BioINSouth

Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe

Deliverable 4.2

Benchmark

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Bio-based Industries Consortium

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BioINSouth

Supporting regional environmental sustainability assessment for the BIO-based sectors to improve INnovation, INdustries and INclusivity in SOUTH Europe

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1 Introduction

The BioINSouth project is part of the Horizon Europe framework Programme, specifically addressing the topic Horizon-JU-CBE_2023-S-02 call. Its primary objective is to assist decision-makers to incorporate considerations of ecological limits into their regional bioeconomy strategy and roadmaps in southern European regions by the incorporation of considerations of ecological limits into their regional bioeconomy strategies and roadmaps, when it comes to circular bio-based activities. The consortium involved in this project covers the Southern European Regions including Greece, Cyprus, Turkey, Italy, Portugal, Czech Republic, Slovenia, France and Spain.

The deliverable D4.2 outlined LEITAT's role in analysing the most sustainable, efficient, and innovative bio-based industries and process across Europe. The goal was to establish a roadmap for their potential implementation and adaption in southern European regions, aligning with bio-based processes developed both across EU and globally. To achieve this, LEITAT conducted a critical analysis and benchmarking, supported by a systematic literature review of bibliographic sources on the latest trends in the field and complemented by multiple interviews with companies in the sector. The methodology focused on three key pillars defining a bio-based system: i) Feedstock, ii) Processes, and iii) Products or Chemical Platforms, the aim was to identify systems that produced a wide range of bio-based products while maximizing biomass conversion efficiency, minimizing feedstock requirements, and reducing the CO_2 footprint

2 General concepts/Biorefinery

2.1 Introduction

The biorefinery concept is not new; it is a concept that dates to the 19th century, when food production feedstocks such as sugar were already being developed, from basic products to more sophisticated final products (sucrose, agarose, etc.) using various processing technologies have already been developed. Since then, the biorefinery industry has grown and become more complex encompassing new feedstocks, processes and technologies. Advanced biorefineries, once established on a commercial scale, will open the door to new business opportunities. However, new platform technologies are still being developed for these advanced biorefineries. A major strength for the establishment of biorefineries is their sustainability, which means that biorefineries apply a whole new value chain to feedstocks and waste materials from different origins and cover the whole Life Cycle Sustainability Assessment (LCSA). LCSA combines LCA for environmental impacts, LCC for economic impacts and S-LCA for social impacts.

2.2 Concepts of biorefineries

In the global transition towards sustainable development and the transition from a fossil-based to bio-based economy, biorefineries have emerged as an important technology, that enables the efficient conversion of renewable biomass, such as agricultural residues, algae, and organic waste, into a spectrum of valuable products, including fuels, chemicals, materials and energy, while reducing the environmental impact of greenhouse gas emissions and persistent pollution and supporting the transition to a circular bioeconomy. Inspired by the concept of petroleum refineries, that process crude oil into multiple products, biorefineries aim to maximise resource efficiency by utilising all components of biomass in a sustainable and economically viable manner.

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Biorefineries can be classified according to four main characteristics: 1) feedstock (vegetable oils, lignocellulose, algae, and organic waste), 2) conversion technologies (thermochemical, biochemical, chemical, and mechanical processes), 3) platform intermediates (sugar, lignin, syngas and crude bio-oil) and 4) final products (biofuel, chemicals and biopolymers). Figure 1 shows an example of a complete biorefinery industry structured according to these characteristics.

Biorefineries have evolved over time, resulting in different generations reflecting technological advancements and product diversification:

1. First-Generation Biorefineries: These biorefineries primarily focus on producing biofuels, such as bioethanol and biodiesel, through processes like fermentation and transesterification. While they have contributed significantly to the renewable energy sector, their product range is currently limited to fuels and animal feed. These advanced biorefineries, however, go beyond biofuels and incorporate various technologies to produce a wider array of bio-based products. They employ multiple feedstocks, such as lignocellulosic biomass, and produce a few main products, such as biofuels and chemicals, with better resource efficiency.

2. Second-Generation Biorefineries: These advanced biorefineries produce a wider array of bio-based products by incorporating various technologies that go beyond biofuels. Employing multiple feedstocks (lignocellulosic biomass), they produce several main products (biofuels and chemicals), thereby achieving greater resource efficiency.

3. Third-Generation Biorefineries: Third-generation biorefineries are at the forefront of innovation. They explore diverse feedstocks, such as algae, waste and CO_2, and use advanced, emerging biochemical processes to produce high-value products with significant market potential, including biofuels, bioplastics, nutraceuticals and pharmaceutical compounds.

2.2.1 Types of biomasses.

Biorefinery can process different kinds of biomass from different origin such as agriculture, industrial, livestock, etc. This large spectrum of biomass allows to create a new value chain of both intermediate and final product that can be introduced in different economic sectors such as feed, cosmetic, pharmaceutical etc. Despite the great investment to develop new technologies, there is still a challenge in their high production associated with the variability of feedstocks even inside of a same line of plants, algae, etc. In this section, a summary of the most used or interested feedstock are well described. It is important to remark that some potential feedstocks are not commercially available since there is no availability in the region of interest or due to the low level and lack of maturity of technology. ☐

2.2.1.1 Feedstocks:

Based on nature origin, the feedstocks can be classified in three different generations:

1. First generation of feedstocks/biomass are starch and edible triglycerides. Triglyceride originated from plant or animal resources and are composed by fatty acid and glycerol. On the other hand, starchy such as corn and sugarcane feedstock are derived from glucose due to the easy way to hydrolyse glucose to simple monomers.

2. Second generation of feedstocks is concentrated on develop an alternative to crops and triglycerides using lignocellulosic biomass and their derivatives as cellulose, hemicellulose and lignin convert in simple sugars. Lignocellulose come from forestry biomass or agricultures

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biomass or waste. Chemical or physical pretreatment of lignocellulosic biomass are needed to depolymerize the lignin and extract both hemicellulose and cellulose. These products can be used as chemical platform to obtain other bio-products or to produces heat and electricity.

3. Third generation of feedstock is composed by algae biomass and their derivatives. Algae biomass holds significant potential due to its high lipid content, the ease of cultivation in different growth media. In addition, algae's ability to convert CO_2 into wide range of chemical compound (which varies by algal species) contributes to reducing the global warning emissions.

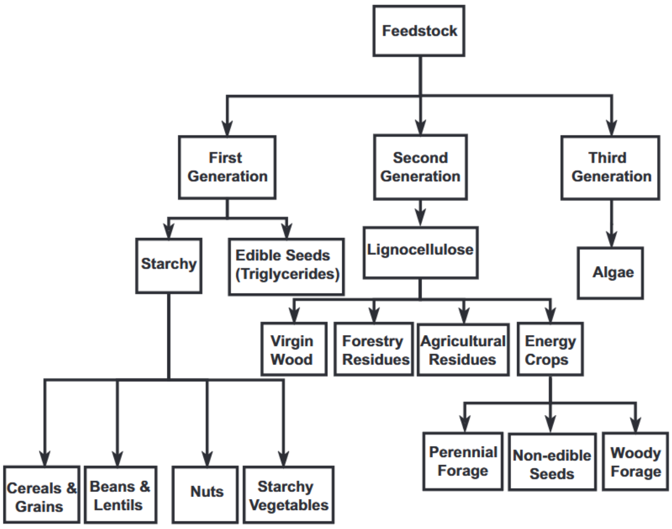

Figure 1. Scheme of three different generations feedstocks.[1]

In 2021, a public JRC report published a study about chemical and material driven biorefineries in the EU and beyond.[2] This report analysed 298 biorefineries distributed in Europe, in term of feedstocks, type of biomass, etc. Figure 22 shows: a) some graphs extracted from the public data obtained, b) the main products extracted from these feedstocks and c) the general classification of biomass. The most used feedstock in 2021 was agriculture, followed by forestry, waste, marine and other. In the case of types of biomasses, the most used is primary biomass accounting for 77.3%.

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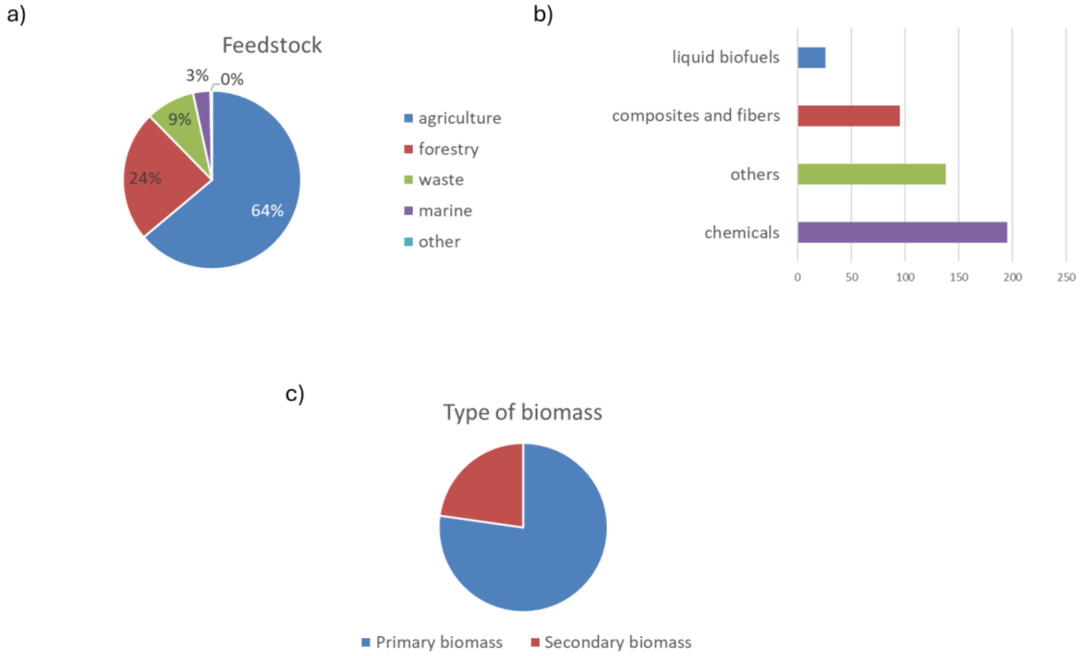

Figure 2. a) Classification of biorefineries by feedstock category, b) number of refineries by product categories and type of biomass.

2.2.1.2 Classification of feedstock.

- Forest biomass

Forest biomass facilitates the introduction of new bioproducts in addition to traditional wood, pulp, and paper products. The forest biorefinery utilizes advanced technologies to convert sustainable woody biomass, provides new value chain using renewable resources and supports the sustainable management of forest lands. Most woody species produced through the exploitation of forest biomass resources are pulps mills, and forest residue generated from cleaning and maintenance of forest masses. The main interesting products that it can be produced from this biomass are lignocellulose, (hemi)cellulose that can be processed to obtain bio-products such as ethanol, syngas, glycerol and derivations, furans[3], etc.

- Agricultural

Agricultural feedstock is the most used because of their variability, abundance and distribution in the regions involved in the project. It was the first feedstock which started to use in biorefineries, and their knowledge is broader compared to other. As we mentioned previously, the most used agricultural feedstocks are crops and residues from agricultural activities. Crops are biomass produced through agricultural cultivation activities by harvesting. Residues from agricultural activities are biomass waste resulting from cultivation and transformation of agricultural products. However, other agricultural biomass such as olive and wine biomass has gained interest in the last years in all the southern European regions.

- Industrial biomass

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Byproducts and waste from industrial facilities in the agri-food sector: olive oil production, citrus processing, seed oil extraction, wine and alcohol industry, canning, brewing, animal production, nut production, rice production and algae processing.

Byproducts and waste from industrial facilities in the forestry sector: first and second transformation forestry industries (bark, sawmills, carpentry, etc.), byproducts from the cellulose industry (black liquor), from the recovery of lignocellulosic materials (pallets, building materials, old furniture, etc.

- Urban waste

It is the biodegradable fraction of urban waste that is generated daily in all locations. Additionally, sewage sludge, wastewater and HORECA waste (frying oils, etc.) are included in this category.

- Aquaculture biomass
    - Algae, marine-shell (crustacean) and fish waste processing.
    - Microalgae are single-cell photosynthetic micro-organisms mainly found (but not only) in aquatic environments. These organisms can synthetise important amounts of lipids, proteins, carbohydrates as well as other compounds with biological activity in a very short timeframe from three basic ingredients: solar radiation, carbon dioxide (CO_2) and fertilizers/nutrient-rich water.

2.2.2 Types of processes.

Biomass can be processed into biorefinery platforms, depending on the nature of the feedstocks. These platforms converted a large variety of products in energy-driven or material-driven materials. In the case of energy-driven the final product are biofuels, power and heat, whereas material-driven are food, chemicals, biomaterials, etc.

- **Biochemical:** In this technique, microorganisms and enzymes convert organic compounds such as lignocellulosic, hemicellulose to sugars such as glucose, pentose, etc. Then, by a fermentation process to produce bioethanol or other bio alcohols. In general, biochemical process can be summarized in four steps:

    1. Pre-treatment where biomass is treated to make it suitable for hydrolysis.
    2. Enzymatic hydrolysis to break down complex organic compounds into simpler molecules.
    3. Fermentation where various microbes are used to ferment those simple molecules to produce bio alcohols.
    4. The final step involves separating and purifying the bio-ethanol from the fermentation broth, this is typically done through distillation dehydration, or other separation techniques.

- **Chemical:** Chemical conversion techniques are dehydration, hydrogenation, hydrogenolysis oxidation, hydrolysis, dehydration and isomerization. The chemical conversion conditions have a lower cost impact to work with lower temperature and pressure compared with thermochemical process. Other chemical conversion processes are hydrolysis and supercritical conversion of biomass.

- **Mechanical:** The most used mechanical process is extraction or recovery from crude to products. This procedure usually involves a pre-pressing treatment of the feedstock to recover part of the product. After that, a pressure around 95,000 kPa is applied to extract the rest of the content.

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Others mechanical process are briquetting biomass and distillation. Ohers mechanical processes such as briquetting of biomass and distillation process are also used to recover chemical.

- **Thermochemical:** This technique mostly involves the processing of biomass at high temperature and/or pressure. The thermal degradation of the biomass yields intermediates, which can be further upgraded into value-added products with the help of numerous other techniques like pyrolysis or gasification. Overall, thermochemical conversion mainly comprises four key processes: combustion, gasification, pyrolysis, and liquefaction. While thermochemical conversion involves direct combustion, gasification, and pyrolysis, liquefaction also plays a significant role in converting biomass into liquid fuels or chemicals under moderate temperatures and high pressure.

2.2.3 Chemical platforms

Chemical platforms derived from biomass are critical to the transition toward a sustainable bioeconomy. These platforms represent key intermediary molecules produced during the conversion of renewable biomass and serve as versatile building blocks for manufacturing value-added products, these primary platforms can be converted to a wide range of marketable products such as, polymers, chemicals and other bio-based materials. Unlike their fossil-based counterparts, bio-based platforms offer a renewable and often carbon-neutral alternative that is in line with global sustainability goals.

The production of these platforms typically involves biochemical, chemical, thermochemical and mechanical processes applied to different feedstocks. Lignin derivatives, furfural, levulinic acid, lactic acid, succinic acid, sugar alcohols and other key chemicals are currently in commercial production. A major advantage of these platforms is their potential to reduce dependence on fossil resources while creating circular chemical production systems. However, challenges remain in terms of optimising yield, scalability and economic viability. Ongoing research focuses on improving catalytic processes, feedstock flexibility and integration with existing industrial infrastructure. By combining renewable resources with green chemistry, chemical platforms derived from biomass represent a vital route to decarbonising industries and achieving a more sustainable future.

2.3 Internal questionnaire.

This section presents the results of an internal questionnaire that we performed at the beginning of these tasks. The aim of this internal questionnaire was to gain an overview of the biomass, processes and technologies that the consortium partners would like to study in more detail. In addition, this survey allows us to do conduct specific research on biorefineries, types of feedstocks, etc. The survey was sent to all consortium members, and we received 11 responses (Since some project participants have non-technical backgrounds). The survey is divided into the availability, interest and commitment of feedstock in each the region, the most used processes and final products. Within the information collected from this internal questionnaire was used to find companies and industries working with the most selected feedstocks and processes were identified. The interview structure/template is attached in Annex 5.1.

The first question was to confirm whether the participants agreed to take part in the internal questionnaire. The second question concerned the origin of the participants in the internal questionnaire. Regarding the graph for question 2 (Figure 3), at least one member from each of the countries participating in the BioINSouth project responded, except for France and the Czech Republic.

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Figure 3. Participant consent and country selection.

Questions 3 and 4 (**Errore. L'origine riferimento non è stata trovata.**) were formulated to explore the availability and the most promising biomass that can be found in the southern regions. The first question (question nº 3) related to this block was to know the availability of the biomass in the region. Agricultural biomass appears to be the most available at 36%. It is followed by municipal waste at 27% and then by livestock and forest biomass at 14% each. Finally, there is industrial waste at 9%. Question 4 was formulated to get an overview of the most relevant biomass from an industrial point of view. Based on the results selected by the respondents, agricultural biomass accounted for 41%, municipal waste for 23% and livestock and industrial waste for 14%. In general, it can be said that some of the most promising biomass is not yet being used because the technology is not yet sufficiently advanced. This applies to municipal waste, which although it is the most readily available feedstock, is the least relevant from an industrial point of view. In the case of agricultural waste, however, there is a consistency between availability and use.

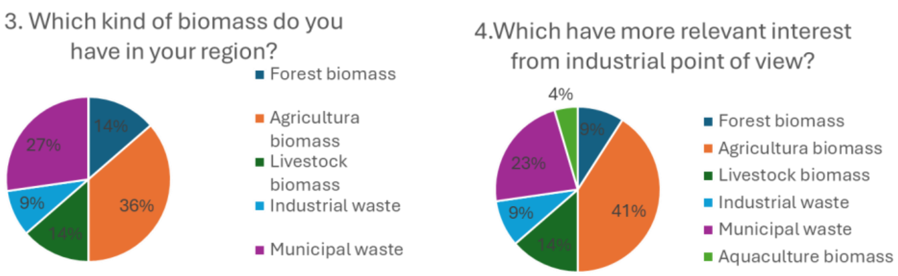

Figure 4. Distribution of Biomass types and industrial preference in the region.

The next set of questions aimed to establish the availability, usage and potential of different feedstocks in the region. Regarding question 5 (Figure 5), which asked about the most available feedstock in the region, 32% of participants chose food waste. The second most available feedstock was lignocellulose at 23%, with the remaining options receiving less than 15% of the total responses. Question 6 asked about the most used feedstock in the southern region. According to the graph, food waste, oil-based residues and lignocellulose were the most popular choices, with 24% and 19% respectively. The other feedstocks received less than 10% of the votes. To conclude this section of the questionnaire, we asked which feedstock was the most promising. This cannot be matched with the availability of the feedstock, as parameters such as the level of maturity of the technology have to be considered. Looking at the graph, the most popular choices were lignocellulose, algae and municipal waste with 27%, 24% and 19% of the votes respectively.

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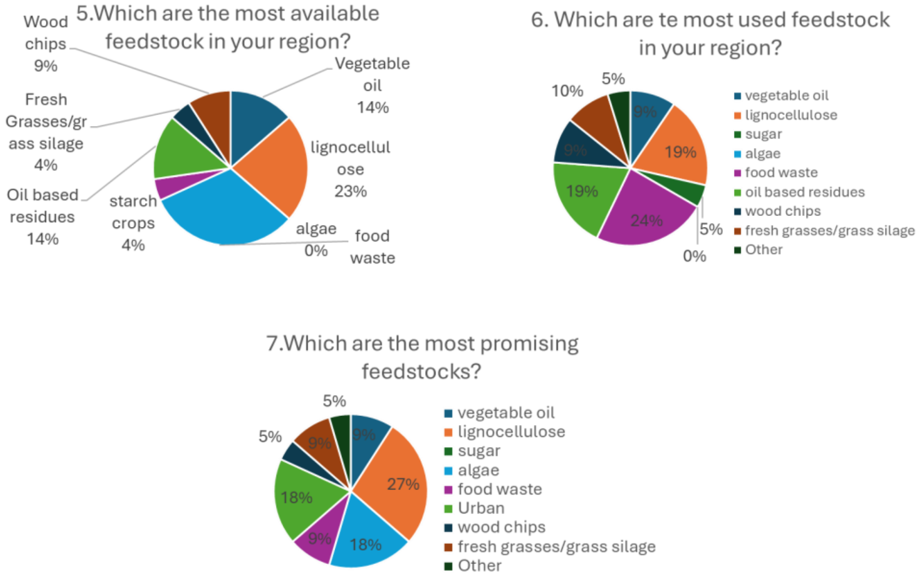
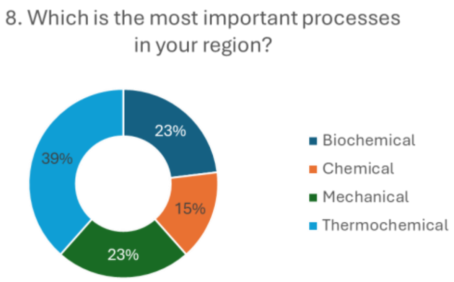


Figure 5. Comparative analysis of feedstock availability, current usage, and future promise in the region.

The idea of this part of the questionnaire was to obtain information about the most used processes and the most produced chemical platforms or products that can be found in the southern regions (Figure 6). Regarding question nº 8, the thermochemical process was the most selected, followed by biochemical, mechanical and chemical processes. It is important to note that a specific technology was used depending on the feedstock processed. Question 9 listed a group of different chemical products. Most of the products were not selected by any of the respondents, but Figure 6 shows a summary table of the most frequently selected chemical products. Ethanol and lactic acid are the most frequently chosen, followed by glycerine. In addition, 3 respondents chose 'other' as an option, but did not specify which chemical product they would have added to the list. In question 10, where we asked about the final product produced by biorefineries, the answers are balanced between final and intermediate products.



9. Which are the most produced chemical platforms in your region?

Produced chemical platforms	Number of votes	Percentage (%)
Lactic acid	3	20
Citric acid	1	7
Formic acid	1	7
Glicerol	2	13
Ethanol	3	20
Phenols	1	7
Furfural	1	7
Others	3	20

Figure 6. Survey Questions on key processes and target products in the region.

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Finally, the last part of the question was an open-ended question about their opinion on market opportunities, technological barriers and potential companies to contact.

- Question nº 11: What is the most important market opportunity?
- Question nº 12: Could you list potential companies or biorefineries that could be the subject of a study?

The first question was important to know the level of maturity of the technology and how well these technologies are implemented in the interested region. Regarding the answer, only 2 respondents answered these two questions and due to the low response rate, we decided not to process the data. In the second open question, we asked for possible companies that we could contact for a technical interview to create a map of biorefineries in the South.

3 MARGs technical interview.

This section presents an analysis of the data from various technical MARG interviews conducted by CTA. The interviews conducted by CTA were classified as technical or non-technical depending on the background of the MARGs interviewed. In this deliverable only the technical interviews were analysed, while the non-technical interviews are included in D2.1 under WP2.

The profiles come from different collaborating regions in South of Europe that participated in BioInSouth. To analyse the raw data, we follow a two-step procedure: 1) to encompass the answer in a more general concept, such as type of biomass, general process, etc. and 2) to explain the answer of the respondents in detail.

The analysis of the MARGs was to answer following topics/question:

- The most interesting and unexplored feedstocks of the collaborative regions.
- The most used technologies and the barriers to implement new technologies in the region.
- The impact on the growth of biorefineries, costs of the biorefinery operations and the economic models.

In the **Annex 5.2** the Interview template MARGS WP2 is attached.

Q1: In your opinion, what are the most promising biomass feedstocks for biorefineries in your region, and how their availability could affect growth scenarios for the regional bioeconomy sector?

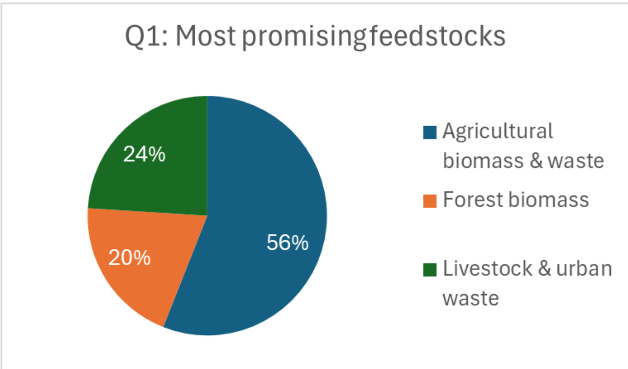

Figure 7. Distribution of most promising feedstocks for bioenergy production.

Based on the responses of the 16 participants (Figure 7), more than half selected agricultural biomass and waste as the most promising feedstock. Examining the answers in more detail, olive biomass and

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wine were identified as the most interesting feedstocks. Forest biomass, livestock waste and urban waste are also of interest for use as feedstocks.

Q2: Are there unexplored sources, such as algae, industrial waste or specific agricultural waste that could become crucial to biorefinery growth?

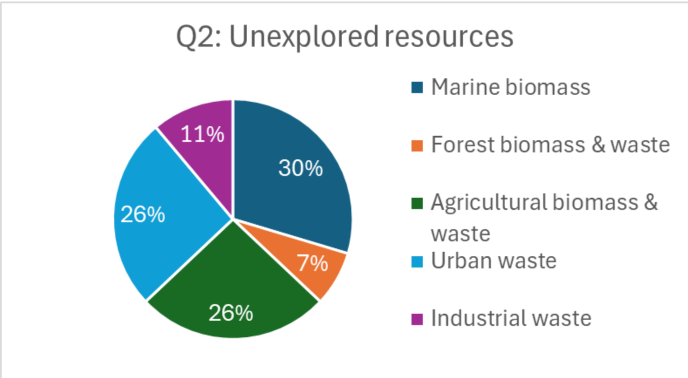

Figure 8. Distribution of unexplored biomass and waste resources by category.

The second question (Figure 8) was about the most interesting unexplored resources that it can be found in the region of interest. Thirty percent of respondents chose marine biomass, specifically algae feedstock as the most unexplored resource. This was followed by agricultural biomass & waste and urban waste with a 26% choosing each option. Compared to the previous question, industrial waste and marine biomass emerged as potential resources.

Q3: From the biorefineries of your region, which technologies are the most used?

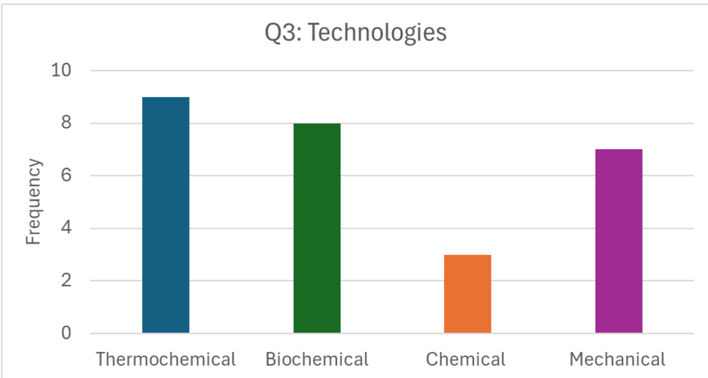

Figure 9, The most commonly used technologies.

As mentioned in the introduction to this deliverable, the type and level of development of technologies play a crucial role in the economics of biorefineries. In addition, the technology used may differ depending on the feedstock processed by the companies, as the product obtained has different routes of production. The most used technologies are: Thermochemical, biochemical, mechanical and chemical, respectively (Figure 9).

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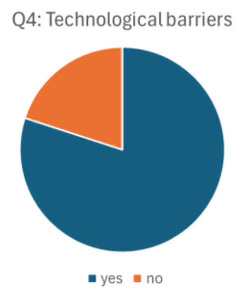
Q4: Have you already identified technological barriers to the implementation of circular bioeconomy new value chains, new processes or the improvement of existing ones in your region? If yes, what could be possible strategies to address that issue.



Responses	Frequency
Scale up processes/pre-industrial	5
Innovative technologies	5
Problems with synergies between industries/ companies (lack of cooperation)	4
Product development	4
Cost of energy/transformation cost	4
Not governmental support	3
Lack of economic competitiveness	2
Logistical problems (transport problems)	2
High tech profile	2
Financial constraints	1
Low volume material	1
Dispersion of raw material	1

Figure 10. Frequency of reported challenges on Technological barriers in industrial innovation

Question 4 (Figure 10) asked about the technological barriers to implementing new processes to find out if they had identified any barriers. This question was therefore divided into two parts: First, a yes/no question about possible technological barriers. If the respondents answered 'yes', the second question asked them to briefly describe the problem they had identified in implementing the technology in their region. The most significant issues identified were scaling up processes and implementing innovative technologies. Lack of cooperation between public and private administrations and product development and transformation costs were also identified as difficulties.

Q5: What innovations in bioprocessing are you most excited about and why? What role will technological innovation play in the growth of biorefineries in your region?

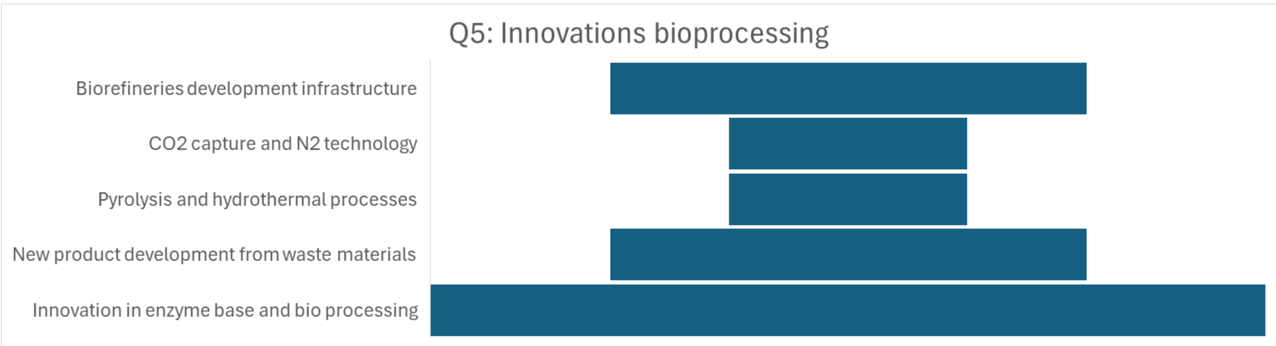


Figure 11. Key innovations in bioprocessing and waste-to-product development.

The answers to this question were divided into six categories or groups based on the answers (Figure 11): biorefinery infrastructure, CO_2 capture and N_2 technology, pyrolysis and hydrothermal processes,

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thermocatalytic and biocatalytic routes, new product development from waste materials and innovation in enzyme-based bioprocessing.

As it can be seen, the most interesting innovation proposals relate to bioprocessing and enzyme-based technology. This is followed by the development of new products from waste materials and the infrastructure development. Regarding bioprocessing, some of respondents expected this new technology to play a crucial role in improving the efficiency, sustainability and scalability of biorefineries. Others noted the advances in enzymatic hydrolysis and synthetic biology that will improve the biomass conversion efficiency. Regarding new product development from waste materials, this is directly related to promising feedstocks, with waste being identified as a potential material for use in biorefineries.

Q6: In your opinion, how far is the biorefinery concept feasible in developing countries? Are we really getting back to nature or increasing the dependency on fossils?

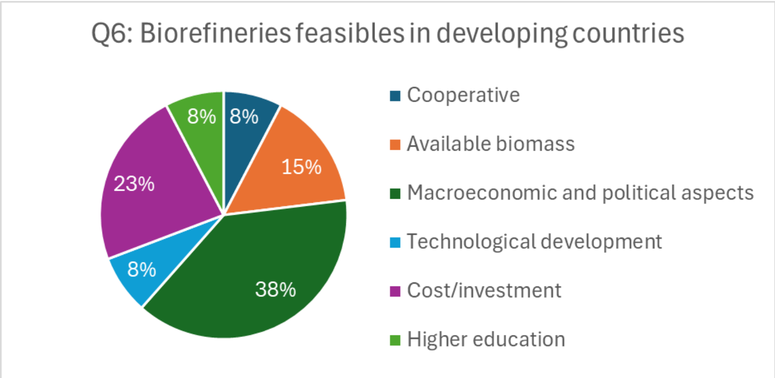

Figure 12. Key factors influencing the feasibility of biorefineries in developing countries.

The purpose of this question was to understand how the development of biorefineries is perceived in collaborative regions. The responses (Figure 12) were grouped into six categories to summarise the answers. 38% of respondents selected macroeconomic and political factors, 23% selected cost and investment, 15% selected available biomass, and 8% selected cooperation, technological development, and higher education. The most important point to note is their belief that the macroeconomic and political aspects could play a crucial role. Alongside the macroeconomic aspect, they also highlighted public or private investment in technological development (23%). The third most popular answer was the availability of biomass in the region (15%), which is directly related to the region's specific climate and seasonality.

Q7: Please rank the following factors in order of their potential impact on the growth of biorefineries in Southern Europe, starting with the most influential and ending with the least.

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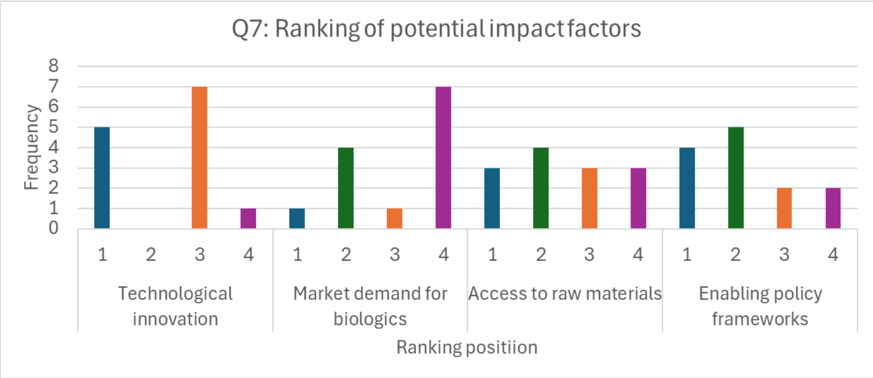

Figure 13. Ranking of potential impact factors on biologics production.

In this question, respondents were asked to rank four potential impact factors on the growth of biorefineries in southern Europe. The graph (Figure 13) was constructed based on the frequency and the position of the rankings. As can be seen, no clear tendency is evident, however, some options were selected more frequently than the others. For example, technological innovation was the first most popular option, followed by enabling policy frameworks as a second option and market demand for biologics as fourth option. Nevertheless, technological innovation appeared as the third popular option. Due to the randomness of the responses, it was difficult to draw general conclusions from the processed data.

Q8: How do you see the evolution of the biomass supply chain in your region?

a) **Biomass availability increases as agricultural, and forestry residues are better utilized.**
b) **There may be supply constraints that hinder the growth of biorefineries.**

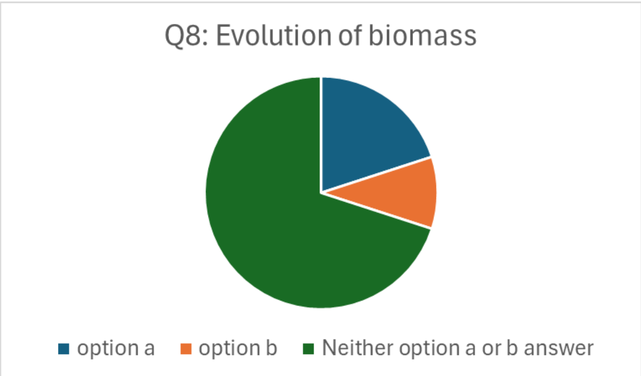

Figure 14. Comparing biomass evolution scenarios.

The objective of this question was to address the evolution of the biomass supply chain in their region based on two assumptions: a) biomass availability increase as agricultural, and forestry residues are better utilized and b) there may be supply constraints that hinder the growth of biorefineries.

Regarding the survey respondents' answers (Figure 14), most did not select either option A or B, but responded as if to an open question (70%). Therefore, based on the general responses, we decided to add a third option. Some respondents said that they were not experts in the field and that both options were complementary with regard to the current situation in their region. Of the respondents who answered options a and b, 20% chose a and 10% chose b. However, it was difficult to conduct a proper analysis of this question based on the above data.

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Q9: Identify any regional disparities based on local biomass availability, infrastructure or government Support that could impact growth scenarios.

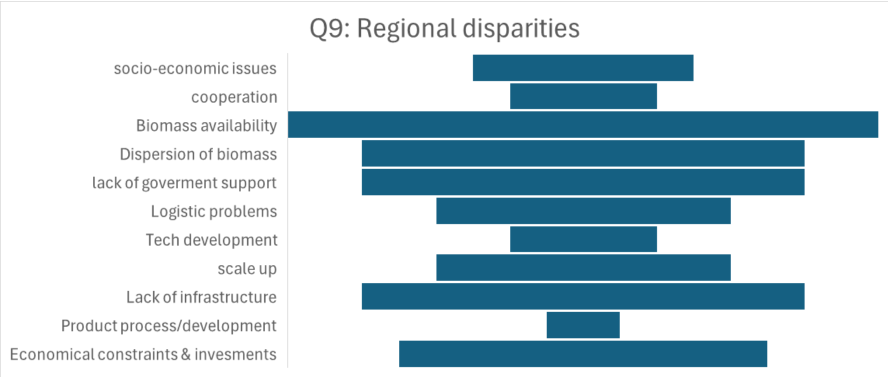

Figure 15. Key challenges in regional biomass utilisation and development.

This open question aimed to elicit general opinions on regional disparities that could directly impact growth scenarios. The answers were grouped into the following 11 categories (Figure 15): It was more difficult to divide them into fewer categories in this case, since there were many factors that could have an impact. Generally, there were no disparities affecting all respondents. Overall, there was a good balance between all the regional disparity groups. However, we could generally identify the most important regional disparities as first, biomass availability; second, biomass dispersion; and third, lack of government and infrastructure. It is also important to note that economic constraints and scaling up were identified as important regional disparities.

Q10: How do you anticipate the cost of biorefinery operations evolving, and how this impact will future growth scenarios in your regions?

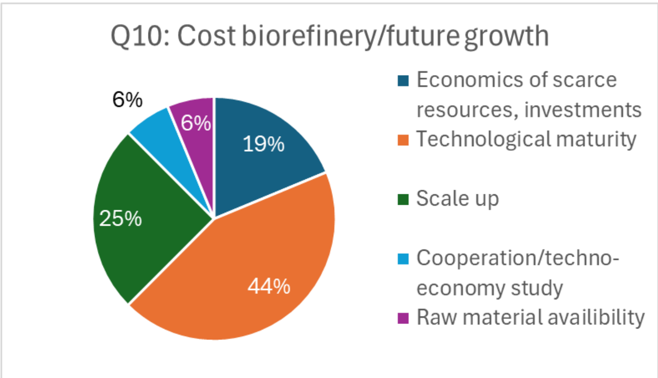

Figure 16. Key challenges and factors influencing the cost and future growth of biorefineries.

Question 10 was designed to gauge the experts' views on the evolution of biorefinery operational costs and their potential impact on regional growth scenarios. Based on the analysis (Figure 16), 44% of responses were categorised as being in the technological maturity group, followed by 25% and 19% for scaling up and investment, respectively. Only 6% of the responses were related to cooperation and raw material availability. Finally, 19% of interviewees confirmed that there is a strong connection between costs and biorefinery processes. These findings demonstrate that technological readiness and implementation scalability are perceived as the primary cost drivers for biorefinery development, collectively accounting for 69% of expert responses. This suggests that the industry is transitioning from

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the experimental phase to the commercialisation phase, in which engineering and implementation hurdles have become more critical than the need for fundamental research or the availability of basic resources (19%). The minimal focus on cooperation and raw material availability indicates that these are not currently considered major constraints on cost evolution or growth potential in the biorefinery sector.

Q11: What impact do you anticipate biorefinery growth having on local economies, particularly in rural or economically disadvantaged regions?

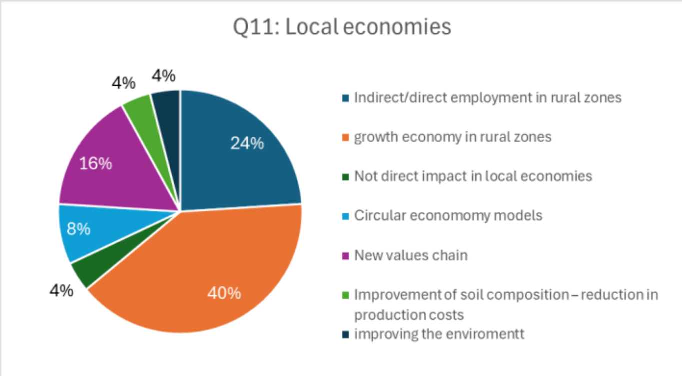

Figure 17. The impact of sustainable practices on local economies in rural areas.

This question aimed to gather opinions on the potential impact of implementing biorefineries on the local economy. This was a crucial point to address (Figure 17), given that most of the feedstocks they currently use, or which could be used in biorefineries, are located outside urban areas. As can be seen, 40% of respondents confirmed that biorefineries could directly impact economic growth in rural areas. Consequently, 24% of respondents indicated that biorefineries would create direct or indirect jobs in these areas. 16% of respondents believed that a new value chain would impact the local economy. The remaining responses accounted for less than 8% of the total, with 4% of respondents suggesting that biorefineries might not directly impact the local economy.

Q12: What economic models or metrics do you recommend for assessing the long-term financial sustainability of biorefineries in Southern Europe?

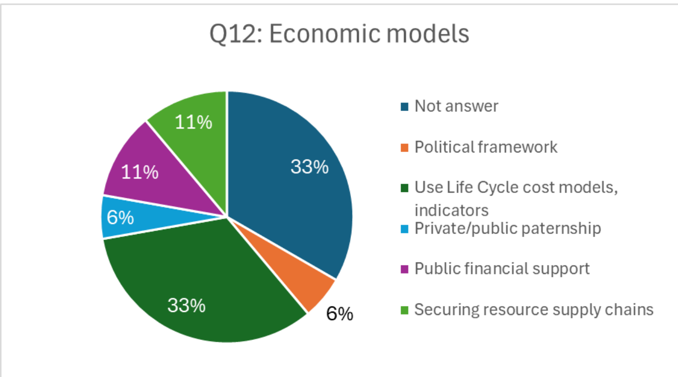

Figure 18. Economic models for securing resource supply chains: Key approaches and their Usage.

This question was included to gain an understanding of the economic model that the interviewee would recommend implementing to ensure the long-term sustainability of biorefineries. As can be seen in the graph (Figure 18), one third of respondents did not answer due to a lack of knowledge about economic

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models. Another third replied that economic models may depend on resource supply chains. The remaining answers were divided between public financial support, cooperation between the private and public sectors, and the use of life cycle costs as an economic model.

Q13: What do you consider the most promising economic scenarios for biorefineries in your region over the next 5-10 years?

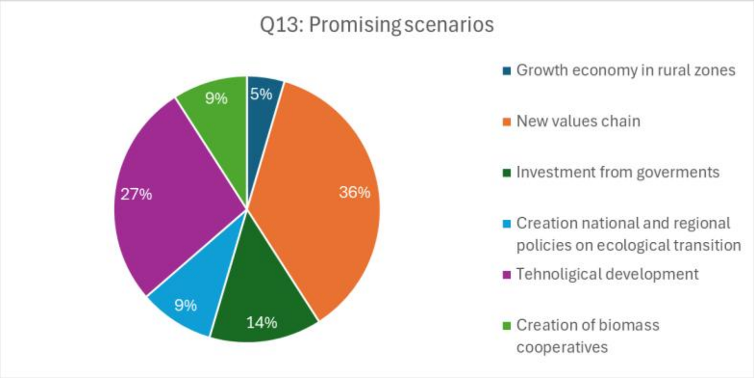

Figure 19. Distribution of promising scenarios for ecological transition and rural economic growth.

Finally, the questionnaire concluded with an open question about the most promising scenarios for the next 5–10 years. The answers were analysed by grouping them into six categories based on the respondents' general opinion (Figure 19). Analysis of the graph shows that 36% of participants mentioned the development of a new value chain in biorefineries. This was followed by the idea that the government should invest in infrastructure (14%) and innovative technologies (27%). The remaining answers had a lower impact.

4 Benchmark Study on European Biorefinery Operations: Trends, Challenges, and Innovations

4.1 Interviews with biorefinery companies

The benchmarking study, which was conducted through interviews with biorefinery companies using a structured questionnaire (see Annex), aims to collect detailed insights into biorefinery operations across Europe, each with unique feedstocks, processes, and market focuses. The companies range from start-ups to large corporations, utilizing feedstocks such as agricultural waste (e.g., banana leaves, olive pomace), forestry residues (e.g., spruce logs), seaweed, and industrial by-products (e.g., spent sulphite liquor). Their products include natural fibres, bioplastics, biochemicals, and specialty ingredients for industries like construction, agriculture, pharmaceutical, cosmetics, and packaging. The interviews focus on challenges and innovations in key areas such as feedstock sourcing, product development, process technologies, sustainability/circularity practices, and regional support. By addressing these critical aspects, the questionnaire aims to highlight industrial trends, best operational practices, opportunities, and challenges to advance sustainable biomass valorisation. The questionnaire is structured into four sections, each targeting essential dimensions of biorefinery operations: Examines availability, seasonality, variability, and logistics to assess supply chain.

1. **Product Strategies:** Explores product diversification, targeted markets, revenue streams, and innovation pathways.

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2. **Process Optimization:** Evaluates Technology implementation, scalability, sustainability (energy efficiency, waste valorisation) and circularity.
3. **Regional and Policy Context:** Analyses specific advantages of location, regulatory barriers, and support mechanisms.

To provide a detailed and representative analysis, the study synthesizes responses from eleven biorefinery operations across Europe (Table 1), covering a diverse range of sectors:

- Agricultural residues: Tezkim, Alvinesa, NATAC Biotech

- Wood and forest biomass: Borregaard, NatStruct

- Marine biomass: Alginor, Tecnoalgae

- Waste valorisation: Venvirotech, Novamont, Envirohemp, Mevaldi

Table 1. Summary of the companies that agreed to participate in this study.

Companies	Location	Feedstocks	Products	Processes	Start up
NatStruct	Germany	Agricultural waste (banana and pineapple, leaves)	Natural fibers	Patent	2025
Borregaard	Norway	Wood	Bioethanol, biopolymers, biovanillin	Sulphite pulping	1889
Alginor	Norway	Algae (*Laminaria hyerborea*)	Medical, health care, nutrition, feed	Confidential	2014
Novamont	Italy	Agricultural	Biodegradable and composite bioplastics	Biotech	1990
Tezkim	Turkey	Agricultura	Bioethanol, citric acid, CO_2 DDGS	Biotech Fermentation	2005
Mevaldi	Netherlands	Forest biomass	Building block for bioplastic (polyurethatne and polyester)	Biotech Fermentation	2020
Envirohemp	Spain	Forest waste	Activated carbon Biochar production	Thermochemic-al	2018
NATAC Biotech	Spain	Agricultural (olive)	Medical, health care, nutrition, animal nutrition	Confidential	2010
Tecnoalgae	Spain	Microalgae	Regenerative agriculture, air purification, water treatment	Not specify	2024
Alvinesa	Spain	Agriculture (olive wine biomass)	Food ingredients, animal nutrition pharmaceutical and nutraceutical industry	Mechanical(ext raction)	1993
Venvirotech	Spain	Bacteria	PHA production	Biochemical (Fermentation)	2018

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4.2 Feedstock

The availability and management of feedstocks are critical for the sustainability and efficiency of biorefineries. This analysis examines the feedstock types, seasonal variations, storage practices, and logistical challenges across eleven interviewed biorefineries in different European (Table 2). The goal is to identify common trends, unique challenges, and best practices in feedstock sourcing and utilization.

Table 2. Summary of the companies participating in this study.

Company	Feedstock Type	Seasonality	Storage Practices	Logistics & Suppliers	Key Challenges	Future Outlook
NatStruct	Banana & pineapple leaves, Lavander	Low seasonality	No storage needed	Cooperative suppliers (≤ 50 Km)	Machinery access	Expansion to South America
Borregaard	Spruce logs, Spent sulphite liquor (SSL)	All year	Wood stored (for months), SSL in buffer tanks (few days)	10 + suppliers, (≤ 100 Km); SSL (via pipelines) Permits required (emissions, certifications).	EU regulations on forestry	Competition for wood biomass
Alginor	Macroalgae (Laminaria seaweed)	All year (controlled)	Minimal storage; processed immediately	Self-harvesting under permits	High sensitivity to feedstock quality	Farmed seaweed, other seaweeds species
Novamont	oleaginous dry crops, Agro-Industrial waste, exhausted oils	Stable supply Seasonal (corps)	Integrated storage in supply chains	Local/regional suppliers Permits required for waste handling	Diversification needed,	Circular economy focus
Tezkim	Corn Bran	All year	Stored in silos (30-45 days)	20 + suppliers (≤ 400 Km)	Starch content variability	Increasing ethanol production
Mevaldi	2° generation feedstocks (glucose, sucrose)	Stable (tank farms)	No storage; direct processing	3 European suppliers	High purity requirements	Scaling to 20 ktons/year
Envirohemp	Olive pits vineyard waste	Seasonal (harvest dependent)	Limited storage capacity	Multiple small/large suppliers (≤ 100 Km)	Heterogeneity of feedstock	New feedstocks
NATAC Biotech	Medicinal & aromatic plants Agro-industrial waste	Seasonal (dried for stability)	Stored for ≤2 years (10 % humidity)	20 + regional suppliers	Contaminant variability	New plant (2025) for scalability

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Company	Feedstock Type	Seasonality	Storage Practices	Logistics & Suppliers	Key Challenges	Future Outlook
Tecnoalgae	Microalgae for wastewater	All year	No storage, continuous cultivation	Purchased from algae banks	Light & temperature dependence	Expanding to bacteria based systems
Alvinesa	Wine, grape pomace, Olive wastewater	Seasonal (August-Octobre)	Premium pomace processed immediately	50 % of Spain's pomace supply	Quality variability (polyphenol content)	Scaling premium product lines
Venvirotech	Organic waste, Brewery yeast	All year	No storage; modular on-site processing	Installs reactors at supplier sites	High variability in waste streams	-

Key observations on feedstocks in biorefineries:

- Diverse Feedstock Sources:
  - Biorefineries utilize a wide range of feedstocks, including agricultural waste (banana leaves, grape pomace), forestry products (spruce logs), marine biomass (macroalgae), and industrial by-products (brewery waste, Spent Sulphite Liquor).
  - Some companies (e.g., Novamont, Envirhemp) focus on circular economy principles by repurposing waste streams.
- Seasonality and storage challenges:
  - Agricultural feedstocks (e.g., grape pomace, olive pits) are highly seasonal, requiring dry storage (up to two years for NATAC Biotech).
  - Non-seasonal feedstocks (e.g., macroalgae, industrial waste) allow for continuous production without storage needs.
  - Wood-based feedstocks (e.g., Borregaard) require long-term storage (months) but remain stable.
- Feedstock variability and process sensitivity:
  - High sensitivity: Macroalgae (Alginor, Tecnoalgae) and premium grape pomace (Alvinesa) require strict quality control due to compositional changes.
  - Low sensitivity: Wood (Borregaard) and second-generation sugars (Mevaldi) are more homogeneous, reducing processing adjustments.
- Logistics and supplier networks
  - Most biorefineries rely on multiple suppliers (e.g., Tezkim has more than 20 corn suppliers).
  - Transportation: Some collect feedstocks directly (e.g., NATAC Biotech, Alginor), while others rely on suppliers (e.g., Borregaard).
  - Regulatory permits are critical, especially for waste-derived feedstocks (e.g., Novamont, Borregard).
- Future feedstocks trends:
  - Expansion into new feedstocks: Some companies (e.g., Alginor, Envirhemp) are exploring alternative biomass sources.
  - Climate and policy impacts: Borregaard anticipates future wood shortages due to EU regulations, while Tezkim expects increased corn availability.
  - Energy costs and sustainability: Rising energy prices (Mevaldi, Alvinesa) and water scarcity (NatStruct) are key concerns.

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Conclusion:
The analysed biorefineries exhibit a wide range of feedstock strategies, from the incorporation of seasonal agricultural residues to the utilisation of stable industrial by-products. While some face challenges such as seasonality and regulatory barriers, others benefit from robust supplier networks and flexible storage solutions. Future success will depend on increasing feedstock flexibility, investing in regional supply chains and embracing circular economy practices. The diversity of these approaches demonstrates the adaptability of biorefineries in the transition to a bioeconomy. Policymakers can support this sector by addressing regulatory inconsistencies and promoting incentives for the sustainable use of biomass.

4.3 Products

The eleven biorefinery companies participating in this report operate across a variety of sectors and utilise different types of feedstock to produce a wide range of bio-based products (see Table 3). These products serve multiple markets, including agriculture, construction, food, pharmaceuticals, chemicals, and biopolymers. This analysis examines their product portfolios, market targets, revenue distribution, client bases and sales strategies. The aim is to identify trends and similarities, as well as unique approaches, across these companies.

Table 3. Overview of biorefinery products.

Company	Products	Target Markets	Revenue Distribution	Product Type Intermediate/Final	New Product Development	Client Base	Sales Force
NatStruct	natural fibers, pulp	Construction, automobile, textile	Dominated by 2 products	Both intermediate and final	Product for reduce mineral wool and polyurethane	2-3 medium sized companies	Direct sales
Borregaard	ca. 800 chemicals from wood	Global B2B markets (cellulose, lignin, vanillin)	Wide range; high-value products dominate	Mostly intermediates	3-4% turnover on R&D	Several thousand clients	Own sales offices and distributors
Alginor	alginate, Fucoidan, cellulose	Health, nutrition, cosmetics	Alginate dominates	Ingredients (B2B)	Collaboration with institutions	Not yet commercial	Own sales forces
Novamont	Bioplastics, chemicals building blocks	Agriculture, packaging	Mater-Bi bioplastics	Granules (intermediates)	Internally and in collaboration	Wide range of different clients	Direct and distributors
Tezkim	Bioethanol, CO_2, Citric acid	Cosmetics, carbonated beverages, animal feed	Ethyl alcohol dominates	Intermediates products	External collaborations	ca. 10 large clients	Own sales team
Mevaldi	Bioplastic intermediates	Polyester, polyurethane markets	Small group of products	Intermediates products	European & subcontracting projects	Small number of clients	Direct sales
Envirohemp	Biochar, Activated carbon	Agriculture	Biochar dominates	Final product	Developing enriched biochar	Online and distributors	Both direct and intermediaries
NATAC Biotech	Botanical extract	Nutraceuticals, pharmaceuticals, animal feed	Olive-based extracts dominate	Ingredients (B2B)	In-house R&D	ca. 500 clients	Own logistics
Tecnoalgae	microalgae solutions	Waste water treatment, agriculture, urban air purification	agricultural biostimulant	Final product/service	In-house R&D	Diverse (agriculture, municipalities)	Direct and intermediaries
Alvinesa	Polyphenols, wine concentrate, Grape seed oil	Food supplements, enology, animal feed	Balanced revenue	Both intermediate and final	In-house R&D	ca. 800 clients in 50 countries	Own sales team

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Venvirotech	PHA, short chain fatty acid,	Cosmetics, packaging,textils	PHA blends dominate	Intermediate (PHA)	In-house R&D	Few clients (early stage)	Direct sales

Key observations on biorefinery products

- **Product Diversity**: Most companies produce multiple products, often with one or two dominating revenue streams (e.g., **Borregaard**'s lignin chemicals, **Novamont**'s bioplastics).
- **Market Targets**: Companies target diverse markets, including construction, agriculture, pharmaceutical, cosmetics, and packaging. Some (e.g., **Alvinesa**, **NATAC BIOTECH**) focus on sectors such as nutraceuticals.
- **Revenue Distribution**: Dominance of 1–2 key products are common, though **Borregaard** and **Alvinesa** have more balanced portfolios.
- **Product Type**: Intermediates are prevalent, but some (e.g., **Envirhemp**, **Tecnoalgae**) produce final products.
- **Innovation**: Research & development is often collaborative (e.g., **NatStruct**, **Novamont)** or in-house (e.g., **NATAC**, **Venvirotech**).
- **Client Base**: Larger firms (**Borregaard**, **Alvinesa**) serve thousands of clients, while startups (**Venvirotech**, **Mevaldi**) have limited clients.
- **Sales Strategy**: Most companies use direct sales, but some (e.g., **Novamont**, **Envirhemp**) rely on intermediaries for distribution.

Conclusions:

The biorefinery sector studied exhibits a balance of specialisation and diversification, with companies using innovative processes to convert biomass into valuable products. Although intermediates currently dominate, end products are emerging in areas such as biochar and microalgae solutions. Revenue concentration in key products highlights the important roles of scalability and market demand. Innovation is driven by a combination of collaborative partnerships and in-house research and development. Future growth will depend on expanding product portfolios, optimising supply chains and adapting to evolving regulatory and sustainability requirements.

4.4 Process

4.4.1 Technologies

The biorefinery sector is diverse, using different feedstocks and technologies to produce biobased products. This section analyses the technological aspects of participating biorefineries, examining their production processes, innovative technologies, process control variables, scalability, market presence and global competitors. The findings are summarised in the Table 4 below, followed by key observations and conclusions.

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Table 4. Summary Technological Aspects of Participating Biorefineries

Company	Main Production Steps	Innovative/advantageous Technology	Process Control Variables	Scaling Plans	Similar Plants	Global Top Players
NatStruct	Waste leaf processing→ Natural fibers and pulp	Patent-pending machinery for fiber extraction	Feedstock composition, machinery parameters	Yes, scaling planned	Some similar plants in the region	None identified
Borregaard	Sulphite pulping Cellulose→ lignin, vanillin, ethanol	Sulphite pulping for multi-product output.	Cooking conditions, product quality metrics	Debottlenecking and capacity increases planned	Few global sulphite biorefineries	Borregaard is a market leader in lignin and vanillin
Alginor	Macroalgae harvesting→ Alginate extraction→ By-product utilization	Free-formaldehyde processing	Seasonal composition of seaweed	Pilot plant; scaling by 2025	Unique biorefinery for alginate	None identified
Novamont	Agricultural waste→ Bioplastics (Mater-Bi), biochemicals.	Proprietary starch-polyester blending technology.	Water, energy use, emissions	Continuous expansion of circular bioeconomy model	Few similar integrated plants	Novamont is a leader in compostable bioplastics
Tezkim	Corn/wheat → Ethanol, CO_2	Fermentation technology for high-purity ethanol.	Starch content, temperature, pressure	Capacity increases under consideration	Common in Turkey (3 local plants)	No global leader highlighted
Mevaldi	Sugar feedstocks→ Bioplastics intermediates (fermentation + catalysis)	Hybrid fermentation-chemical catalysis	Sugar purity, fermentation yields	Scaling to 20K tons	Few competitors in Europe	Chinese companies lead in sugar-based bioplastics
Envirohemp	Agro-industrial waste→ Biochar and activated carbon.	Rotatory kiln for pyrolysis.	Temperature, particle size, humidity.	No immediate plans; depends on demand	Some similar plants in Spain.	several well-known companies
NATAC Biotech	Plant extraction (medicinal/agri-waste) → Nutraceuticals.	Proprietary extraction and purification tech	Active compound concentration, contaminants	New factory planned for 2025	Unique in Extremadura, Spain.	Competitors exist but no clear global leader
Tecnoalgae	Microalgae cultivation→ Water treatment, air purification.	Modular bioreactors for diverse applications	Light, temperature, oxygen levels	Expanding reactor production	Similar plants in Andalusia	Necton and Neoalgae are regional competitors
Alvinesa	Wine/olive waste→ Polyphenols, tartaric acid, alcohol	Multi-stream waste valorization	Polyphenol content, alcohol levels.	Expanding health/nutrition division	Unique combined wine/olive biorefinery	Alvinesa is a global leader in wine waste valorization
Venvirotech	Organic waste→ PHA bioplastics via	Acidogenic fermentation & solvent-free PHA extraction	Green solvent extraction/acid concentration	Scaling to 20K tons	First industrial-scale PHA-	Chinese PHA producers (e.g., Pha

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	bacterial fermentation				from-waste plant	Builder) dominate)

Key Observations

- **Diverse Feedstocks and Processes:**
  - Feedstocks range from agricultural waste (Novamont, Alvinesa) to macroalgae (Alginor) and organic residues (Venvirotech).
  - Processes include mechanical extraction (NatStruct), chemical pulping (Borregaard), and fermentation (Tezkim, Mevaldi).
- **Innovation Highlights:**
  - Patented Technologies: NatStruct and NATAC Biotech rely on proprietary machinery/extraction methods.
  - Circularity: Novamont and Venvirotech emphasize zero-waste designs (e.g., solvent recycling, byproduct valorization).
  - Modular Systems: Tecnoalgae's adaptable bioreactors stand out for decentralized applications.
- **Scalability Challenges:**
  - Most companies (e.g., Venvirotech, Mevaldi) plan scaling but find feedstock consistency and energy costs as barriers.
  - Smaller players (Alginor, Envirhemp) face funding and regulatory hurdles.
- **Market Position:**
- Borregaard and Novamont are EU leaders in lignin and bioplastics, respectively.
- Chinese firms dominate PHA (Venvirotech's competitor) and activated carbon (Envirhemp's competitor).

Conclusion:

The biorefinery sector exhibits significant technological diversity, driven by feedstock specificity and the pursuit of circular economy objectives. Although European companies dominate niche markets such as lignin and wine waste, they face intense global competition, particularly from China, in the production of scalable bioplastics and chemicals. Key challenges include securing sustainable supplies of feedstock, optimising energy use and navigating the regulatory landscape. In order to compete with established fossil-based industries, the company's future growth will depend on strategic scaling, establishing partnerships, and policy support.

4.4.2 Sustainability/Circularity

The analysis of the eleven biorefineries questionnaires reveals that their sustainability and circularity practices (Table 5) exhibit significant variations based on feedstock, process type, and regional factors. The analysis focuses on key aspects such as resource efficiency, waste management, and carbon footprint, highlighting both challenges and innovative solutions.

Table 5. Summary of Sustainability/Circularity Aspects.

Company	Water/Energy Challenges	Solvent Use & Alternatives	Main Waste Streams & Treatment	CO_2 Reuse	Highlighted Sustainability Practices
NatStruct	Water scarcity; energy costs impact more	No solvents	Minimal waste	No	Pulp for packaging with negative

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					carbon footprint
Borregaard	Energy costs; water abundant	Water-based; Minor use of solvents, high reuse rates	Organic waste incinerated for steam; biogas production	No	LCA-certified products; Gold in EcoVadis status
Alginor	High water costs; energy less critical	No solvents	85% raw material discarded; exploring valorisation	No	Free-formaldehyde processing; circular use of seaweed
Novamont	Energy costs prioritized; water managed via LCAs	No solvents	Recovery of THF intermediate generated from wastewater; 71% waste recycled.	Research projects for CO_2 valorisation	Regenerative agriculture; ISO 14067 carbon footprint certification
Tezkim	Natural gas costs dominate	No solvents.	CO_2 liquefied and sold; no solid waste	CO_2 sold to beverage industry	Energy-efficient reprocessing; circular CO_2 utilization
Mevaldi	Energy (electricity) is critical	No solvents	Fermentation residues; catalyst recycling (10% cost)	CO_2 produced but not reused	Focus on fossil fuel replacement
Envirohemp	Energy costs (gas) is major cost	No solvents	Biochar waste reused for energy	CO_2 reused in pyrolysis	Biochar sequesters 3t CO_2 per ton produced
NATAC Biotech	Energy (electricity) is major cost	No solvents	No waste streams	Minimal	Focus on regional biomass and low-water processes
Tecnoalgae	Energy (electricity) dominates costs	No solvents	Algae biomass reused for biofertilizers/fuels	Algae absorb CO_2	High CO_2 capture efficiency (exceeds trees)
Alvinesa	Energy self-sufficiency (97%); water recycled	Hexane/water; high reuse rates	Grape residues for energy/animal feed	Minimal	energy is self-provided to maximize resource value
Venvirotech	Water recycling	Green solvents (90% reused)	Bacterial biomass for fertilizers; solvent recovery	Research on bacterial CO_2 capture	PHA bioplastics from waste

Key Findings

- **Energy vs. Water Challenges:**
  - Energy costs (especially electricity/natural gas) are the primary concern for 8/11 companies, while only NatStruct and Alginor highlighted water scarcity.
  - Borregaard and Novamont mitigate energy impacts via renewables (hydropower/solar).
- **Waste Valorisation:**

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- Most companies (e.g., Alvinesa, Envirhemp) recycle waste (e.g., grape residues, biochar) for energy or feed, reducing landfill dependence.
- Alginor and Novamont face high waste ratios (85% and 29%, respectively), but invest in circular solutions (e.g., THF recovery).

- **CO_2 Management:**
  - Only Tezkim actively monetize CO_2 (beverage industry); others emit or research reuse (Venvirotech, Novamont).
  - Tecnoalgae's algae-based CO_2 capture stands out for its efficiency.
- Innovation in Solvents:
  - Venvirotech leads in green solvent use (patented methanol/dimethylcarbonate), while Novamont rely on recovery of THF intermediate.
- **Certifications & Partnerships:**
  - Borregaard (EcoVadis Gold) and Novamont (B Corp) show real actions for a greener future

Conclusion

Biorefineries demonstrate a strong shift towards circularity, particularly with regard to waste valorisation and energy efficiency. However, challenges remain in terms of CO_2 reuse and finding suitable solvent alternatives. Regional disparities, such as water scarcity in southern Europe versus energy costs in Norway, influence priorities. Companies that integrate life cycle assessment (LCA) frameworks (e.g. Borregaard and Novamont) or novel technologies (e.g. Venvirotech's polyhydroxyalkanoate (PHA) and Tecnoalgae's reactors) are leading the transition to low-carbon biorefining. Future policies should incentivise the utilisation of CO_2 and the standardisation of waste-to-resource pathways to amplify these efforts.

4.5 Regional support/policies

The location and regulatory environment of biorefineries have a significant influence on their operational efficiency, sustainability, and economic viability. This analysis examines the regional support and policies affecting the eleven biorefineries studied, focusing on the reasons for their current locations and the impact of local regulations. The findings are summarised in below (Table 6) and discussed in the following sections.

Table 6. Summary of Regional Support and Local Policies in Biorefineries.

Company	Location Factors	Negative Local Regulations
NatStruct	Biomass availability (Banana leaves, pineapple leaves, lavender)	No negative regulations reported
Borregaard	Proximity to forests, water resources, and retrofitting of existing industrial sites	Norway's non-EU membership creates tax barriers in the EU
Alginor	Biomass availability (macroalgae).	No negative regulations reported
Novamont	Conversion of disused or decommissioned sites industrial sites, biomass availability, and local value chains	No negative regulations reported
Tezkim	Proximity to corn suppliers, local ownership	Lower biofuel usage mandates compared to the EU
Mevaldi	Ecosystem support for fermentation and hydrogenation processes	No negative regulations reported
Envirohemp	Biomass availability (agro-industrial waste).	Biochar not yet recognized in EU carbon footprint credit
NATAC Biotech	Biomass availability (medicinal plants), tax incentives	Some plant species require special documentation not needed elsewhere

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Tecnoalgae	Strategic location for talent acquisition, biomass availability	Microalgae sector lacks regulatory recognition as a CO_2 sink in Andalusia
Alvinesa	Historical ties to wine production regions, biomass availability	No negative regulations reported
Venvirotech	Proximity to Barcelona for talent, modular installation near feedstock suppliers	Variability in plastic waste management pricing in Spain compared to the EU

Key Findings

- **Location Factors:**
  - **Biomass Availability:** The most common reason for plant locations (e.g., NatStruct, Alginor, NATAC Biotech, Tezkim).
  - **Retrofitting Industrial Sites:** Novamont and Borregaard emphasized repurposing old industrial facilities to reduce environmental impact and costs.
  - **Local Value Chains:** Interaction with local suppliers and clients was critical for Novamont and Alvinesa.
  - **Tax and Incentives:** NATAC Biotech and Tezkim benefited from regional tax incentives or investment support.
- **Regulatory Challenges:**
  - Non-EU Barriers: Borregaard faces tax disadvantages due to Norway's non-EU status.
  - Carbon Credit Recognition: Envirhemp and Tecnoalgae highlighted gaps in EU policies for biochar and microalgae as carbon sinks.
  - Biofuel Mandates: Tezkim noted lower usage requirements in Turkey compared to the EU.
  - Waste Management: Venvirotech cited inconsistent waste management fluctuating in Spain.

Conclusion

The analysis reveals that biorefineries prioritize locations with easy access to feedstock and supportive regional policies, such as tax incentives or reuse of industrial sites. However, regulatory misalignment particularly regarding carbon credit recognition, waste management, and ethanol mandates poses challenges for some companies. To promoting growth in the bio-based sector, policymakers should address these gaps, ensuring harmonization across regions and clearer frameworks for emerging technologies such as biochar and microalgae.

5 Bibliography on the Next-Generation Circular Multiproduct Biorefinery

5.1 Introduction

This section presents a bibliographic study of the Next-Generation Circular Multiproduct Biorefinery (NG-CMB) concept, synthesising insights from recent academic research and industrial advancements. By reviewing key literature, this analysis explores innovations in feedstock utilisation, processing technologies, and value-added product development. The cited studies emphasise the transformative potential of NG-CMBs in promoting resource efficiency, circularity, and sustainability within the bioeconomy.

The next-generation circular multiproduct biorefinery (NG-CMBs)[4] sometimes introduced as Cascade Biorefinery Strategy[5] is an innovative and holistic approach to biomass valorisation, designed to maximize resource efficiency, minimize waste, and support a carbon-neutral bioeconomy. Unlike conventional

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biorefineries, which often follow linear processing models with limited product diversification, NG-CMBs integrate advanced bioconversion technologies, smart cascading systems, and circular economy principles to transform diverse feedstocks such as agricultural residues, algae, and organic waste and CO_2 into multiple high-value products (fuels, chemicals, materials, and nutrients) in a closed-loop system.

Key innovations include:

- **Flexible Feedstocks:** Processes diverse biomass (crop waste, algae, CO_2).
- **AI & Smart Systems:** Optimizes yields and energy use in real time.
- **Engineered Microbes:** CRISPR-tailored strains for high-efficiency biofuel/chemical production.
- **Zero-Waste Design:** Integrates cascading processes to repurpose all byproducts.
- **Green Catalysis:** Uses enzymes, electrocatalysis for low-energy reactions.
- **Modular Systems:** Scalable, decentralized units for local biomass processing.

These advances promise to enhance sustainability, reduce waste, and improve cost-effectiveness compared to traditional refineries.

5.2 Feedstocks for multi-product biorefineries.

Multi-product biorefineries represent an innovative and sustainable paradigm in biomass processing, moving beyond single-output systems to maximize resource efficiency and economic viability. Unlike conventional biorefineries that focus on producing a single product, such as bioethanol or biodiesel, this novel concept integrates multiple conversion pathways including biochemical, thermochemical, and mechanical processes to transform renewable feedstocks (agricultural residues, algae, or organic waste) into a diverse portfolio of high-value outputs. These outputs can include biofuels, bioplastics, pharmaceuticals, nutraceuticals, fertilizers, and even energy, all within a single facility.

The key novelty lies in the synergistic valorisation of biomass components (lignin, cellulose, hemicellulose, and other extracts), ensuring minimal waste and increased profitability. Advanced process integration, the cascading use of resources, and smart catalytic or biotechnological innovations further enhance sustainability. By mimicking nature's zero-waste principles and leveraging circular economy strategies, multi-product biorefineries provide a transformative solution that reduces reliance on fossil fuels, lower greenhouse gas emissions, and create resilient bio-based supply chains. This holistic approach establishes them as cornerstones of the emerging bioeconomy.

Multi-product biorefineries convert a variety of biomass feedstocks into value-added products and biofuels. Therefore, the choice of feedstock has a critical impact on efficiency, product range and sustainability. The four most recent key types are lignocellulose, algae, agricultural residues and municipal waste.

5.2.1 Lignocellulosic biomass

Lignocellulosic biomass, which includes wood, grasses, and crop residues, is Earth's most abundant renewable material. It consists of cellulose, hemicellulose, and lignin. Current research focuses on improving pretreatment and enzymatic hydrolysis.
Baruah et al[6] reviewed lignocellulosic pretreatment methods trends for lignocellulosic biomass, focusing on sustainable methods for value-added product conversion. They highlighted the potential of combined physical, chemical and biological approaches for improved efficiency and reduced environmental impact.

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5.2.2 Agricultural residues

Agricultural residues (straw, husks and stalks) are a major underused biomass source. Their quality affects biorefinery efficiency and range of product diversity. Zabed et al[7] reviewed agricultural and forest residues for bioethanol, and key technologies pretreatment like hydrolysis or fermentation process. Highlights challenges in cost-effective sugar conversion and proposes integrated biorefinery approaches for sustainable commercialization.

5.2.3 Municipal solid waste

Municipal solid waste (MSW) is a promising low-cost, abundant feedstock for multi-product biorefineries. However, its heterogeneous nature requires advanced sorting and conversion technologies, which have been the focus of recent research. Sharker et al[8] explore sustainable methods to convert municipal solid waste (MSW) into biofuels and added-value chemicals. The study compares biological (anaerobic digestion, composting and fermentation) and thermochemical (pyrolysis, gasification and hydrothermal carbonization) conversion routes, highlighting the resulting products (e.g. added-value chemicals, biogas, bio-oil, syngas) and their applications. Key challenges include feedstock variability, high costs, and technological barriers. The review emphasizes the potential of MSW's in a circular bioeconomy, aligning with SDGs for clean energy and sustainable cities.

5.2.4 Algal biomass

Algal biomass is a promising biorefinery feedstock thanks to its rapid growth, CO_2 capture and potential to produce a variety of products. Recent research has focused on optimising cultivation, enhancing lipid yield and improving extraction and conversion methods.

Chew et al[9] reviewed the potential of microalgae as a sustainable biorefinery feedstock for producing high-value compounds (chemicals, proteins, fatty acids) in addition to biofuels. It discusses key challenges, including cost-effective cultivation, harvesting, and extraction methods, and emphasises the need for integrated biorefinery approaches to improve economic viability. The authors also explore future trends in optimising microalgal strains and downstream processing for commercial scalability.

5.3 Processing technologies for multi-product biorefineries

Multi-product biorefineries convert biomass into biofuels and other value-added products. These technologies can be categorized broadly into biochemical, thermochemical, and hybrid processes. Recent advances have improved the efficiency and sustainability of biorefinery operations.

5.3.1 Biochemical conversion

Biochemical conversion uses enzymes and microorganisms to break down biomass into biofuels and chemicals. This process are particularly effective for carbohydrate-rich feedstocks and notable progress has been made is this area recently.

Enzymatic hydrolysis has emerged as a key technology in biochemical conversion. Recent work by Ogunyewo et al[10] investigates the cooperative effect of novel cellulose enzyme combinations on cellulose degradation. The combination of the enzymes significantly enhances saccharification efficiency, demonstrating their synergistic potential to improve the conversion of biomass in biofuel and biorefinery applications.

Fermentation technologies have also made remarkable progress. Tran et al[11], the study adresses the key bottleneck in lignocellulosic biorefineries (slow xylose fermentation during glucose-xylose co-utilization)

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by combining genetic modifications in an engineered *Cerevisiae Strain* (XUSEA) yest with temperature optimization. This dual approach eliminates sequential sugar consumption, enhancing simultaneous co-fermentation for scalable and cost-effective bioethanol production. The findings demonstrate a promising strategy to improve industrial bioprocess efficiency and sustainability.

5.3.2 Thermochemical conversion

Thermochemical conversion processes use heat and catalysts to convert biomass into fuels and chemicals. Recent advancements have greatly expanded their capabilities, enabling them to handle a wide range of feedstocks with improved efficiency.

5.3.2.1 Pyrolysis:

Pyrolysis technologies have seen significant advancements in recent years. Bi et al[12] investigate the catalytic fast pyrolysis (CFP) of Kraft lignin using synthetic hierarchical HZSM-5 and Hβ zeolites prepared through alkaline post-treatment methods that demonstrated superior performance in CFP of Kraft lignin by combining enhanced mass transfer with preserved acidity. This study emphasises the importance of optimising pore structure and acidity to maximise the yield of condensable volatiles and minimise oxygenates. This advances the potential of lignin as a renewable feedstock for biofuels and chemicals.

5.3.2.2 Hydrothermal liquefaction (HTL):

Hydrothermal liquefaction has emerged as a promising technology due to its ability to efficiently convert wet biomass without the need for energy-intensive drying steps. Recent work by Chen et al[13] demonstrated a continuous HTL system for the conversion of algal biomass, achieving a bio-crude yield of 55 wt% and an energy recovery rate of 75%. Furthermore, combining this process with nutrient recovery and wastewater treatment provides a feasible approach to sustainable biofuel production that offers additional environmental benefits.

5.3.3 Hybrid conversion processes

Hybrid conversion processes merge biochemical and thermochemical methods, leverage their respective strengths while mitigating their limitations. These integrated processes improve biorefinery efficiency and product diversity.

One notable example is the combination of gasification and syngas fermentation. Anggraini et al[14] investigate the production of bioethanol by syngas fermentation using acetogenic bacteria (Clostridium ljungdahlii) in a microporous hydrophobic polypropylene hollow fibre membrane (HFM) and compare its performance with a conventional stirred tank reactor (STR) without HFM. The research addresses the challenge of low mass transfer rates of CO and H_2, which are key substrates in syngas fermentation. The HFM-supported bioreactor offers a promising solution to overcome mass transfer limitations in syngas fermentation, leading to higher ethanol yields and productivity.

5.4 Value-added products from multi-product biorefineries

This section examines recent progress and innovations in the production of different value-added outputs from multi-product biorefineries, with an emphasis on chemicals, polymers, nutraceuticals, and specialty chemicals.

5.4.1 Biochemicals

The synthesis of biochemicals in multi-product biorefineries has attracted considerable interest because of its potential to replace petroleum-based chemicals and support a greener chemical sector. Recent progress in this field has focused on enhancing production efficiency, diversifying the types of

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biochemicals generated, and developing innovative conversion methods. Table 7 summarizes recent advancements in biochemical production in multi-product biorefineries, focusing on the most promising biochemicals.

Table 7. Recent advancements in biochemical production in multi-product biorefineries.

Biochemical	Feedstock	Production method	Implications
Succinic acid[15]	glucose and glycerol for synergistic effects	fermentation sugar by *Yarrowia lipolytica*	High-efficiency production enhances economic viability and scalability of multi-product biorefineries
Lactic acid[16]	Lignocellulosic biomass	Genetically Modified Microbial	Lowers production costs through sustainable raw materials and creates value from by-products
1,3-propanediol[17]	Crude glycerol and Fish meal	Clostridium Tyrobutyricum	Utilization of crude glycerol and inexpensive nitrogen sources like fish meal
Itaconic acid[18]	Wheat bran	*Aspergillus awamori for enzyme*	Valorises wheat bran, an abundant by-product and Optimal enzyme production
Butyric acid[19]	Kitchen wast and sewage sludge	Acidogenic Fermentation	Suggesting scalable methods for industrial applications
Fumaric acid[20]	Glucose, starch and agricultural waste	Engineering in *Aspergillus* species	Cost-Effective & Sustainable Production and Higher Yields & Productivity
Levulinic acid[21]	Tobacco stalk	Lewis acid catalyst $Al_2(SO_4)_3$ and NaCl	Crucial intermediate for Chemicals and fuels, strengthening the value chain of biorefinery products

5.4.2 Biopolymers

Biopolymers are an important group of value-added products that can be produced in multi-product biorefineries. These biodegradable and renewable substitutes for traditional plastics help to address the growing problems of plastic pollution and resource depletion. Recent studies have focused on creating innovative biopolymers, enhancing their properties, and refining production processes.

Polyhydroxyalkanoates (PHAs) are gaining attention as sustainable biopolymers due their biodegradability and versatile properties. Kumar et al[22] explore the production of polyhydroxyalkanoate (PHA) co-polymers using Bacillus spp. fed with volatile fatty acids (VFAs) derived from hydrolysed biowastes (pea-shells, potato peels, apple pomace, and onion peels). This method offers a sustainable, cost-effective route for PHA co-polymer production, leveraging biowaste valorisation and reducing reliance on petrochemical feedstocks.

Polyethylene furanoate (PEF) is another promising biobased alternative to petroleum-based polyethylene terephthalate (PET). However, conventional PEF production via polycondensation faces challenges, including long reaction times, high energy requirements, and thermal degradation leading to discoloured products. Rosenboom et al[23] This study presents an improved synthesis method using ring-opening polymerisation (ROP) of cyclic PEF oligomers (cyOEF), which enables rapid, high-yield production of bottle-grade PEF. ROP provides a scalable, energy-efficient route to high-quality PEF, overcoming key limitations of traditional polycondensation. This method not only enhances PEF production but also has potential applications for other diffusion-limited polymer systems.

Advances in biopolymer production demonstrate the potential of multi-product biorefineries for a sustainable plastics industry. However, scale-up, cost reduction and consistent quality across feedstocks and batches remain challenges.

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5.4.3 Nutraceuticals

The production of nutraceuticals in multi-product biorefineries offers added value by capitalising on the growing consumer demand for natural health-promoting compounds. Recent studies highlight novel nutraceutical compounds from biorefinery feedstocks and improved extraction and purification methods.

The production of **omega-3 fatty acids**, especially EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid), has achieved notable progress in multi-product biorefineries. Asimakopoulou et al[24] explored a sustainable method to produce omega-3 fatty acids, especially DHA (docosahexaenoic acid), from wheat straw feedstock. The process involves fractionating of the wheat straw using an acid-free oxidative organosolv fractionation (OxiOrganosolv), which separates the plant material into useful components such as sugars and lignin. These sugars are then used to grow a type of marine algae (Crypthecodinium colnii) known for its ability to produce omega-3 fatty acids. This process offers a promising way to produce omega-3s from renewable plant waste, reducing reliance on fish oil and supporting eco-friendly biorefineries.

The extraction of **polyphenols** from lignocellulosic biomass is another promising area of research. Caballero Galván et al[25] investigated the extraction of polyphenolic compounds from olive waste residues (pruning biomass, olive leaves, and exhaust pomace) using supercritical fluid extraction (SFE) with CO_2 and 60% ethanol as a cosolvent. The research compared SFE at different pressures with conventional solvent extraction (SE) to evaluate the efficiency of polyphenol recovery and antioxidant activity, offering a sustainable and efficient alternative to conventional methods. This approach is in line with the new biorefinery concepts, enabling the valorisation of olive-derived biomass into high-value products for pharmaceutical and food industries.

A significant advancement in this area is the extraction of **astaxanthin**, a valuable natural pigment and potent antioxidant used in the food, cosmetic, and pharmaceutical industries. Molina et al[26] developed an efficient method to extract astaxanthin from Haematococcus pluvialis microalgae. The study focused on the use of safe, food-grade solvents and simple mechanical processing to break down the tough cell walls. The research shows that natural astaxanthin can be efficiently extracted using safe, simple methods, making it more practical for commercial use. These findings could help make natural astaxanthin more competitive with synthetic versions. The method is particularly promising because it uses safe solvents and doesn't require extreme conditions, making it easier and cheaper to scale up for industrial production.

These innovations demonstrate the ability of multi-product biorefineries to produce high-value nutraceuticals while efficiently utilising diverse biomass feedstocks. However, barriers remain in scaling up production, maintaining product purity.

5.4.4 Specialty chemicals

The production of specialty chemicals in multi-product biorefineries is attracting interest because of their elevated value and wide range of applications across different industries. Recent studies have focused on creating innovative production methods, improving product synthesis routes and extraction methods, and expanding the range of speciality chemicals that can be produced from sustainable feedstocks.

A key advance in this area is the production of **5-hydroxymethylfurfural** (HMF), a highly versatile platform chemical with a wide range of applications in fine chemicals pharmaceuticals, and polymers, as reported by Liu. et al[27] . The authors successfully demonstrated the efficiency and sustainability of HMF production from cellulose biomass using a biphasic method with a deep eutectic solvent. By using a synergistic catalytic system of Sn-β and Molten Salt Hydrates (MSHs). The optimised process achieved a remarkable 5-HMF yield of 66.88%, highlighting the potential of this approach for industrial applications. The

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reusability of the catalyst and the use of renewable cellulose as a feedstock further underline the environmental and economic benefits of this technique.

One more critical area of research is the production of bio-based solvents as substitutes for petroleum-derived solvents. Hao et al[28] developed a simpler way to produce **γ-valerolactone** (GVL), a valuable biofuel and green solvent with applications in multiple industrial, directly from agricultural waste. Using a catalysed cascade reaction system, they achieved 78% yield from furfural and successfully converted feedstocks like corncobs with good yields. This method is more efficient and eco-friendlier than others and also produced valuable co-products such as furfural and alkyl levulinates, demonstrating the ability to produce multiple chemicals simultaneously in biorefineries.

Conclusion:

These developments demonstrate the potential of multi-product biorefineries to produce a variety of value-added specialty chemicals from renewable sources, thereby improving their economic and environmental sustainability. However, scaling-up production, optimising processes for complex feedstocks, and competing with low-cost petroleum-based routes remain key challenges. Although progress highlights their potential, further research and development (R&D) is needed to address challenges in process integration, scaling up and economic viability, in order to reinforce the bioeconomy.

6 A summary of all the biomass processing industries analysed in this study

The biorefinery sector encompasses a wide range of industries that are dedicated to converting renewable biomass into value-added products, including from biofuels and biochemicals to biopolymers and nutraceuticals. The benchmark study of European biorefineries covers about 36 distinct biomass processing industries based on feedstocks, technologies, and end products, as detailed in the benchmark study of European biorefineries. These industries demonstrate the versatility of biomass valorisation, by utilising agricultural residues, forestry waste, algae, and organic by-products, thereby promoting sustainability and circularity in the bioeconomy. The categorised list below reflects the multifaceted nature of modern biorefining.

Classification of Biomass Processing Industries:

1. Agricultural Waste Processing: Examples: Conversion of banana leaves, pineapple leaves, and corn bran into fibres, bioethanol, or chemicals (NatStruct, Tezkim).

2. Wood Processing: Sulfite pulping of spruce logs for lignin and vanillin (Borregaard).

3. Algae Processing: Macroalgae (*Laminaria hyerborea*) into alginate and fucoidan (Alginor); microalgae for wastewater treatment (Tecnoalgae).

4. Second-Generation Feedstock Processing: Glucose and sucrose from lignocellulosic biomass for bioplastics (Mevaldi).

5. Olive Waste Valorization: Olive pomace and pits into polyphenols or activated carbon (NATAC Biotech, Envirohemp).

6. Vineyard Waste Processing: Grape pomace into tartaric acid and wine concentrate (Alvinesa).

7. Organic Waste Fermentation: Brewery yeast and food waste into PHA bioplastics (Venvirotech).

8. Biochar Production: Pyrolysis of olive pits and vineyard residues (Envirohemp).

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9. Activated Carbon Production: Thermochemical conversion of forest waste (Envirohemp).

10. Bioplastics Manufacturing: Mater-Bi from agricultural waste (Novamont); PHA from organic waste (Venvirotech).

11. Bioethanol Production: Fermentation of corn bran (Tezkim); wood-based ethanol (Borregaard).

12. Citric Acid Production: By-product of corn processing (Tezkim).

13. Alginate Extraction: Macroalgae processing for healthcare products (Alginor).

14. Fucoidan Production: Derived from seaweed (Alginor).

15. Cellulose Processing: Wood and algae into cellulose fibers (Borregaard, Alginor).

16. Biopolymer Intermediates Production: Polyurethane/polyester building blocks from glucose (Mevaldi).

17. Nutraceutical Extracts Production: Botanical extracts from olive waste (NATAC Biotech).

18. Polyphenols Extraction: Liquid extraction from grape pomace (Alvinesa).

19. Tartaric Acid Production: Valorization of wine residues (Alvinesa).

20. Grape Seed Oil Production: Mechanical extraction from wine industry by-products (Alvinesa).

21. PHA Bioplastics Production: Bacterial fermentation of organic waste (Venvirotech).

22. Microalgae Solutions for Agriculture: Algae-based biostimulants (Tecnoalgae).

23. Wastewater Treatment Using Microalgae: Modular bioreactors for nutrient recovery (Tecnoalgae).

24. Natural Fiber Production: Banana leaf pulp for textiles (NatStruct).

25. Lignin Valorization: Sulfite pulping by-products into chemicals (Borregaard).

26. Vanillin Production: Biobased vanillin from lignin (Borregaard).

27. Syngas Fermentation: Hybrid gasification-fermentation for ethanol (Anggraini et al.).

28. Hydrothermal Liquefaction (HTL): Algal biomass into bio-crude (Chen et al.).

29. Catalytic Fast Pyrolysis (CFP): Kraft lignin into biofuels (Bi et al.).

30. Enzymatic Hydrolysis: Cellulose degradation for sugars (Ogunyewo et al.).

31. Supercritical Fluid Extraction (SFE): Polyphenol extraction from olive waste (Caballero Galván et al.).

32. Modular Bioreactor Systems: Decentralized algae cultivation (Tecnoalgae).

33. Zero-Waste Biorefinery Design: Closed-loop systems for solvent recovery (Novamont, Venvirotech).

34. CO_2 Valorisation: CO_2 sales to beverage industries (Tezkim).

35. Municipal Solid Waste Processing: MSW transformation into biofuels and chemicals (Sharker et al.).

36. Industrial By-Products Valorisation: Spent sulphite liquor utilization (Borregaard).

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7 General Conclusion:

The deliverable begins with an outline the fundamental principles of biorefineries, which convert renewable biomass into fuels, chemicals, and materials. This process mirrors the multi-product approach of petroleum refineries but with a focus on sustainability. Biorefineries are classified based on feedstock (e.g. lignocellulose, algae), their conversion technologies (thermochemical, biochemical, mechanical, chemical), and their final products (chemicals, biopolymers, nutraceuticals). Three generations of biorefineries are distinguished: The first generation focuses on producing biofuels with limited by-products. The second generation uses diverse feedstocks such as agricultural waste to produce a broader range of products. The third generation explores the use of advanced feedstocks such as algae and CO_2 to produce high-value outputs such as pharmaceuticals and speciality chemicals.

A key component of the deliverables is the benchmark study, which analyses biorefinery operations across Europe. The study highlights that agricultural and forestry biomass are the most commonly used feedstocks, while the potential of urban waste and algae remains largely unexplored. Challenges such as seasonality, storage logistics, and regulatory barriers are identified. In terms of products, biorefineries typically produce both intermediate chemicals (e.g., ethanol, lactic acid) and final products (e.g., bioplastics), with revenues often concentrated in one or two key outputs. Thermochemical and biochemical processes dominate current technologies, though innovations such as enzymatic hydrolysis and hybrid systems (e.g., combining gasification with fermentation) are emerging. Sustainability practices vary, with energy costs and CO_2 reuse being critical concerns. Companies such as Novamont and Borregaard are recognized as leaders in circular economy practices, including zero-waste design and life cycle assessment (LCA).

The deliverable also examines regional support mechanisms and concludes that biorefinery locations are often chosen based on biomass availability and policy incentives. However, regulatory inconsistencies (such as gaps in the recognition of carbon credits for biochar and microalgae) pose challenges to growth.

A forward-looking section discusses next-generation biorefineries, which prioritise multi-product output (e.g., simultaneous production of biofuels and biochemicals) and improved circularity. Promising feedstocks include lignocellulosic biomass, agricultural residues, municipal solid waste, and algal biomass. Advanced technologies such as AI-driven process optimisation, CRISPR-engineered microbes, and modular biorefinery systems are identified as key enablers for future scalability and efficiency.

The deliverable includes findings from internal questionnaires and interviews with MARGs (Multi-Actor Reference Groups). These show that agricultural biomass and waste are seen as the most promising feedstocks in Southern Europe, while algae and municipal waste remain underexplored. Technological barriers, such as scaling up innovative processes and securing funding, are cited as major hurdles. Respondents also stress the need for supportive policies, regional cooperation, and investment in infrastructure to unlock the bioeconomy's potential.

The BioINSouth deliverable also emphasises that the economic viability of biorefineries in Southern Europe is highly dependent on the maturity of the technologies used. Key findings may include:

1. Technology Maturity Drives Costs

- Mature technologies, such as first generation bioethanol production, are economically viable but face limitations due to feedstock competition and lower environmental benefits.

- Advanced biorefineries (third generation, using algae or waste) face higher initial costs due to complex processes such as enzymatic hydrolysis or hybrid thermochemical-biochemical systems. However, these technologies offer long-term sustainability and product diversification.

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2. Scalability Challenges

- Companies such as Venvirotech (PHA production) and Mevaldi (bioplastic intermediates) have identified scalability as a barrier that requires further research and development to reduce energy consumption and variability in feedstock.

- Companies that use modular systems (Tecnoalgae's bioreactors) show promise in terms of decentralised, cost-effective operations, but they need policy support to grow.

3. Circular Economy Integration

- Zero-waste designs (Novamont's bioplastics) and CO_2 valorisation (such as Tezkim's CO_2 sales) improve the economics of biorefineries by creating additional revenue streams.

- Regulatory gaps, such as the lack of carbon credits for biochar, hinder financial sustainability despite technological readiness.

4. Regional Disparities

- Southern Europe's biomass availability (olive pomace, agricultural residues) provides a strong foundation for biorefinery feasibility. However, the lack of harmonized policies and underdeveloped infrastructure in some regions creates uncertainties that can slow investment returns.

- Public-private partnerships and EU funding mechanisms, such as the Horizon Europe programme, play a critical role in mitigating investment risks associated with emerging biorefinery technologies.

In conclusion, the deliverable underlines the importance of biorefineries in the transition to a sustainable bioeconomy. It calls for harmonised policies, technological innovation, and cross-sector collaboration to address challenges such as feedstock variability, high operating costs, and regulatory fragmentation. By leveraging regional strengths and adopting integrated biorefinery models, Southern Europe can increase its competitiveness in the global bio-based market while advancing environmental goals.

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BioINSouth Info Box

The BioINSouth project aims to support decision-makers to incorporate considerations of ecological limits into their regional bioeconomy strategies and roadmaps relevant to circular bio-based activities. We aim to develop guidelines and digital tools, considering the safe and sustainable by design (SSbD) assessment framework, to support the adoption of innovative methodologies to assess environmental impacts in multiple industrial bio-based systems, increasing regional competitiveness and innovation capacity, and contributing to the EU fair & green transition.

Find out more:

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