are financially viable. Nonetheless, due to logistical challenges, labour, and operating expenses, some of these value chains may not be economically sustainable, and in certain situations, they require incentives for their development. Initiatives such as renewable energy incentives, funding for pilot plants, incorporating recycled materials in green procurement policies, carbon pricing, and eliminating regulatory obstacles can all positively influence the economics. For example, the biogas produced from manure enjoys significant advantages from feed-in tariffs, while bone fertiliser can gain from recognition under fertiliser regulations and possibly from critical raw material strategies. Utilisation of fruit waste could increase with stricter bans on organic waste disposal and biofuel mandates. Hence, the role of policymakers is crucial in facilitating these processes. Successful initiatives like the BBTWINS project serve as proof of concept that can lead to scaling up and cost reduction.

- **Competitive Advantages and Sustainability**: Products derived from these waste streams frequently possess inherent competitive advantages within the current market landscape. They often carry a narrative of sustainability—keratin sourced from pig hair and collagen from pig skin help prevent pollution, appealing to environmentally conscious consumers; bone hydroxyapatite has applications in pharmaceuticals and oral hygiene; biogas from manure mitigates methane emissions from slurry and generates bioenergy; and peach pruning can provide energy and heat, diminishing the reliance on traditional open burning methods. This differentiation can result in price premiums or, at the very least, ease market entry against conventional alternatives. Sustainability assessments generally indicate significant environmental benefits, including a reduced carbon footprint, less extraction of primary resources, and minimised waste-related impacts. On a social level, these value chains have the potential to create job opportunities in rural regions and enhance waste management practices, addressing community issues such as odour and open burning smoke while contributing to rural development.

- **Technical Maturity and Innovation Needs**: The technical status or technological maturity differs across different waste streams. Certain processes, such as the anaerobic digestion of manure, composting, and combustion, are commercially established but still have room for improvement (e.g., modular biorefineries utilising digital twins to enhance efficiency). Other technologies, like keratin and collagen extraction and biorefineries for polyphenols from peach fruits, are currently in the pilot or demonstration phase and require scaling up and cost reduction. Therefore, ongoing research and development are crucial to enhance the yields of keratin, collagen, hydroxyapatite, and polyphenol extraction and to create effective small-scale machinery for collecting biomass from pruning. The EU's research initiatives and private sector innovations are making strides in these areas, as highlighted by the BBTWINS project. Nevertheless, further advancements in these fields and additional R&D projects will progressively mitigate risks and reduce costs, facilitating broader adoption of these technologies and methods.

When comparing different regions and sectors, it becomes clear that Europe is at the forefront of advancing agri-food waste valorisation, driven by initiatives like the Green Deal, Farm-to-Fork strategy, and Circular Economy Action Plan, along with a heightened public awareness of environmental issues. Comparisons across sectors—such as the utilisation of agricultural versus forestry biomass or the processing of slaughterhouse waste versus fish waste—indicate that methods developed in one area can be adapted or transferred to another.

In conclusion, establishing sustainable value chains from pig manure, byproducts from slaughterhouses, waste from peaches, and pruned orchard materials is increasingly essential and entirely achievable. This shift converts environmental burdens into economic opportunities, aligning with goals for climate action, resource efficiency, and rural empowerment. While there are still hurdles regarding market development, logistics, and initial financial viability, the direction is unmistakable: the agri-food sector of the future will focus as much on its output of bio-based products and energy as it will on its primary food production. By leveraging these frequently underestimated waste streams, Europe can progress toward a robust circular economy where “waste” is almost entirely eliminated.

Ultimately, the effectiveness of these value chains will not only be gauged by profits and advancements in environmental quality and socio-economic upliftment in rural regions. With ongoing innovation, supportive policies, and the entrepreneurial spirit of involved parties, the years ahead may see these previously marginal wastes emerge as vital resources in Europe’s bio-based economy. The BBTWINS project exemplifies both the progress made thus far and a strategic guide for expanding these promising value chains throughout Europe.

References

[1] S.M. Safieddin Ardebili. Green electricity generation potential from biogas produced by anaerobic digestion of farm animal waste and agriculture residues in Iran. Renew. Energy, 154 (2020), pp. 29-37, 10.1016/J.RENENE.2020.02.102.

[2] M.I. Alfa, D.B. Adie, S.B. Igboro, U.S. Oranusi, S.O. Dahunsi, D.M. Akali. Assessment of biofertilizer quality and health implications of anaerobic digestion effluent of cow dung and chicken droppings. Renew. Energy, 63 (2014), pp. 681-686, 10.1016/J.RENENE.2013.09.049.

[3] Sans, P.; Combris, P. World meat consumption patterns: An overview of the last fifty years (1961–2011). Meat Sci. 2015, 109, 106–111.

[4] S. Mehariya, A.K. Patel, P.K. Obulisamy, E. Punniyakotti, J.W.C. Wong. Co-digestion of food waste and sewage sludge for methane production: current status and perspective. Bioresour. Technol., 265 (2018), pp. 519-531.

[5] G. Lourinho, L.F.T.G. Rodrigues, P.S.D. Brito Recent advances on anaerobic digestion of swine wastewater. Int. J. Environ. Sci. Technol., 17 (12) (2020), pp. 4917-4938.

[6] G.D. Gebreeyessus. Effect of anaerobic digestion temperature on sludge quality. Waste Biomass Valori., 11) (2020), pp. 1851-1861.

[7] N.A. Duan, D. Zhang, C. Lin, Y. Zhang, L. Zhao, H. Liu, Z. Liu. Effect of organic loading rate on anaerobic digestion of pig manure: methane production, mass flow, reactor scale and heating scenarios. J. Environ. Manag., 231 (2019), pp. 646-652.

[8] W. Zhang, Q. Wei, S. Wu, D. Qi, W. Li, Z. Zuo, R. Dong- Batch anaerobic co-digestion of pig manure with dewatered sewage sludge under mesophilic conditions. Appl. Energ., 128 (2014), pp. 175-183.

[9] B. Mohamed, K. Mounia, A. Aziz, H. Ahmed, B. Rachid, A. Lotfi. Sewage sludge used as organic manure in Moroccan sunflower culture: effects on certain soil properties, growth and yield components. Sci. Total Environ., 627 (2018), pp. 681-688.

[10] P. Latifi, M. Karrabi, S. Danesh. Anaerobic co-digestion of poultry slaughterhouse wastes with sewage sludge in batch-mode bioreactors (effect of inoculum-substrate ratio and total solids). Renew. Sust. Energ. Rev., 107 (2019), pp. 288-296.

[11] S. Mehariya, A.K. Patel, P.K. Obulisamy, E. Punniyakotti, J.W.C. Wong. Co-digestion of food waste and sewage sludge for methane production: current status and perspective. Bioresour. Technol., 265 (2018), pp. 519-531.

[12] S. Borowski, J. Domański, L. Weatherley. Anaerobic co-digestion of swine and poultry manure with municipal sewage sludge. Waste Manag., 34 (2) (2014), pp. 513-521.

[13] Wang M., Zhang X.Y., Zhou J., Yuan Y.X., Dai Y.M., Li D., Liu X.F., Yan Z.Y. The dynamic changes and interactional networks of prokaryotic community between co-digestion and mono-digestions of corn stalk and pig manure. Biores. Tech. 2017;225:23–33. doi: 10.1016/j.biortech.2016.11.008.

[14] Mata-Alvarez J., Dosta J., Romero-Güiza M.S., Fonoll X., Peces M., Astals S. A critical review on anaerobic co-

digestion achievements between 2010 and 2013. Renew. Sustain. Energy Rev. 2014;36:412–427. doi: 10.1016/j.rser.2014.04.039.

[15] Fujita M., Scharer J.M., Mooyoung M. Effect of corn stover addition on the anaerobic digestion of swine manure. Agric. Wastes. 1980;2:177–184. doi: 10.1016/0141-4607(80)90014-1.

[16] Wu X., Yao W.Y., Zhu J., Miller C. Biogas and CH4 productivity by co-digesting swine manure with three crop residues as an external carbon source. Biores. Tech. 2010;101:4042–4047. doi: 10.1016/j.biortech.2010.01.052.

[17] Withers, P. J. A., Rodrigues, M., Soltangheisi, A., De Carvalho, T. S., Guilherme, L. R. G., Benites, V. D. M., et al. (2018). Transitions to sustainable management of phosphorus in Brazilian agriculture. Scientific Reports, 8(2537), 1–13. https://doi.org/10.1038/s41598-018-20887-z.

[18] Kunz, A., Miele, M., & Steinmetz, R. L. R. (2009). Advanced swine manure treatment and utilization in Brazil. Bioresource Technology, 100(22), 5485–5489. https://doi.org/10.1016/j.biortech.2008.10.039.

[19] Karunanithi, R., Szogi, A. A., Bolan, N., Naidu, R., Loganathan, P., Hunt, P. G., et al. (2015). Phosphorus recovery and reuse from waste streams. Advances in Agronomy, 131, 173–250. https://doi.org/10.1016/bs.agron.2014.12.005.

[20] Vaccari, D.A., 2011. Sustainability and the phosphorus cycle: inputs, outputs, material flow, and engineering. Environ. Eng 12, 29e38.

[21] Sperlich, A., Warschke, D., Wegmann, C., Ernst, M., & Jekel, M. (2010). Treatment of membrane concentrates: Phosphate removal and reduction of scaling potential. Water Science and Technology, 61(2), 301–306. https://doi.org/10.2166/wst.2010.800.

[22] Larsdotter, K., La, J., Jansen, C., & Dalhammar, G. (2017). Biologically mediated phosphorus precipitation in wastewater treatment with microalgae biologically mediated phosphorus precipitation in wastewater treatment with microalgae. Environmental Technology, 28, 953–960. https://doi.org/10.1080/09593332808618855.

[23] Ngatia, L. W., Hsieh, Y. P., Nemours, D., Fu, R., & Taylor, R. W. (2017). Potential phosphorus eutrophication mitigation strategy: Biochar carbon composition, thermal stability and pH influence phosphorus sorption. Chemosphere, 180, 201–211. https://doi.org/10.1016/j.chemosphere.2017.04.012.

[24] Peng, L., Dai, H., Wu, Y., Peng, Y., & Lu, X. (2018). A comprehensive review of phosphorus recovery from wastewater by crystallization processes. Chemosphere, 197, 768–781. https://doi.org/10.1016/j.chemosphere.2018.01.098.

[25] Laridi, R., Auclair, J.-C., Benmoussa, H., & Benmoussa, A. H. (2017). Laboratory and pilot-scale phosphate and ammonium removal by controlled struvite precipitation following coagulation and flocculation of swine wastewater. Environmental Technology, 26, 525–536. https://doi.org/10.1080/09593332608618533.

[26] Li, R. h., & Li, X. y. (2017). Recovery of phosphorus and volatile fatty acids from wastewater and food waste with an iron-flocculation sequencing batch reactor and acidogenic co-fermentation. Bioresource Technology, 245(September), 615–624. https://doi.org/10.1016/j.biortech.2017.08.199.

[27] Penn, C., Chagas, I., Klimeski, A., & Lyngsie, G. (2017). A review of phosphorus removal structures: How to assess and compare their performance. Water (Switzerland), 583(9), 1–22. https://doi.org/10.3390/w9080583.

[28] Fernandes, G. W., Kunz, A., Steinmetz, R. L. R., Szogi, A., Vanotti, M., Flores, É. M. d. M., & Dressler, V. L.

(2012). Chemical phosphorus removal: A clean strategy for piggery wastewater management in Brazil. Environmental Technology, 3314(14), 1677–1683. https://doi.org/10.1080/09593330.2011.642896.

[29] Lapeña D, Vuoristo KS, Kosa G, Horn SJ, Eijsink VGH (2018) Comparative assessment of enzymatic hydrolysis for valorization of different protein-rich industrial byproducts. J Agric Food Chem 66:9738–9749.

[30] Shestakova, A.; Timorshina, S.; Osmolovskiy, A. Biodegradation of Keratin-Rich Husbandry Waste as a Path to Sustainable Agriculture. Sustainability 2021, 13, 8691.

[31] G.M. Raghavendra, K. Varaprasad, T. Jayaramudu, Chapter 2 - biomaterials: design, development and biomedical applications, in: S. Thomas, Y. Grohens, N. Ninan (Eds.), Nanotechnology Applications for Tissue Engineering, William Andrew Publishing, Oxford, 2015, pp. 21–44.

[32] T. Billiet, M. Vandenhaute, J. Schelfhout, S. Van Vlierberghe, P. Dubruel, A review of trends and limitations in hydrogel-rapid prototyping for tissue engineering, Biomaterials 33 (2012) 6020–6041.

[33] J.S. Temenoff, A.G. Mikos, Biomaterials: the Intersection of Biology and Materials Science, Pearson/Prentice Hall, 2008.

[34] N. Lertcumfu, P. Jaita, S. Manotham, P. Jarupoom, S. Eitssayeam, K. Pengpat, G. Rujijanagul, Properties of calcium phosphates ceramic composites derived from natural materials, Ceram. Int. 42 (2016) 10638–10644.

[35] M. Sadat-Shojai, M.T. Khorasani, E. Dinpanah-Khoshdargi, A. Jamshidi, Synthesis methods for nanosized hydroxyapatite with diverse structures, Acta Biomater. 9 (2013) 7591–7621.

[36] P. O'Hare, B.J. Meenan, G.A. Burke, G. Byrne, D. Dowling, J.A. Hunt, Biological responses to hydroxyapatite surfaces deposited via a co-incident microblasting technique, Biomaterials 31 (2010) 515–522.

[37] Bhattacharya SC, Kumar S., Renewable Energy Technologies in Asia: A Review of Current Status. Thailand: Pathumthani; (2000), http://www.retsasia.ait.ac.th.

[38] Hoogwijk M., Faaij A., van den Broek R., Berndes G., Gielen D., Turkenburg W., Exploration of the ranges of the global potential of biomass for energy, Biomass Bioenergy, 25 (2003), pag. 119– 33.

[39] D. Garcìa-Galindo, M. Gòmez-Palmero, P.E.S. Germer, L. Pari, V. Alfano, A. Dyjakon, J. Sagarna, S. Rivera, C. Poutrin. Agricultural pruning as biomass resource: generation, potentials and current fates. An approach to its state in Europe. 24th Eur. Biomass Conf. Exhib. 6-9 June 2016 (2016), pp. 1579-1595 Amsterdam.

[40] R. Spinelli, N. Magagnotti, C. Nati. Harvesting vineyard pruning residues for energy use. Biosyst. Eng., 105 (2010), pp. 316-322, 10.1016/j.biosystemseng.2009.11.011

[41] R. Spinelli, N. Magagnotti, C. Nati, L. Pari, J.L. Vanneste. Recovering kiwifruit pruning residues for biomass production. Trans. ASABE, 55 (2012), pp. 1-8.

[42] Walling, E.; Trémier, A.; Vaneeckhaute, C. A review of mathematical models for composting. Waste Manag. 2020, 113, 379–394.

[43] Roy, D.; Azais, A.; Benkaraache, S.; Drogui, P.; Tyagi, R.D. Composting leachate: Characterization, treatment and future perspectives. Rev. Environ. Sci. Biotechnol. 2018, 17, 323–349.

[44] Ajmal, M.; Aiping, S.; Uddin, S.; Awaisa, M.; Faheem, M.; Ye, L.; Rehmans, K.; Ullah, M.S.; Shi, Y. A review on mathematical modelling of in-vessel composting process and energy balance. Biomass Convers Biorafin. 2020, 10, 1–13.

[45] Külcü, R.; Yaldiz, O. The composting of agricultural wastes and the new parameter for the assessment of the process. Ecol. Eng. 2014, 69, 220–225.

[46] Li, Z.; Lu, H.; Ren, L.; He, L. Experimental and modeling approaches for food waste composting: A review. Chemosphere 2013, 93, 1247–1257.

[47] Muradoğlu F.; Küçük O.. Determination of Bioactive Composition of Some Peach Cultivars. J. Anim. Plant Sci. 2018, 28 ((2),).

[48] Loizzo M. R.; Pacetti D.; Lucci P.; Núñez O.; Menichini F.; Frega N. G.; Tundis R. Prunus Persica Var. Platycarpa (Tabacchiera Peach): Bioactive Compounds and Antioxidant Activity of Pulp, Peel and Seed Ethanolic Extracts. Plant Foods Hum. Nutr. 2015, 70 (3), 331. 10.1007/s11130-015-0498-1.

[49] Bumharter, C., Bolonio, D., Amez, I., Martínez, M., Ortega, M. 2023. New opportunities for the European Biogas industry: A review on current installation development, production potentials and yield improvements for manure and agricultural waste mixtures. Journal of Cleaner Production, Volume 388, 135867. https://doi.org/10.1016/j.jclepro.2023.135867.

[50] Bórawski, P., Bełdycka-Bórawska, A., Kapsdorferová, Z., Rokicki, T., Parzonko, A., & Holden, L. (2024). Perspectives of Electricity Production from Biogas in the European Union. Energies, 17(5), 1169. https://doi.org/10.3390/en17051169

[51] Ruckli, A. K., Hörtenhuber, S. J., Ferrari, P., Guy, J., Helmerichs, J., Hoste, R., Hubbard, C., Kasperczyk, N., Leeb, C., Malak-Rawlikowska, A., Valros, A., & Dippel, S. (2022). Integrative Sustainability Analysis of European Pig Farms: Development of a Multi-Criteria Assessment Tool. Sustainability, 14(10), 5988. https://doi.org/10.3390/su14105988

[52] Karunanithi, R., Szogi, A. A., Bolan, N., Naidu, R., Loganathan, P., Hunt, P. G., et al. (2015). Phosphorus recovery and reuse from waste streams. Advances in Agronomy, 131, 173–250. https://doi.org/10.1016/bs.agron.2014.12.005.

[53] Sperlich, A., Warschke, D., Wegmann, C., Ernst, M., & Jekel, M. (2010). Treatment of membrane concentrates: Phosphate removal and reduction of scaling potential. Water Science and Technology, 61(2), 301–306. https://doi.org/10.2166/wst.2010.800.

[54] Banasaz, S., & Ferraro, V. (2024). Keratin from Animal By-Products: Structure, Characterization, Extraction and Application—A Review. Polymers, 16(14), 1999. https://doi.org/10.3390/polym16141999

[55] Matinong, A. M. E., Chisti, Y., Pickering, K. L., & Haverkamp, R. G. (2022). Collagen Extraction from Animal Skin. Biology, 11(6), 905. https://doi.org/10.3390/biology11060905

[56] Shi, H., Zhou, Z., Li, W., Fan, Y., Li, Z., & Wei, J. (2021). Hydroxyapatite Based Materials for Bone Tissue Engineering: A Brief and Comprehensive Introduction. Crystals, 11(2), 149. https://doi.org/10.3390/cryst11020149

[57] Nevzorova, T.; Kutcheroy, V. Barriers to the wider implementation of biogas as a source of energy: A state-of-the-art review. Energy Strategy Rev. 2019, 26, 100414.

[58] Alam Hossain Mondal, J.M.; Kamp, L.M.; Pachova, N.I. Drivers, barriers, and strategies for implementation of renewable energy technologies in rural areas in Bangladesh-An innovation system analysis. Energy Policy 2010, 38, 4626–4634.

[59] Hart A, Ebiundu K, Peretomode E, Onyeaka H, Nwabor OF, Obileke K. Value-added materials recovered from waste bone biomass: technologies and applications. RSC Adv. 2022 Aug 10;12(34):22302-22330. doi:

10.1039/d2ra03557j.

[60] García-Aparicio MDP, Castro-Rubio F, Marina ML. Unlocking peach juice byproduct potential in food waste biorefineries: Phenolic compounds profile, antioxidant capacity and fermentable sugars. Bioresour Technol. 2024 Mar;396:130441. doi: 10.1016/j.biortech.2024.130441.

[61] Campos DA, Gómez-García R, Vilas-Boas AA, Madureira AR, Pintado MM. Management of Fruit Industrial By-Products-A Case Study on Circular Economy Approach. Molecules. 2020 Jan 13;25(2):320. doi: 10.3390/molecules25020320. PMID: 31941124; PMCID: PMC7024247.

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

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

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

[65] 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.

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

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

[68] 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.

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

[70] 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.

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

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

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

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

[75] Fujitsu Integrated Report 2023 n.d.

[76] MANUREFINERY - Smart modular mobile biorefining of manure to zero-waste maximising resource and nutrient recovery for feed and fertiliser bioingredients in rural areashttps://www.cbe.europa.eu/projects/manurefinery#:~:text=,based%20solutions%20and%20bioingredients.