WG3 Biorefinery Applications

CA 20127

Waste biorefinery technologies for accelerating sustainable energy processes (WIRE)

Deliverable D3.4 – Roadmap for Bio-based Fuels and Products and Circular Economy Viability Assessment

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Funded by the European Union

Table of contents

List of acronyms

AD	Anaerobic digestion
AI	Artificial intelligence
DQI	data-quality scoring
HTL	Hydrothermal liquefaction
GHG	Greenhouse gas
LCA	Life-Cycle Assessment
LCC	Life-Cycle Costing
MCA	Multi-Criteria Assessment
MCI	material circularity index
PHA	polyhydroxyalkanoates
S-LCA	Social Life-Cycle Assessment
TEA	Techno-Economic Analysis
TRL	Technology Readiness Level
WtE	Waste-to-Energy
WWTP	Wastewater treatment plants

INTRODUCTION

Biorefineries as integral components of the bioeconomy convert renewable biomass into value-added products for reducing dependence on fossil resources while promoting circularity. Hence, energy, agriculture, and environmental sectors play a crucial role in the operation of biorefineries in line with different policies and regulations. However, there should be coordination among these sectors in order not to cause any conflicts or overlap regulations for biorefinery projects. On the other hand, not only regulatory issues but also technical and economic issues lead to challenges in biomass conversion processes. Accordingly, economic barriers are high capital costs and a lack of market competitiveness, whereas the regulatory and policy complexities cause risks and uncertainties in the scaling up of biorefineries. Hence, research and development studies should investigate cost reduction and process simplification to provide the economic feasibility of biorefineries. Especially, the biorefinery market may be unpredictable, which can influence the profitability and long-term financial sustainability of related projects as well as diminish the necessary capital investments. Hence, a strategic decision-making approach should be provided to overcome these barriers with effective collaboration amongst stakeholders in research, industry, and policy domains. Besides, policy support, competition, and consumer preferences are the other factors affecting the market dynamics for biofuels, biochemicals, and biomaterials.

Within the framework of WIRE and WG3, the roadmap was developed based on different interconnected stages, which are essential for building the concept of a biorefinery and for valorizing products and by-products obtained from various interrelated processes:

1. Development stages
2. Technological and Market Barriers
3. Emerging Technologies
4. Feasibility and Circular Economy Readiness
5. Identification of recommended Tools/Methods
6. Environmental and Economic Trade-offs

The report was elaborated according to the scheme shown in the table, developed by WG3 participants during online and in-person meetings. The resulting scheme enabled the identification of a roadmap for processes/products related to biogas from anaerobic digestion (AD), bioethanol, biofuels, biocrude produced through HTL, the use of bio-monomers for biopolymers, the recovery of materials recovered from wastewater treatment, the recycling of plastic fibers, and biofertilizers.

<table>
<tr><th colspan="4">Objective</th></tr>
<tr><td colspan="4">To define a shared roadmap for the development of bio-based fuels and products and to assess their feasibility within a circular economy framework.</td></tr>
<tr><th colspan="4">Input to the roadmap</th></tr>
<tr><td colspan="2">What are the main development stages (short-, mid-, long-term) for relevant bio-based fuels or products or biomaterials in the biorefinery context?</td><td>What technological or market barriers must be overcome at each stage?</td><td>Which emerging technologies (from low to high TRL) are worth focusing on?</td></tr>
<tr><th colspan="4">Feasibility and circular economy readiness</th></tr>
<tr><td colspan="2">How can we realistically assess the circular economy potential of bio-based products?</td><td colspan="2">Which tools/methods (e.g., LCA, LCC, S-LCA, circularity indicators) do you recommend?</td></tr>
<tr><th colspan="4">What environmental or economic trade-offs should be considered for different sectors?</th></tr>
<tr><td>Chemistry / Engineering</td><td>Biotechnology</td><td>Economics / Industrial Policy</td><td>Environmental / Sustainability</td></tr>
<tr><td>Realistic timelines for scaling up? Roadmap to improve selectivity and yield of bio-based processes.</td><td>Development of optimized strains for waste or low-cost substrates, Roadmap for producing high-value bio-based molecules.</td><td>Key elements for circular business models, Policy actions needed to support the bio-based transition.</td><td>Long-term environmental impact assessments, Key factors for closing material and energy loops.</td></tr>
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Table 1: Scheme proposed for the roadmap for WG3: biorefinery applications.

1. Bioethanol

The increasing global energy demand, coupled with the need to transition from a fossil-based economy to a circular and bio-based one, has positioned bioethanol as a crucial renewable energy source and a key component of biorefinery applications (Mizik, 2021; Kazmi et al., 2025).

Furthermore, the economic viability of bioethanol production can be improved through enzyme immobilization and recycling, which enhance enzyme stability and reusability, leading to increased productivity and a reduction in operational costs (Afedzi et al., 2025).

Beyond technical and economic challenges, the successful commercialization and adoption of lignocellulosic bioethanol also depend on establishing supportive policy frameworks and social considerations (Afedzi et al., 2025). The integrated production of bioethanol from various by-products and waste materials represents a sustainable approach that supports the transition to a circular bioeconomy (Osmolak et al., 2025; Ogawa et al., 2024). The ongoing advancements in feedstock diversification, process optimization, and supportive policy development are critical for bioethanol to fulfill its potential as a cornerstone of sustainable energy and the biorefinery concept.

The development of a bio-based fuels and products roadmap for bioethanol can be conceptualized in three stages, which reflect the Technology Readiness Level (TRL) of the technologies, and for each step, the technological or market barriers must be overcome:

- **Short-term (TRL 7–9):** This stage focuses on the optimization and commercial scale-up of existing, mature technologies. The primary focus is on 1G bioethanol production from food crops like corn and sugarcane (Jain and Kumar, 2024). The goal is to improve process efficiency and expand production capacity. For lignocellulosic 2G bioethanol, the short-term focus is on improving specific, high-cost steps, such as enzyme and cell immobilization, which are at a TRL of 6-7 (Chacón-Navarrete et al., 2021).
- **Barrier:** The main barrier is the high capital cost of building large-scale biorefineries. Market-wise, the challenge is maintaining competitiveness with fluctuating fossil fuel prices and overcoming the food vs. fuel debate associated with 1G bioethanol (Mizik, 2021; Mvelase et al., 2023).

- **Mid-term (TRL 4–6):** This stage is dedicated to scaling up promising, but not yet commercialized, technologies. It involves the full-scale implementation of 2G bioethanol production from lignocellulosic biomass, such as agricultural waste and wood residues (Jain and Kumar, 2024). A key goal is to develop and integrate zero-waste biorefinery concepts that produce bioethanol alongside high-value co-products to enhance economic viability (Barua et al., 2023; Osmolak et al., 2025).

- **Barrier:** The major technological barrier is the high cost and complexity of the pretreatment process for lignocellulosic biomass (Jain and Kumar, 2024). Market barriers include securing a consistent and low-cost feedstock supply and the need for a mature market for the co-products of the zero-waste biorefinery concept (Afedzi et al., 2025; Barua et al., 2023).

- **Long-term (TRL 1–3):** This stage focuses on fundamental research and the exploration of new, innovative pathways. This includes the development of 3G and fourth-generation 4G biofuels from algae and genetically modified organisms (Jain and Kumar, 2024; Kazmi et al., 2025). Research at this stage is focused on basic science, such as improving biomass yield from microalgae and engineering strains for efficient conversion.
- **Barrier:** The primary barriers are the low yields and high production costs of advanced biofuels from algae and other feedstocks (Kazmi et al., 2025). Furthermore, there are socio-political barriers related to public acceptance of genetically modified organisms and the environmental risks of their release (Kazmi et al., 2025).

Emerging technologies (from low to high TRL) that deserve particular attention are for bioethanol production in biorefinery:

- Filamentous Fungal Pellets: This low-TRL technology is a promising, sustainable biomaterial for immobilizing different cell types, including yeast for fermentation (Ogawa et al., 2024). Its use as a low-cost carrier can significantly improve process efficiency.
- Immobilized Enzyme/Cell Reactors: A more mature technology (TRL 6-7), immobilized cell reactors are crucial for enhancing fermentation performance for 2G bioethanol (Chacón-Navarrete et al., 2021). Focus should be on developing durable, low-cost carriers to reduce operational costs.
- Integrated Biorefineries: A mid-to-high TRL concept, the development of integrated biorefineries is essential for creating a circular bioeconomy. These facilities would produce not only bioethanol but also other valuable products like bioplastics, biochemicals, and bio-based materials from the same feedstock (Barua et al., 2023; Osmolak et al., 2025).

A realistic assessment of a product's circular economy potential requires a holistic view that goes beyond simple recycling and considers the entire value chain (Kazmi et al., 2025). It should be based on the following principles:

- Waste Valorization: The ability to utilize waste streams, by-products, and non-edible biomass as feedstock (Kazmi et al., 2025).
- Resource Efficiency: Maximizing the use of raw materials, water, and energy throughout the production process.
- Minimization of Environmental Impact: Reducing greenhouse gas emissions, water pollution, and land-use change.

To assess the circular economy potential, a combination of analytical tools is recommended:

- LCA is a crucial tool for quantifying the environmental impacts of a product from "cradle to grave" or "cradle to cradle" (Kazmi et al., 2025). It can be used to compare the environmental footprint of bio-based products with their fossil-based counterparts.
- LCC: assesses the total cost of a product over its lifetime, helping to identify economic trade-offs (Afedzi et al., 2025).
- S-LCA: evaluates the social impacts and potential socio-economic trade-offs, such as job creation, community well-being, and land-use conflicts (Mvelase et al., 2023; Yaverino-Gutiérrez et al., 2024).
- Circularity Indicators: These are specific metrics designed to measure the degree of circularity of a product or process, such as the MCI.

However, environmental and/or economic compromises should be considered, such as:

- Environmental Trade-offs: The primary trade-off is the potential for land-use change associated with feedstock cultivation, which can lead to biodiversity loss and soil degradation, especially for 1G biofuels (Mvelase et al., 2023). There is also the trade-off between water use for biomass production and its availability for other purposes.
- Economic Trade-offs: The main economic trade-off is between the high initial investment costs of new technologies and the long-term economic benefits (Afedzi et al., 2025). Furthermore, the profitability of a biorefinery can be highly dependent on the market value of its co-products, making it a more complex business model than traditional fuel production (Osmolak et al., 2025).

However, some aspects should be adopted in order to make progress in building a roadmap for bioethanol as well as for biorefinery products.

1. Integrated Process Design: Development of modular and flexible biorefinery designs that can handle various feedstocks and produce a portfolio of products, adapting to market demand.
2. Cost-Effective Pretreatment: Research into novel and less energy-intensive pretreatment methods for lignocellulosic biomass to reduce the overall cost of 2G bioethanol production (Jain and Kumar, 2024).
3. Development of Optimized Strains: Focus on creating robust microbial strains, possibly through genetic engineering, that can efficiently ferment a wide range of low-cost, waste-based substrates, including those containing inhibitors (Yaverino-Gutiérrez et al., 2024).
4. High-Value Molecule Production: Roadmap for producing high-value bio-based molecules alongside bioethanol from a single feedstock, thereby improving the economic feasibility of the entire process (Barua et al., 2023).
5. TEA of Co-products: Develop comprehensive TEAs that model the profitability of integrated biorefineries by including the entire value chain, from feedstock acquisition to co-product sales.
6. Policy Roadmap: Create a policy roadmap for a circular bioeconomy, including regulatory frameworks and financial incentives that support the transition from a linear to a circular system and reduce investment risks (Afedzi et al., 2025).

2. Biogas from Anaerobic digestion

A sustainable provision of feedstock and an effective organic waste recycling system should be promoted to support the short-term development of AD-based biogas systems. These systems can serve as a foundational element in the broader bioeconomy framework, converting organic residues into biogas for energy and digestate for use as biofertilizer.

In the long-term, biogas plants may diversify their output by integrating into biorefinery models, thus enabling the co-production of bioenergy, biomethane, and other value-added biobased products. This diversification would support the creation of new market segments and increase revenue streams, particularly in rural and agricultural areas.

Moreover, a stable and supportive policy framework, alongside a clear long-term commitment from the government, is essential to encourage investment in AD infrastructure. As highlighted by Makepa and Chihobo (2024), national bioeconomy strategies and implementation roadmaps are key to ensuring policy certainty and long-term viability of such initiatives in Turkey.

While long-term contracts, often with a price increase clause, are considered, the economic security they provide for the biogas plant is low. Because, the construction of new facilities in the region and the fluctuations in agricultural product prices significantly impact the biogas market. Besides, during the operation of a biogas plant, the following issues should be considered in the long term:

- The production, harvesting, storage, or supply of raw materials, material preparation and loading, and application of fermentation residues to the field as fertilizer (e.g., grain production, harvesting, and storage), legal limits, and the need for pathogens elimination.
- Market barriers: Using biogas where it is produced (i.e., in or close to the biogas plant) is not always an economically and ecologically sound alternative. Electricity generation inevitably generates heat; however, this heat energy cannot be effectively utilized at the biogas plant or close to its location. On the other hand, the sales price of electricity is highly variable, ranging from approximately 8 to 30 ct/kWh, depending on the type and quantity of materials used, the power of the plant, etc. Hence, the plant owners cannot predict their potential profit. Moreover, it will not be possible to effectively utilize all of the heat energy generated in practice, although a certain percentage is required to heat the process. However, the use of the residual heat is highly dependent on the season. Hence, preparing the biogas and supplying it to the natural gas grid should be considered, which must be overcome at the investment stage. Additionally, an adequate silage capacity should be provided near the biogas plant to reduce transportation costs. On the other hand, it should be taken into account that the expected energy recovery from biogas may be variable
- Legal regulation: The main income from biogas plants, excluding gas supply facilities, is 'electricity'. Since its price and the duration of the fee (year of commissioning + 20 calendar years) are regulated by law, revenues generated from electricity sales can be planned without risk. However, selling heat is a much more challenging task than selling electricity. Therefore, even when selecting a location, consideration should be given to potential heat sinks (e.g. plant's own heat needs etc.). These facilities essentially derive their income from the gas they sell. Since there is any legal regulation on this issue, the price of gas is generally determined through negotiation between the gas supplier and its customer.
- Economic investments: The purpose of a biogas plant operation is to gain income, expand energy production, and invest in new biogas plants in the future. However, this requires

additional investments ranging from €6,000 to €8,000/ha, tying together capital and land for a long period of approximately 20 years. Since one of the objectives for a biogas plant is to get a reasonable financial return on the capital invested, this can be verified with the help of a reliable investment calculation.

- **Key factors for closing material and energy loops.**

Utilizing the heat generated during a process providing Power-Heat Coupling, along with electricity sales, is increasingly becoming a decisive factor in the economic success of a biogas plant. Whether heat utilization opportunities can contribute to this, and if so, how, depends primarily on the amount of heat purchased.

The starting point for establishing a biogas plant should be the amount of the material (e.g. farm manure etc.) that will be used as the feedstock, the amount of heat that will be effectively utilized, the area required for material preparation and storage, and the potential for utilization of fermentation residues. Furthermore, not only the amount of materials but also their dry matter (DM) contents should also be evaluated (i.e. 0.2 kW/cattle). Because of, pricing regulations of the Renewable Energy Law, the net amount of electrical energy produced from these materials will not be based on wet material. In addition, other potential materials or residuals (silage leftovers, organic wastes, and raw plant-based by-products, etc.) can be used when needed based on their quantity and availability. However, transportation distances and additional costs should be taken into account.

If agricultural products are to be used, when planning the agricultural biogas plant, the farmer must clearly determine the portion of the land that will be allocated for biogas production, and the quantities of each crop that will be grown (i.e. about 0.5 hectares/kWel on average). Accordingly, low-cost and high-yield crops per unit of organic DM or m^3 of methane should be preferred by taking into account the seasonal impact. However, purchasing biomass is frequently preferred when sufficient material cannot be provided on their own land.

The most important factor in deciding to design/construct a biogas plant is whether the capital and labor inputs will be adequately compensated. Because, in order to realistically assess the circular economy potential of biogas, the plant operation must be feasible and positively contribute to the increase of the economy. In this context, sensitivity analysis should be done to determine which factor(s) have the greatest impact on the economics of a biogas plant. In this way, profit changes when factors related to the specified quantities are changed, and could be predicted (i.e., profit change in €/year). The highest impact is observed by the changes in gas yield, methane content, electricity efficiency, and material costs, especially in the plants that are operated with a high renewable waste content. Changes in factors such as operating hours, maintenance and repair costs, and heat sales have a lesser impact.

Besides, since heat energy cannot be effectively utilized at the biogas plant or close to its location, spatial separation of biogas production and utilization may be feasible under certain circumstances. In this case, in addition to establishing a raw biogas pipeline that transports biogas for use at a location that is a few hundred meters to several kilometers away, gas preparation and supply to the general natural gas network should also be planned.

3. Development Stages of Bio-Based Fuels, Products, and Materials in the German Biorefinery Context

The development of bio-based fuels, bioproducts, and biomaterials within the biorefinery framework can be broadly classified into short-, mid-, and long-term phases. These stages reflect the progression from fundamental research to technological demonstration and full commercial deployment, with particular relevance to the German innovation landscape.

- Short-term: Research and Pilot Testing in the early stage, research focuses on fundamental studies and laboratory-scale proof of concept for biochemical, thermochemical, and hybrid conversion processes. Technologies such as HTL, gasification, enzymatic hydrolysis, fermentation, and catalytic upgrading are tested in pilot-scale setups to optimize process parameters and conduct preliminary techno-economic and environmental assessments. Comprehensive characterization of bio-based feedstocks and products, combined with process modeling and simulation, supports the design of scalable systems and informs scale-up strategies.
- Mid-term: Scale-Up and Demonstration: This phase involves semi-industrial demonstration projects that validate process integration, operational robustness, and long-term stability under realistic conditions. The flexible handling of heterogeneous feedstocks and the combination of different conversion pathways are central to this stage. Advanced life cycle and techno-economic assessments are conducted to evaluate sustainability metrics, greenhouse gas emissions, socio-economic impacts, and regulatory compliance. Digital technologies, including real-time sensor networks, AI-assisted optimization, and digital twin applications, are increasingly integrated into demonstration plants to enhance process control and system efficiency.

- **Long-term:** Commercialization and Market Integration. In the final stage, commercial-scale biorefineries are established, capable of processing large volumes of variable biomass continuously. These facilities rely on mature, reliable technologies and fully integrated value chains. Market adoption depends on standardized certification, supportive policy frameworks, and increased consumer acceptance of bio-based alternatives. Long-term goals include the transition to circular bioeconomy models that ensure full valorization of biomass, ongoing environmental performance monitoring, and incorporation of social and sustainability considerations into business strategies.

Germany plays a leading role in this structured development process, with institutions such as the Deutsches Biomasseforschungszentrum (DBFZ) and other public-private consortia supporting process innovation, pilot plant operation, and digitalization. National bioeconomy strategies and targeted funding further enable the translation of research into commercially viable, sustainable biorefinery systems. This staged approach addresses core challenges, including feedstock variability, process complexity, digital integration, and regulatory alignment, to ensure successful industrial implementation.

Evaluating the circular economy potential of bio-based products from biorefineries requires integrated, multi-dimensional approaches that go beyond environmental criteria alone. Key methods include LCA to quantify environmental impacts, TEA, (ISO,2006), to assess cost-effectiveness and market viability, and MCA to balance ecological, technical, economic, and social factors.

These quantitative tools must be complemented by qualitative insights into regulatory frameworks, societal acceptance, and organizational feasibility. Dedicated assessment platforms, such as those developed by IEA Bioenergy Task 42, support structured evaluation across scales. Furthermore, long-term monitoring from pilot and demonstration plants is critical to validate environmental performance and operational stability in real-world conditions.

This integrative assessment approach enables a realistic understanding of both the sustainability and practical implementation of bio-based innovations. It supports the identification of promising value chains, helps overcome innovation barriers, and informs strategic decisions in research, development, and commercialization.

4. HTL and biocrude

Although significant efforts have started several years ago, the following breakdown highlights a clear roadmap on how HTL and solar HTL could progress from the conceptual and lab-scale stage to full commercialization, taking into account the market barriers.

- **Short-term (1–3 years)**: Current research in the short term is highly focused on feedstock versatility, biocrude upgrading, and energy efficiency improvements. Laboratory studies continue to test diverse feedstocks, including agricultural residues, sewage sludge, and plastics, to establish correlations between feedstock type, process conditions, and product quality. Advances in catalysis and reaction kinetics dominate the research agenda, with increasing attention on in-situ upgrading to reduce downstream costs. Solar-assisted HTL remains at the experimental stage, with studies investigating the integration of solar concentrators and simulated solar heating to partially substitute fossil-derived heat input (Poravou et al., 2023). Research trends also show growing interest in aqueous phase valorisation and nutrient recovery, driven by circular economy considerations (Watson et al., 2020).
- **Barrier:** At the short-term stage, the main technological barriers include the lack of standardised protocols for feedstock preparation, reaction monitoring, and product characterisation, which complicates reproducibility and comparison across research groups. Biocrude upgrading methods remain immature, and in solar-assisted HTL, intermittent solar supply and low thermal efficiency have a detrimental effect on process validation. On the market side, uncertainty around regulatory classification of HTL products, lack of incentives for biofuels, and insufficient business models for small-scale pilot demonstrations hinder industrial engagement.

- **Mid-term (3–7 years):** The mid-term stage is characterized by the growing number of continuous-flow pilot plants, which are increasingly reported in the literature as Castello et al. (2018) have described thoroughly in their review paper. Here, research is trending towards solving engineering challenges such as slurry handling, fouling, and corrosion in continuous systems. Collaborative projects are emerging to integrate HTL into municipal and agricultural waste management systems, demonstrating its potential as a WtE pathway. For solar-assisted HTL, current research trends are exploring techno-economic analyses of hybrid systems combining concentrated solar power with HTL, as well as thermal energy storage integration to stabilize operations (Pearce et al., 2016). Another trend is the coupling of HTL with hydrotreating in refineries, where research groups and industrial partners are testing co-processing of HTL biocrudes with petroleum fractions.

- **Barrier:** During the mid-term stage, technological barriers focus on scaling continuous HTL processes, including reactor fouling, corrosion, solids handling, and integration of biocrude upgrading at pilot scale. As far as solar-assisted HTL is concerned, thermal energy storage, process control under variable solar input, and hybridization with conventional heat sources remain challenging. Market and policy barriers include the need for regulatory alignment, permitting for pilot plants, and investment risk associated with unproven continuous systems. Unclear incentives for co-product valorisation and circular economy benefits also slow adoption. Collaborations between academia, industry, and policymakers are required to de-risk pilot demonstrations and establish operational guidelines.

- **Long-term (8+ years):** Long-term research trends point toward industrial-scale deployment and digitalisation. Current efforts in computational modelling and machine learning are laying the foundation for advanced process control and predictive optimisation of HTL reactors (Xi et al., 2024). At the same time, policy-oriented studies are increasingly addressing the role of HTL biocrudes within EU biofuel targets, sustainability criteria, and regulatory frameworks for renewable fuels. Solar-assisted HTL is projected to play a stronger role in long-term sustainability, with research trending toward integration with large-scale solar thermal plants and coupling with other renewable processes to reduce lifecycle emissions. The long-term trajectory is thus moving from technology validation toward market integration, underpinned by digitalization, regulatory support, and diversified business models.
- **Barrier:** At the long-term stage, technological barriers shift toward achieving fully integrated, multi-product biorefineries with optimized energy efficiency and high reliability. Challenges include long-term reactor durability, advanced process control, efficient solar integration, and digital twins for predictive maintenance. Market barriers remain significant: economic competitiveness against fossil fuels, establishment of robust supply chains for feedstock, and clear policy frameworks and incentives are critical to attract industrial investment. Moreover, acceptance of HTL biocrudes and derived products in the fuel and chemical markets requires standardization and certification, as well as demonstration of lifecycle sustainability.

From an environmental perspective, HTL offers advantages in terms of reducing landfilling and enabling nutrient recovery from the aqueous phase. However, high process temperatures and pressures require significant energy input, which may offset greenhouse gas savings if fossil-derived heat is used.

Solar-assisted HTL can mitigate this issue by substituting a portion of fossil energy with renewable solar thermal input, but this introduces trade-offs related to land use for solar collectors, intermittency of solar input, and the additional materials and infrastructure required for thermal storage.

Furthermore, valorisation of the aqueous phase and solid residues (i.e., biochar) must balance energy recovery, water quality impacts, and potential emissions from further processing.

From an economic point of view, HTL systems face trade-offs between feedstock flexibility, process complexity, capital and operational expenditures.

Continuous-flow systems offer higher throughput and improved efficiency, but require significant investment in corrosion-resistant reactors, pumps, and monitoring systems.

Co-processing HTL biocrudes with petroleum fractions can reduce upgrading costs, yet introduces dependency on refinery infrastructure and market fluctuations in fossil fuel prices. Solar-assisted HTL can reduce operational costs for heat, but requires higher upfront capital investment and site-specific optimisation to ensure cost-effectiveness.

Finally, policy incentives, subsidies, and market demand for bio-based fuels and co-products strongly influence economic feasibility, and trade-offs between scale, product diversity, and environmental performance must be evaluated to maximize overall value.

5. Biogas and struvite recovery: Input to the roadmap

Struvite crystallization and AD enable sustainable nutrient recovery and biogas production, but industrial uptake is limited by technical gaps such as scaling, tailored pretreatments, inhibitor control, and energy efficiency. Product quality, post-processing, and co-production of valuable bioproducts are key for market uptake. Regulatory gaps, unclear standards, and weak incentives also limit commercialization. Academia–industry collaboration, pilot demonstrations, and circular business models are needed to scale lab innovations. Roadmaps stress optimized processes, pilot validation, and large-scale integration. Major barriers remain—technological inefficiencies, high costs, fragmented rules, and low incentives—yet solutions like advanced monitoring, electrochemical methods, and co-production models can improve feasibility. Harmonized standards, supportive policies, and strong partnerships are crucial for sustainable scaling.

The development of biogas and struvite recovery can be visualized in three stages.

- **In the short term (1–3 years),** the focus is on pilot-scale demonstrations using livestock and municipal waste streams, while optimizing parameters such as pH, magnesium dosing, pretreatment and purification techniques, as well as feeding strategies.

- **In the mid-term (3–7 years),** scaling up to industrial-scale biorefineries will become crucial, incorporating diverse waste streams, advanced process monitoring, and circular business models.
- **In the long term (7–15 years),** it will aim for full commercialization, harmonized regulations, renewable hydrogen integration, and global standards for bio-based fertilizers and renewable fuels.

Key barriers must be addressed at each stage. Technological challenges include limited understanding of wastewater-specific pretreatments, low phosphorus recovery efficiencies, and small crystal formation in struvite (Yan and Kallikazarou et al., 2025). Both AD and SC face high energy and reagent costs, while regulatory fragmentation and lack of harmonized product benchmarks slow down their adoption (Hukari et al., 2016). Market barriers, including limited incentives and underdeveloped business models, add further uncertainty (de Boer et al., 2018).

Several emerging technologies hold promise for overcoming these limitations. Electrochemical precipitation for struvite (Bagastyo et al., 2022), fed-batch AD (Yan and Kallikazarou et al., 2023) with advanced sensors, and process optimization (Yan and Kallikazarou et al., 2025) can improve efficiency and reliability. Co-production of biopolymers (Pagliano et al., 2017) and nutrient-rich fertilizers (Yan and Kallikazarou et al., 2023) (Yan and Kallikazarou et al., 2023), as well as renewable hydrogen integration for biomethane upgrading (Abd et al., 2023), offer opportunities to enhance economic feasibility and circularity. The circular economy potential of biogas and struvite systems can be assessed by evaluating material recovery, nutrient recycling, and overall process efficiency. Integrated systems that combine energy production with nutrient recovery can maximize the value of waste streams and reduce environmental burdens (Finzi et al., 2020).

Robust assessment tools are essential to ensure feasibility. LCA can capture environmental impacts, while LCC evaluates economic performance. S-LCA highlights stakeholder impacts, and circularity indicators provide insights into material and energy loop closure. Together, these methods offer a comprehensive evaluation framework (Pérez-López et al., 2025).

Environmental and economic trade-offs must also be considered. When considering sustainability, struvite production involves balancing energy use with chemical inputs, which can have a significant impact. In the case of biogas, the key challenge lies in finding the right balance between cost and upgrading efficiency. Biorefineries producing multiple products offer co-benefits but also come with added operational complexities. To define sustainable pathways, it is crucial to factor in long-term soil health, potential risks of eutrophication, and greenhouse gas emissions (Orner et al., 2022).

- General aspect: Roadmap by Scientific Area

From a chemistry and engineering perspective, future efforts should optimize AD and SC yields, followed by improvements in crystal size, and system integration. The long-term target is commercial-scale operation with advanced automation and process control. Biotechnology provides additional opportunities by developing microbial consortia for recalcitrant substrates and engineering strains for improved methane yields and reduced inhibition. Moreover, it can enable the production of high-value co-products directly from digestates (Wang et al., 2023). Economics and industrial policy are pivotal to scaling these systems. Short-term actions include designing circular business models and piloting fertilizer–energy synergies. Clear policy incentives, subsidies, and harmonized regulations are needed to support broader market adoption. Finally, environmental and sustainability aspects must guide the entire roadmap. Long-term monitoring, robust LCA studies, and optimization of material and energy loops will ensure that bio-based fuels and fertilizers are truly circular and aligned with EU sustainability goals.

6. Biobased monomers derived from renewable resources

- Example FDCA Flagship plant from PEFrefernce project … first commercial scale!

Regarding bio-based food packaging, there were several products available already at a commercial scale by 2022 and earlier, such as PHAlike BiopolTM from Metabolx Inc. (USA), which can be utilized for the production of hot and cold cups, cup lids, yogurt containers, and others (Tardy et al, 2022).

One bio-based substance with high potential for the development of novel circular biomaterials is lignin due to its high availability and particularly slow biodegradability, which also allows its use as a carbon source for soils. However, most industrially produced lignin is burnt as a cheap fuel in the forestry and pulp and paper sectors. Therefore, a more resource-efficient use of lignin with a transition of a WtE use of lignin towards value-added materials such as bioplastics, carbon materials, or fine chemicals has great potential for the coming years.

Recent research and development in nanotechnology and material science showed that lignin-based materials can contribute strongly to carbon fixation and thus circularity of novel biorefinery concepts. When considering a cradle-to-cradle design, the utilization of lignin opens the path for integrating technical materials into the biological cycle since lignin can be depolymerized by microbial agents and further converted into nutrients. This, in consequence, avoids technical materials waste accumulation in nature (Tardy et al, 2023). Applied lignin research is mostly still located rather than in the lower (long-term) TRLs, even if in recent years several spin-off companies for lignin products were founded and eventually gathered funding for further company development.

To name a few, there are:

- Lignovations (https://lignovations.com/), founded by TU Wien (Vienna, Austria) alumni;
- LignoFlow (https://www.lignoflow.com/), founded at Stockholm University;
- Proligreen (https://www.brightmateria.com/), which comes from Wallenberg Wood Science Center;
- LigniLabs (https://lignilabs.de/en/) deriving from Max Planck Institute for Polymer Research;
- LignoSphere (https://www.lignosphere.fi/) from Aalto University;
- LigniCore (https://lignicore.se/) from Stockholm University.

Still, most lignin scientific developments are stuck in the laboratory scale and take a long time to reach higher TRLs. However, on the other side, there are also examples for market-ready lignin-derived materials, such as Lignode® battery anode material produced by Stora Enso, or UPM BioPiva™ lignin, which is supposed to be able to replace two-thirds of the phenol in the glue used to prepare their in-house produced plywood (Correa Guillen 2025).

Regarding lignin, nanoparticles are considered one of the most important emerging building blocks. There are several scalable production methods for LNPs, but some of them are facing environmental or techno-economic problems when it comes to recycling organic solvents from aqueous solvent mixtures. Further, there is a lack of biodegradability or recycling studies of LNPs used in composites with natural or synthetic polymer matrices. Besides LNPs, lignin shows big potential in thermoplastic blends and biobased aromatic thermosets, which is backed up by the exponential growth of research reports about lignin-based polymers, which range from fundamental research to chemical recycling and reprocessing strategies of the produced biobased materials (Tardy 2023).

Regarding the life cycle of biomaterials, elements such as the availability or requirement of recycling streams, potential environmental hazards, and their biodegradability must be considered and investigated in detail (Tardy et al, 2022). The quantification of environmental impacts can often be difficult to quantify, and certain recommendations should be considered to improve the comparability of LCA works, such as inclusion of diverse impact categories different from CO2 emissions, inclusion of end-of-life scenarios, adhesion to standardization guides and third-party verifications, additional metrics like the Material Circularity Indicator, and extend LCAs to higher TRLs to proof the reliability of lab-scale LCA (Tardy 2023).

7. 3R-BioPhosphate Ltd – Industry Perspective on Research Gaps and Collaboration Opportunities in Biorefinery Applications

A key priority request form companies and industries is the implementation and demonstration of the first full-scale industrial or commercial production, supported by a TRL9 replication model to validate the maturity, scalability, and reproducibility of the technologies involved. Demonstrating credible high-TRL scale-up activities is therefore essential to de-risk investments and accelerate industrial uptake.

At the same time, it is necessary to identify and address the technological and market barriers that may impede progress. These barriers may include limitations in process efficiency, feedstock availability, infrastructure readiness, regulatory constraints, and market acceptance.

In parallel, attention should be directed toward emerging technologies across the full TRL spectrum—from early-stage innovations to near-commercial solutions—that have the potential to enhance the competitiveness and sustainability of biofertilizer production. A credible high TRL scale-up demonstration, this is why so much is needed for the first full industrial/commercial production and TRL9 replication model.

Emphasis should be placed on zero-emission and energy-independent processing, with a particular focus on carbon-negative applications that contribute to climate neutrality and long-term environmental resilience.

The feasibility assessment of bio-based products should be grounded in a realistic analysis of their circular economy potential.

Assess user and market driven full industrial perspectives. Short and medium and long term impact assessment of the results for circular economy viability in markets, environment and climate in EU dimension. Substitution potential assessment of the bio-based fuels and products in economically interesting European dimension to replace non-renewable mineral fertilisers at less cost, hence reducing external dependence and risks related to depletion, scored and weighted across all applications. The substitution index, economic importance, supply risk and ”end-of-life recycling rate” impact parameters to be considered, including critical raw material aspects. Contribution assessment to the sustainable and circular bioeconomy to lawfully enter to the market with recovered and upcycled bio-based fuels and products that are synergic with other economic sectors, and therefore to the creation of wealth and quality jobs in rural areas.

For methodological evaluation, a range of practice-oriented tools and approaches is recommended, including LCA, LCC, S-LCA, and circularity indicators. All practice-oriented tools/methods are applicable if a business and market-driven set up performed.

Finally, both environmental and economic trade-offs must be systematically analyzed. The overarching objective remains the Target of zero emission and energy independent processing with C-negative lawful product applications under market-competitive conditions.

8. Chemical recycling converts post-consumer plastics into usable intermediates

This Report on Research Gaps and Key Areas with High Potential for Academia and Industry Collaboration addresses the emerging field of chemical recycling, which offers a transformative approach to managing post-consumer plastic waste. Unlike mechanical recycling, which is limited by material degradation and contamination, chemical recycling enables the conversion of polymeric waste into valuable chemical intermediates such as monomers, naphtha-like hydrocarbon streams, and waxes or oils.

In the biorefinery context, chemical recycling represents a strategic link between waste valorization and the production of renewable intermediates, contributing to the establishment of integrated circular systems. The alignment of these technologies with bio-based processing chains can enhance resource efficiency, reduce dependence on fossil carbon, and foster industrial symbiosis across the plastics, chemical, and bioeconomy sectors.

The following section provides a breakdown across different time horizons.

- **Short term (0–2 years):** define spec windows by destination (refinery vs cracker/monomer); agree harmonized analytics; demonstrate unit-scale trials on plastic and plastic+biogenic oils; deploy acid-gas scrubbing (HCl/HBr/HF) and materials-selection guidance where needed.
- **Mid-term (2–5 years):** implement split routes (PET/PS depolymerization; PO thermal) with polishing sequences commission reference pilot lines; deploy quality-by-design controls (blend rules, inline monitors); manage wastes from sorbents/filters; publish host-acceptance playbooks and open data schemas.
- **Long term (5–10 years):** commercial integration with spec-reliable feeds; digital twins for quality prediction; standard contracts referencing test methods/limits; certified mass-balance recycled content across co-processing chains; integrated EHS & corrosion management.

To fully realize this potential, collaborative efforts between academia and industry are essential to address key research gaps, including catalyst development, process optimization, life cycle performance assessment, and scale-up feasibility. Strengthening such cooperation will be critical to advancing circular carbon management and supporting the transition toward a sustainable, low-emission industrial ecosystem in Europe.

- Tools/methods: ISO-aligned LCA, TEA, LCC, S-LCA; material circularity index; recycled-content mass-balance verification; DQI for oil analytics.
- Assessment focus: net GHG vs fossil; hydrogen demand and utilities; catalyst/solvent footprints; waste streams (acid-gas scrubber solids, spent adsorbents); product displacement credits.
- Trade-offs: severity vs stability; hydrogen intensity vs oxygen/halogen removal; throughput vs fouling; segregation vs campaign flexibility; biogenic blending benefits vs added O/N and corrosion risks.

Conclusions:

The development of bio-based fuels, products, and biomaterials in biorefineries can be divided into three stages: short-, mid-, and long-. In the short-stage, the focus should be on optimizing mature technologies such as pyrolysis, hydrothermal carbonization, anaerobic digestion, and fermentation using available biomass. These processes necessitate enhancements in yield, consistency, and cost-efficiency, in addition to solutions for feedstock variability and logistics. In the mid-stage, the integration of thermochemical and biochemical pathways becomes imperative to diversify outputs into specialty chemicals, advanced biofuels, and multifunctional biomaterials. Long-stage strategies aim at the establishment of fully integrated, region-specific biorefineries equipped with AI-driven optimization, digitized monitoring, and modular infrastructure adaptable to feedstock and market shifts.

Each stage of the process is accompanied by unique barriers. The short challenges confronting the industry include the presence of inconsistent biomass quality and a lack of product standardization. The intermediate phase of a project's development is often stymied by two primary factors. Firstly, the absence of adequate pilot infrastructure impedes the execution of plans, while the discordance between the pace of innovation and the rate at which new ideas penetrate the market creates challenges. The long-stage, development of these regions is confronted with a number of challenges, including policy uncertainty, competition with fossil fuels, and cumbersome approval processes, particularly in the construction and agriculture sectors. Addressing these issues necessitates the implementation of clear regulatory frameworks, the provision of supportive incentives, and the enhancement of public engagement.

The prioritization of emerging technologies across TRLs is imperative. Innovations with a low (1-4) TRL, such as microbial electrosynthesis and enzymatic lignin valorization, demonstrate considerable promise for future advancements. Mid-TRL (5-7) options, such as integrated gasification and HTL, necessitate pilot testing to ascertain their viability. High-TRL (8-9) technologies, such as pyrolysis and AD, are nearing commercialization; however, they require more effective integration into biorefinery systems.

A realistic assessment of the potential of a circular economy necessitates the integration of various analytical tools, including LCA, LCC, and S-LCA. These tools must be employed in conjunction with key circularity indicators, such as the material circularity index and resource efficiency metrics, to provide a comprehensive evaluation of the system's sustainability and effectiveness. In order to facilitate the comparability of the aforementioned tools, as well as to support the process of informed decision-making, it is imperative that these tools be harmonized. A cost-benefit analysis must be conducted, as trade-offs are inevitable. For instance, the use of biochar for carbon sequestration may result in suboptimal market returns, and energy-optimized systems may exhibit subpar performance in terms of circularity if they lack material reuse. Conversely, decentralization fosters resilience; however, it may be superseded by centralized economies of scale. The efficacy of bio-based systems is contingent upon the procurement of sustainable feedstock, the optimization of processing methodologies, and the mitigation of environmental impact throughout the lifecycle.

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