Biological Resources Certifications Schemes

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Type

X	**R**	Document report
☐	**DEM**	Demonstrator, pilot, prototype
☐	**DEC**	Websites, patent fillings, videos, etc.
☐	**OTHER**	

Dissemination Level

X	**PU**	Public, fully open, e.g., web
☐	**SEN**	Sensitive, limited under the conditions of the Grant Agreement
☐	**CI**	Classified, information as referred to in Commission Decision 1001/844/EC

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Table of content

List of figures

List of tables

Publishable executive summary

BioReCer aims to ensure the environmental performance and traceability of biological feedstocks used by the bio-based industries. This will be achieved through guidelines that strengthen current certification schemes by integrating new sustainability and traceability criteria aligned with the EU Taxonomy and EU corporate due diligence regulations. By doing so, BioReCer enhances the added value, usability and social acceptance of bioproducts. The project is structured around three technological pillars:

1. **Development of a multidimensional assessment framework** and a digital BioReCer ICT-tool (BIT) for aggregated and collaborative analysis of biological feedstocks and their supply chains.

2. **Creation of the BioReCer Innovation Ecosystem Living-Lab (BRIE-LL)** using a multi-agent approach and its testing in four bio-based supply chain case studies.

3. **Integration of all generated knowledge** to complement existing certification schemes with new sustainability and traceability criteria applicable at the EU and global scale.

Within this structure, Deliverable D6.2 focuses on the demonstration and validation of BioReCer tools and methodologies. This includes the implementation of a common framework to coordinate the demonstration activities and the involvement of all relevant stakeholders, producers, processors, end-users, consumers, investors, Non-Governmental Organizations (NGOs) and governmental bodies, to ensure that the validation reflects real industrial and regulatory needs.

In D6.2, the BioReCer assessment framework and its circularity indicators, were tested and validated across four representative case studies. Also, the BioReCer ICT tool (BIT) was thoroughly tested and validated across four representative case studies, each covering different feedstocks, processing chains, and end-product types. Furthermore, the environmental trade-offs of the proposed circular economy options were evaluated through Life Cycle Assessment (LCA) to quantify their potential benefits and burdens compared with current baseline systems.

The four demonstration case studies included:

- **Case study 1 – Fishery/sewage sludge (Spain)**: Led by ANFACO, focusing on the Galician marine and wastewater value chains, including fishery/algae by-products and urban/industrial sewage sludge.

- **Case study 2 – Urban biowaste (Italy)**: Led by UNIVPM and validated in the Lombardy region, focusing on sewage sludge (including the one generated by the co-treatment of municipal wastewater and non-hazardous organic liquid waste), OFMSW and agro-industrial residues.

- **Case study 3 – Agro sector (Greece)**: Led by CERTH, focusing on agricultural residues such as pruning waste, straw and other crop-derived by-products generated in the Region of Central Macedonia.

- **Case study 4 – Forestry sector (Sweden)**: Led by RISE, centred on forestry residues such as sawdust, bark and fibre sludge.

Across these four cases, D6.2 demonstrates the practical applicability of the BioReCer methodology, the robustness of its indicators, the functionality of the "BIT Tool", and the capacity of the framework to evaluate environmental performance, circularity potential, and sustainability trade-offs in diverse bio-based value chains.

1 Introduction

1.1 Summary of the WP

WP6 demonstrates the adequacy of the assessment methodologies (through BIT), and the adapted certification scheme developed in previous WPs through a cluster reproducibility assessment integrated in the BioReCer tool. To this purpose, four different case studies in an industrial representative environment in four EU countries were established based on regional data. CETAQUA, ANFACO, CERTH, RISE, UNIVPM lead the case studies in collaboration with SPRING and CAP. The case studies have been selected considering their geographical distribution, type and source of feedstock and the bio-based value chain. This approach was extended to analyse the suitability of the model for the assessment of other relevant biological feedstock flows in Europe. The main outcome of WP6 is the validation of the developed methodology in an agile way and the demonstration of its suitability to be used as a framework for certifying the sustainability, traceability, and origin of a wide range of biomasses.

In the D6.1, preliminary data for the demonstration of the developed methodologies of BioReCer on the four case studies and the study of replicability/transferability were collected. Furthermore, the valuable feedback from the case studies from the bio-based value chains, collected from stakeholder, was evaluated in order to feed the tool and to ensure the quality of the certification schemes. In this deliverable a theoretical framework of the origin, destination, characterisation and potential interest of the identified biomasses has been defined. In addition, the value chains were developed through the production processes of the companies involved as stakeholders. Subsequently, qualitative, and quantitative data were collected and used by other work packages within the project.

1.2 Objectives of the deliverable

The main objective of this deliverable is to validate the BioReCer methodologies and tools through their application in four representative case studies. These case studies encompass different biomass types and industrial contexts across Europe, enabling a comprehensive assessment of the framework’s robustness, adaptability, and replicability. The validation has been conducted in Galicia (Spain), Lombardia (Italy), Central Macedonia (Greece), and Västernorrland (Sweden). The Galician case study (CS1) focuses on the valorisation of fishery and canning by-products together with sewage sludge from wastewater treatment. In Lombardia (CS2), the study addresses urban and industrial biowaste, including sewage sludge, agro-food residues, and the organic fraction of municipal solid waste (OFMSW). The Greek case study (CS3) examines agricultural residues such as straw, tree prunings, and fruit-processing by-products for the production of biofertilisers and particle boards. Finally, the Swedish case study (CS4) concentrates on forestry residues, including sawdust, bark, and fibre sludge, which are used to produce bio-oil and other bio-based chemicals. Together, these four case studies represent key sectors of the European bioeconomy, ensuring that the BioReCer framework and the BIT are tested across diverse biological resources and regional contexts.

1.3 Structure of the report

This deliverable is organised to present the validation of the BioReCer framework and the BIT through the results obtained in the four case studies, complemented by an environmental performance analysis.

The first section focuses on the validation of the BioReCer framework using the data collected from the case studies. For each case, the sustainability and circularity of the corresponding value chains were assessed by calculating the defined circularity indicators and evaluating the level of compliance with the framework's requirements.

The second section summarises the environmental outcomes of the case studies through Life Cycle Assessment (LCA). The LCA provides a complementary quantitative evaluation of the environmental performance of each BioReCer scenario compared to conventional reference systems.

The third section presents the validation of the BIT, which operationalises the framework in a digital environment. It describes how the case study data were introduced into the tool, how circularity indicators were automatically calculated, and how the results were used to verify the consistency and functionality of the system.

Finally, the report concludes with an integrated analysis of the results and key lessons learned from the demonstration activities, outlining the contribution of the BioReCer framework and BIT to future certification schemes and the wider development of the European bioeconomy.

2 Validation of the BioReCer framework

As presented in D2.5 (section 2), the BioReCer project has developed a theoretical framework to evaluate the sustainability and circularity of biological feedstocks. This framework integrates a comprehensive set of principles, criteria, and requirements built around the three key pillars, environmental, economic, and social, while addressing both sustainability and circularity dimensions.

The central objective of this section is to present how the framework has been operationalised and validated through its application to the BioReCer case studies. Given the diversity of organisations and value chains involved, the project adopted a collaborative approach, maintaining a continuous exchange of information and feedback with the case study leaders and external stakeholders. This participatory process ensured that the framework remains robust, adaptable, and relevant to different operational contexts.

As a result, the final BioReCer framework was consolidated, comprising 52 requirements: 29 classified as *basic* (mandatory for compliance) and 23 as *advanced* (intended to promote continuous improvement and progressive alignment with best practices).

Additionally, this section presents the evaluation of the 52 framework requirements for selected actors within the value chains of the four case studies, together with the calculation of quantitative circularity indicators. For this purpose, the methodology described in Deliverable 2.5 (Section 4) was followed, which is schematically illustrated in Figure 1. Together, these analyses demonstrate the practical applicability and transferability of the BioReCer framework across diverse bio-based systems.

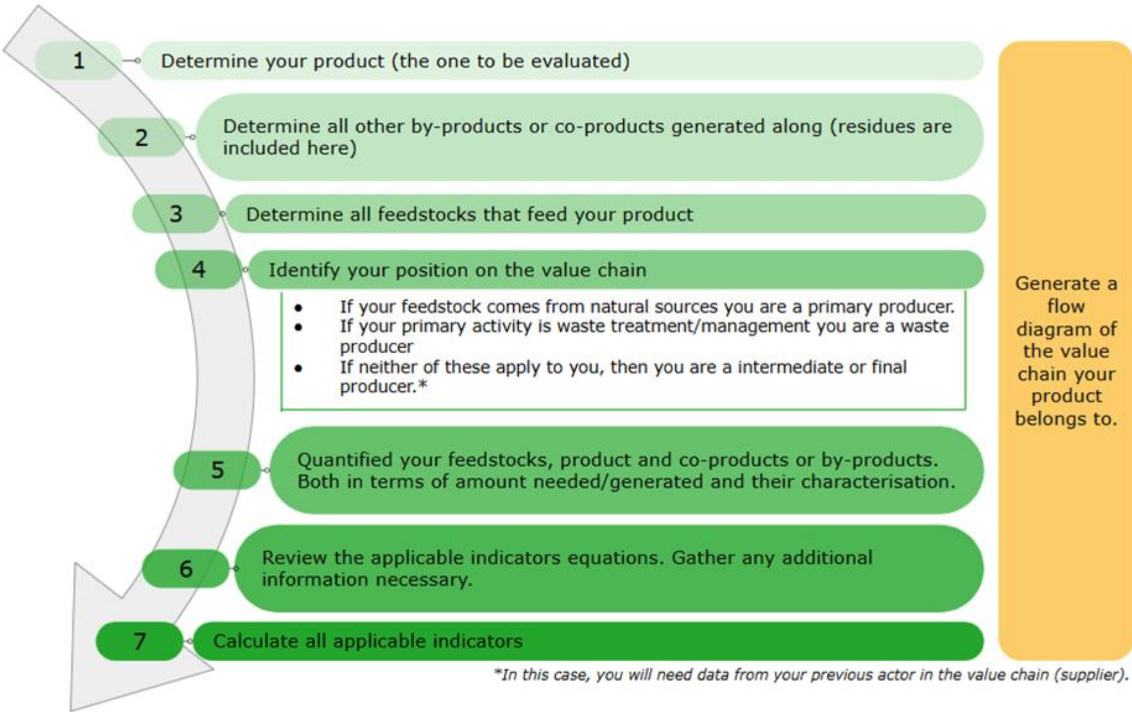


Figure 1. Steps to calculate circularity indicators (D2.5)

2.1 Results of the case studies

The validation of the BioReCer framework was carried out across four representative case studies, each covering different bio-based value chains and geographical contexts within Europe. These case studies encompass a wide range of feedstocks, technologies, and end-products, providing a comprehensive basis for testing the applicability and robustness of the BIT and the BioReCer framework. A more detailed qualitative and quantitative characterisation of each value chain is provided in Deliverables D2.4 and D6.1.

2.1.1 Case study 1: Galicia, Spain

The Galicia case study focuses on byproducts and polysaccharides generated from fishery and algae and sewage sludge generated from urban and industrial wastewater treatment.

2.1.1.1 Fishery

The fishery-based value chain of CS1 focuses on the extraction and valorisation of byproducts obtained from fishery supplied within the Galician fishery sector. In this value chain, fishery byproducts are collected, processed, and refined to obtain high-value fish oil and collagen that can be further used as functional ingredients in several industrial applications, including food, biotechnology, and bio-based materials.

Because the BioReCer methodology requires company-level operational data to ensure precision, comparability, and replicability in the calculation of circularity indicators, the absence of primary industrial data introduces substantial uncertainty into the results. In the fish oil and collagen value chains, the limited participation of industrial actors further constrained data collection, preventing access to detailed input–output information and hindering the generation of robust, process-specific datasets. Therefore, although the indicators were conceptually explored using the best available secondary information, their reliability is significantly lower compared with the polysaccharides case study, where real operational data were provided by participating companies. For a real implementation scenario, the indicators for fish oil and collagen would need to be recalculated using complete and validated industrial data directly supplied by the companies operating these processes.

Concerning the production indicators, no circular production indicators have been calculated for the fish oil and collagen case studies because both value chains were modelled exclusively from literature data and secondary databases. As a result, no process-specific operational inputs (energy consumption, water use, or chemical inputs) are available from real industrial facilities. Therefore, as in other conceptual case studies within the project, the lack of detailed primary data prevents the calculation of the production-stage circularity indicators.

Below, there is a detailed explanation of both value chains.

- **Fish oil**

The fish oil value chain begins with the utilisation of fish by-products, which serve as the primary feedstock for oil extraction. As detailed in the production flow (Figure 2), the process is organised into several sequential phases in which different types of fish oils are obtained, each with increasing degrees of refinement. Throughout these stages, the system incorporates additional raw materials, processing chemicals, and water inputs, while generating losses and specific waste streams at each processing step. Energy consumption is also significant and varies across the different phases of extraction, separation, and purification. This multi-stage configuration reflects a complex industrial process where material and energy flows evolve as the oil is progressively refined. Further details on the fish oil chain can be consulted in Deliverable D6.1.

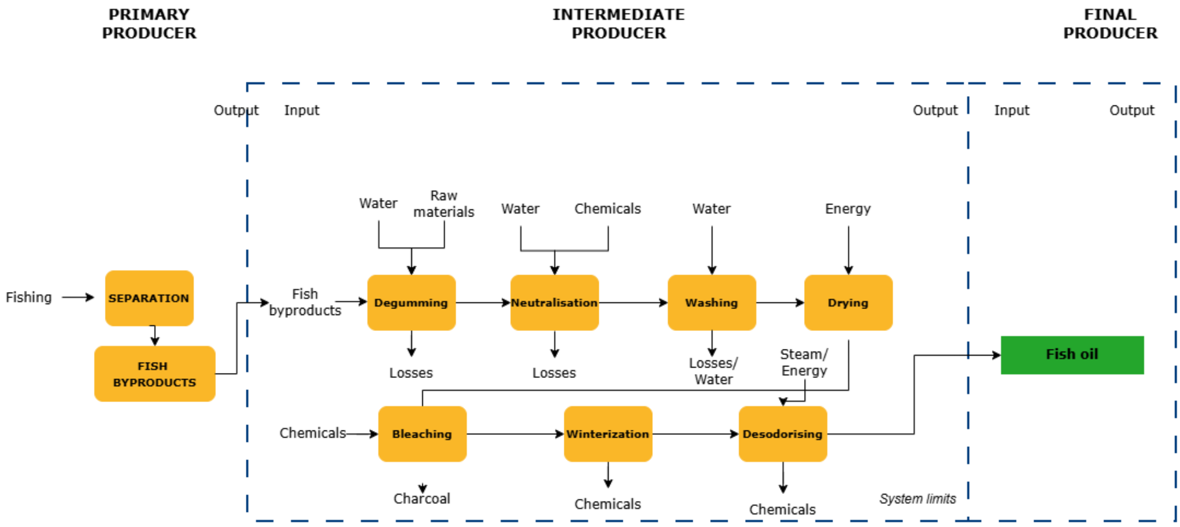


Figure 2. Value chain of fish oil

Circular indicators

This section provides a detailed explanation of the reasons why it was not possible to calculate the circularity indicators for the fish oil value chain within the BIORECER framework. Although the process was conceptually defined and modelled using literature data and secondary databases, the lack of direct participation from industrial partners in this sector and the absence of primary information on operational parameters, yields, and residue management introduced a high degree of uncertainty. As a result, the quantitative assessment of most circularity indicators could not be performed with the required level of precision or representativeness. A detailed description of the indicator calculation methodology and its corresponding equations can be found in Deliverable D2.5, which provides the full framework applied across all BIORECER case studies.

The fish oil production chain begins with the generation of fish by-products, which serve as feedstock for oil extraction and refining. In this context, the definition of indicators such as the *Verified Virgin Renewable Product (VVREN(P))* or the *Circularity Characterisation Factor of Residue (CCF(R))* requires accurate data on the origin, certification status, and proportion of renewable biomass used data that were not available from real producers.

Similarly, indicators related to biomass utilisation, such as the *Modified Biomass Utilisation Factor (MBUF*$_0$*)* and the *Value-Based Biomass Utilisation Factor (VMBUF*$_0$*)*, could not be quantified. These indicators depend on detailed mass balances of raw material, residues, and outputs, as well as the associated values of co-products and by-products. The absence of such data, combined with the heterogeneity of the available literature (which varies depending on species, oil extraction methods, and regional practices), prevented reliable and comparable calculations.

For the intermediate producer stage corresponding to the oil extraction and refining processes data gaps were even more evident. Indicators such as the *Reused Content of Product (REUC(P))*, *Virgin Renewable Content (VRENC(P))*, *Circular Content of Product (CC(P))*, and the *Circularity Characterisation Factor of Bio-Based By-Products (CCF(BBB)n)* could not be determined. These require information on internal recycling streams, the composition of raw materials and chemicals, and the proportion of residues or effluents valorised in subsequent processes. However, since no operational datasets were obtained from fish oil refineries, these values could not be validated.

Indicators assessing production efficiency and biomass valorisation (*EFn(t)*, *VMBUCn*, and *VEFn(t)*) also remained unquantifiable due to the lack of company level input–output. Moreover, the absence of traceable connections between the fish oil producers and subsequent users of the product prevented the estimation of transfer-related indicators such as *BO(X)n+1* and *VBO(X)n+1*, which depend on knowledge of the product's destination and economic contribution within the following stages of the value chain.

In summary, despite attempts to conceptually model the fish oil chain, the absence of primary industrial data, linked to limited company participation, made it impossible to generate reliable circularity indicators. All calculations would have relied solely on bibliographic approximations, which exhibit high variability and low replicability, compromising the methodological robustness required by the BIORECER framework.

- **Collagen**

The collagen value chain begins from fish-derived byproducts, which undergo a structured industrial process to yield partially hydrolysed peptides. As represented in the corresponding flow diagram (Figure 3), the production pathway involves the removal of non-collagenous substances from the initial raw material, followed by controlled hydrolysis and subsequent separation steps. These operations progressively purify the material while reducing its molecular size to obtain bioproducts with the required peptide length. As in the fish oil chain, inputs of chemicals, water, and energy are required at different stages, and various intermediate residues and losses occur throughout processing. Additional information and detailed process diagrams for the collagen chain are provided in Deliverable D6.1.

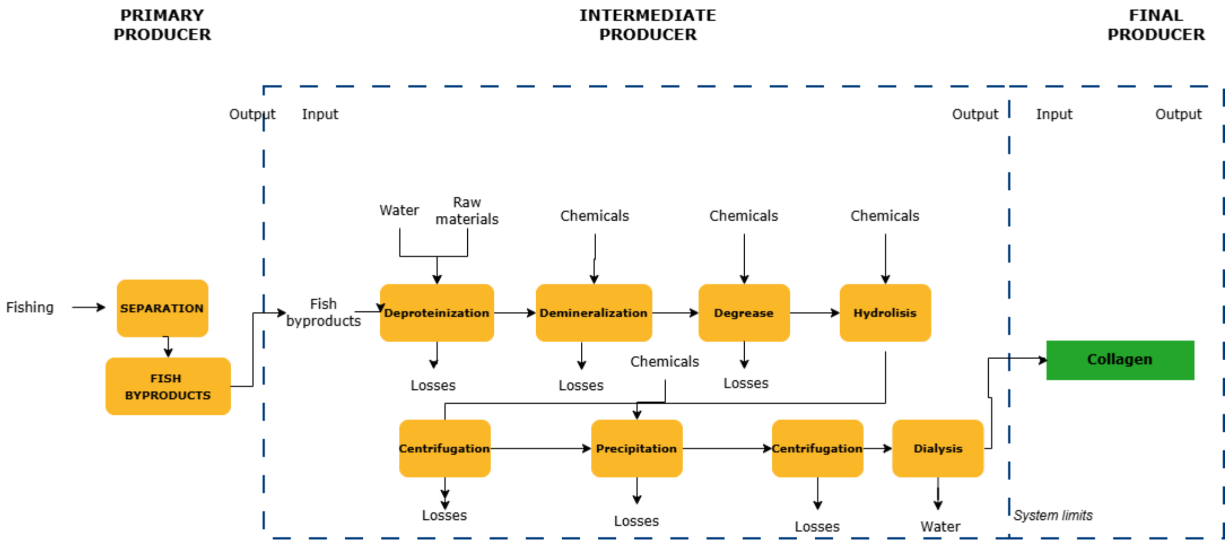


Figure 3. Value chain of collagen

Circular indicators

Similarly to the fish oil value chain, the collagen value chain was also analysed to identify the reasons why circularity indicators could not be calculated under the BIORECER methodology. Despite following the same conceptual and methodological approach, the absence of real industrial data, exacerbated by limited engagement from collagen producing companies, prevented the computation of reliable and representative results. The following section outlines, in detail, the specific data limitations and methodological constraints encountered for each indicator within this value chain. As in the previous case, the full description of indicator definitions and calculation methods is available in Deliverable D2.5.

As with the fish oil chain, the calculation of circularity indicators for this value chain was also not feasible due to insufficient real industrial data. The collagen process, which involves the transformation of fish by-products such as skins, scales, and bones into hydrolysed peptides, requires detailed input–output data on mass flows, yields, and resource consumption that were not available from industrial sources. While the conceptual process could be described from literature, the diversity of extraction methods (acid, alkaline, and enzymatic hydrolysis) and the variability in species and processing technologies make it impossible to assign representative values.

Indicators such as *Verified Virgin Renewable Product (VVREN(P))* and *Circularity Characterisation Factor of Residue (CCF(R))* require traceable and certified information on the origin of the raw materials and the percentage of residues valorised, which was not available from companies. Similarly, *Modified Biomass Utilisation Factor (MBUF$_0$)* and *Value-Based Biomass Utilisation Factor (VMBUF$_0$)* depend on accurate mass balances of the generated products, but no data were provided on the proportion of residues converted into collagen.

In the intermediate stage, representing the industrial extraction and purification of collagen, indicators that rely on process-level data could not be calculated either. These include *Reused Content of Product (REUC(P))*, *Virgin Renewable Content (VRENC(P))*, *Circular Content of Product (CC(P))*, and *Circularity Characterisation Factor of Bio-Based By-Products (CCF(BBB)n)*. Their calculation requires knowledge of recycled inputs, bio-based additives, and the valorisation of liquid or solid side-streams, none of which could be obtained from the sector. The same limitation applies to efficiency and value based indicators (*EFn(t)*, *VMBUCn*, *VEFn(t)*), which rely on economic and production data typically available only through direct industrial collaboration.

Finally, indicators linking the intermediate and final stages of the chain, such as *BO(X)n+1* and *VBO(X)n+1*, could not be established, as there was no information on the proportion of collagen outputs destined for specific sectors (food, cosmetics, or pharmaceuticals) or their market value.

Overall, the collagen case reflects the same challenge as the fish oil chain: the limited participation of industrial partners and the lack of primary operational and economic data prevented the calculation of reliable and representative circularity indicators. Although the processes were conceptually modelled, relying solely on literature values would have introduced excessive uncertainty and hindered comparability across case studies. For both chains, real data from processing companies would be essential to ensure methodological consistency and accurate validation of the BIORECER framework.

2.1.1.2 Polysaccharides

The fishery-based value chain of Case Study 1 also focuses on the extraction and valorisation of polysaccharides obtained from marine algae generated or supplied within the Galician fishery sector. In this chain, algal biomass is collected, processed, and refined to obtain high-value polysaccharides that can be further used as functional ingredients in several industrial applications, including food, biotechnology, and bio-based materials. For a more detailed description of this value chain and its processing stages, information is available in Deliverables D6.1 and D2.4

The polysaccharide value chain from algae offered access to real, traceable, and process-specific data provided by regional partners. These datasets covered the full pathway, allowing for accurate calculation of the indicators, as well as reliable implementation of the BIT platform. This ensured that the validation exercise reflected realistic industrial conditions and produced results aligned with the methodological requirements of the project.

Of the 29 basic requirements listed in the BioReCer framework, the analysed polysaccharides company complies with 25. The remaining 4 are not applicable to this type of organization. As a result, the company fully complies with the BioReCer framework (Figure 4).

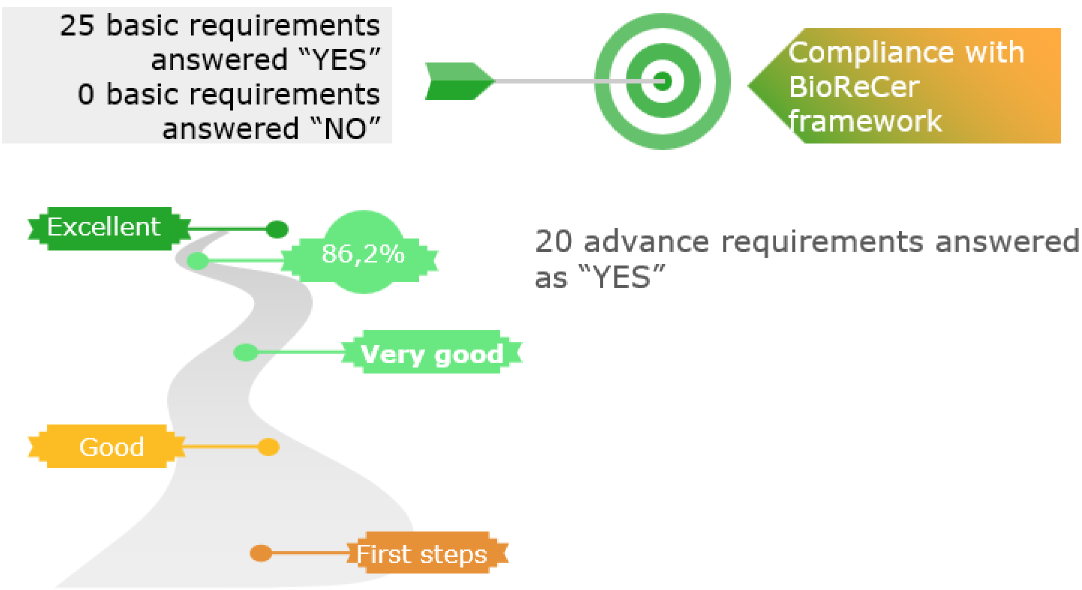


Figure 4. Analysis of requirements in CS1 (polysaccharides)

Additionally, of the 23 advanced requirements, the analysed polysaccharides company complies with 20. Table 1 shows the four basic requirements that are not applicable and the related justification.

Table 1. Requirements that are not applicable in CS1

Non applicable requirement	Comment
The company shall indicate whether it adopts ecosystem regeneration and rehabilitation measures	This does not apply to this type of company because the company operates an industrial processing facility and does not carry out activities directly affecting natural ecosystems
The company shall have evaluations about the state of the biodiversity within the area and a plan to maintain and improve biodiversity	This does not apply to this type of company because the company is located in an industrial zone that has no natural habitats or biodiversity-sensitive areas within its premises.
The company characterizes the introduced genetically modified species	Polysaccharides production is carried out through conventional physical, chemical, and biological processes, which do not involve the use or introduction of genetically modified organisms (GMOs)
The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	This does not apply to this type of company because the process occurs under controlled conditions without releasing anything into the ecosystem.

The Spanish CS focuses on the valorisation of marine biomass, specifically macroalgae collected from the Galician coast. The selected value chain explores the production of a biofertilizer using a cellulosic cake obtained as a side-stream from polysaccharide extraction. The aim is to demonstrate how marine resources, often underutilised, can be transformed into value-added bioproducts aligned with circular bioeconomy principles.

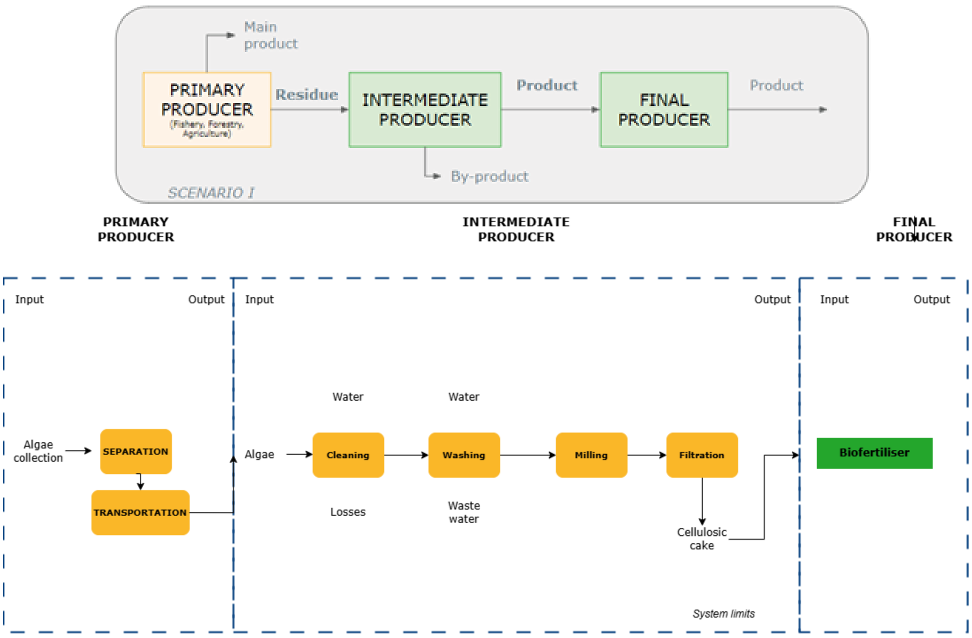


Figure 5. Position of each actor in the CS1 (fishery) value chain

For the calculation of the circularity indicators, the following value chain has been considered:

- Collection of macroalgae (primary production).
- Processing of algae biomass to obtain high-value polysaccharides (intermediate production).
- Recovery of the residual fraction (cellulosic cake), which is used as a biofertilizer (final production).

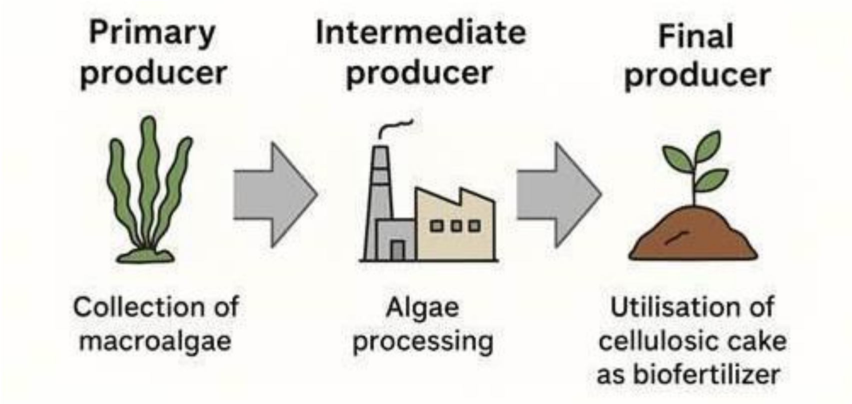


Figure 6. Value chain of CS1 - polysaccharides

In the algae value chain, bio-based products are generated across two stages. The intermediate producer extracts polysaccharides from harvested algae for use in food, cosmetic, or pharmaceutical applications, producing the cellulosic cake as a co-product and minor residues such as process water with organic load. At the final producer stage, this cellulosic cake is fully valorised into biofertilizer, which constitutes the main product, with no additional co-products generated.

No fossil-based feedstocks are used in either stage, except for auxiliary inputs such as energy or chemicals in the extraction process, which are not considered biological resources. Non-valorised residues, such as processing losses, are excluded from the value chain under analysis.

For the quantification and characterisation of the flows, the input/output tables outlined in deliverables D6.1 and D2.4 were taken into account. The indicators selected for the validation of all actors are those numbered as in D2.3.

- **Collection of algae biomass (Primary producer)**

The first stage of the value chain involves the harvesting of macroalgae from the Galician coast. The collected biomass is transported to a processing facility. At this stage, the main product is raw algal biomass, while unavoidable residues (e.g., moisture losses, fractions unsuitable for processing) are generated. Following the methodology outlined in D2.5, the role of this actor is defined as a primary producer since the feedstock originates directly from natural resources.

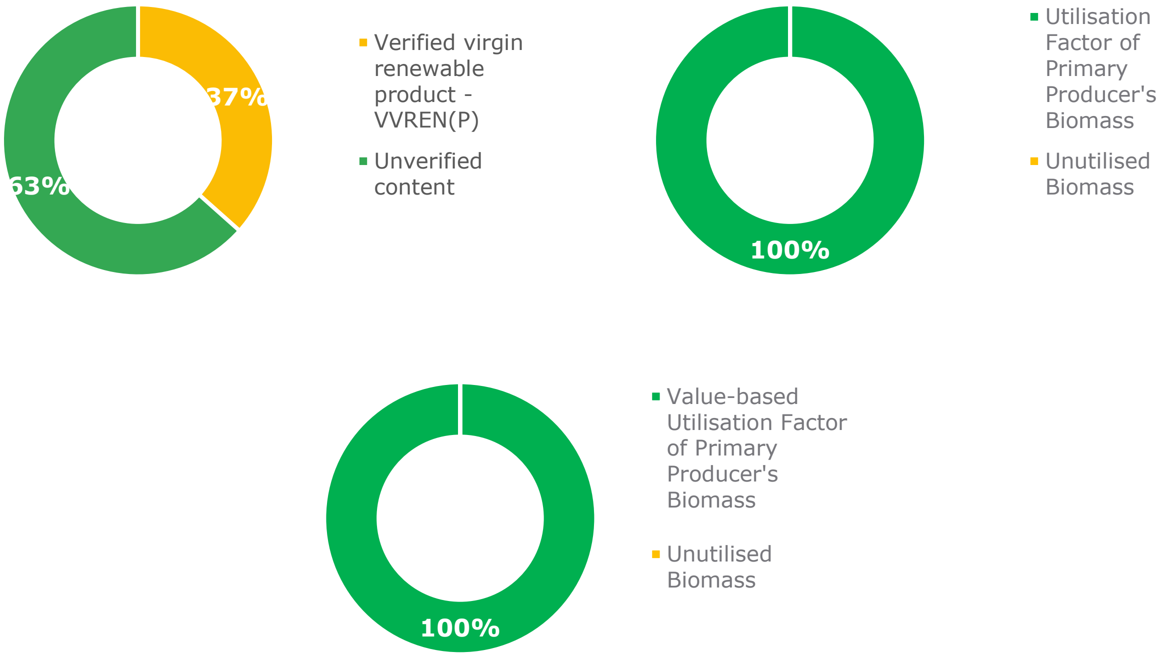


Figure 7. Results of circularity indicators of CS1 – primary producer

The verified virgin renewable (VVREN) product for algae is 37% while the remaining 63% corresponds to unverified renewable material. The utilisation factor of the primary producer is calculated at 100%, indicating that none of the harvested algal biomass remains unutilised. All material entering the system is directed towards processing pathways with market-relevant applications, showing an optimal alignment with circular economy principles. Similarly, the value-based utilisation factor also reaches 100%, demonstrating that the biomass is not only fully used but also allocated entirely to value-generating outputs. No fractions are downgraded to low-value uses or discarded as waste.

Production indicators

Table 2 presents energy-related production circularity indicators for the primary producer. The primary producer is responsible for algae cultivation, which relies mainly on renewable resources such as solar radiation and seawater nutrient cycling. No significant outflow of renewable energy occurs at this stage. Using the total chain values as reference, the inflow of renewable energy (797 kWh) and total energy inflow (1.721 kWh) reflect the strong contribution of the cultivation step to the proportion of renewable energy used. The Renewable Energy Content (REC) of the chain (46.31%) is therefore largely driven by this actor. Energy intensity (EI) remains low at this stage because no thermal extraction processes are yet applied.

Table 2. Circularity indicators related to energy for the primary producer.

Energy related indicators	Value	Unit
Renewable energy for production process (REC)	46.3	%
Energy Intensity to produce the product (EI)	0.10	KWh/unit

Energy Intensity performance in comparison to industry average (EIP)	0.11

Table 3 presents water-related production circularity indicators for the intermediate producer. Cultivation uses high volumes of environmental water, contributing significantly to the circular water input component (CWI = 216,139 m^3/year). As most of the water comes from seawater or recirculated culture media, this actor strongly influences the high Circular Water Withdrawal (CWW = 31.0%). Discharges at this stage are minimal and largely recirculated, supporting the Internal Water Recirculation (IWR = 0.037).

Table 3. Circularity indicators related to water for the primary producer.

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	31	%
Circular water discharge for the total production process for the generated product (CWD)	15	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	0.037	m^3/year
Water Intensity to produce the product (WI)	2.4	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	140.6	

In the case of process-function production circularity indicators for the primary producer, no process-function chemicals are added during cultivation. Consequently, all chemical-related indicators remain equal to zero for the primary producer: CPFC/M = 0%, PFC/MI = 0, and PFC/MIP = 0.

- **Processing stage (Intermediate producer)**

In the second stage, the harvested algae are processed to extract polysaccharides with applications in food, cosmetics and other industries. During this process, the main product is the extracted polysaccharides, while the side-stream cellulosic cake emerges as a by-product. This by-product is of particular interest, as it is valorised in the subsequent step of the value chain.

The actor involved in this stage is characterised as an intermediate producer, as the inputs are biological resources that undergo industrial processing. Circularity indicators here reflect both the efficiency of polysaccharide recovery and the valorisation potential of the cellulosic cake.

For the intermediate producer stage of CS1 (algae), the circularity indicators were defined following a structured approach. This stage focuses on the extraction of polysaccharides as the main bio-based product, while generating the cellulosic cake as a valorisable co-product and minor residues such as process water. The actor is classified as an intermediate producer, transforming biological inputs into high-value products. All input and output flows were quantified and characterised using data from Deliverables D6.1 and D2.4, distinguishing between the main product, co-products, and non-valorised residues.

Figure 8 shows the results of the relevant indicators, including utilisation factors and residue valorisation rates.

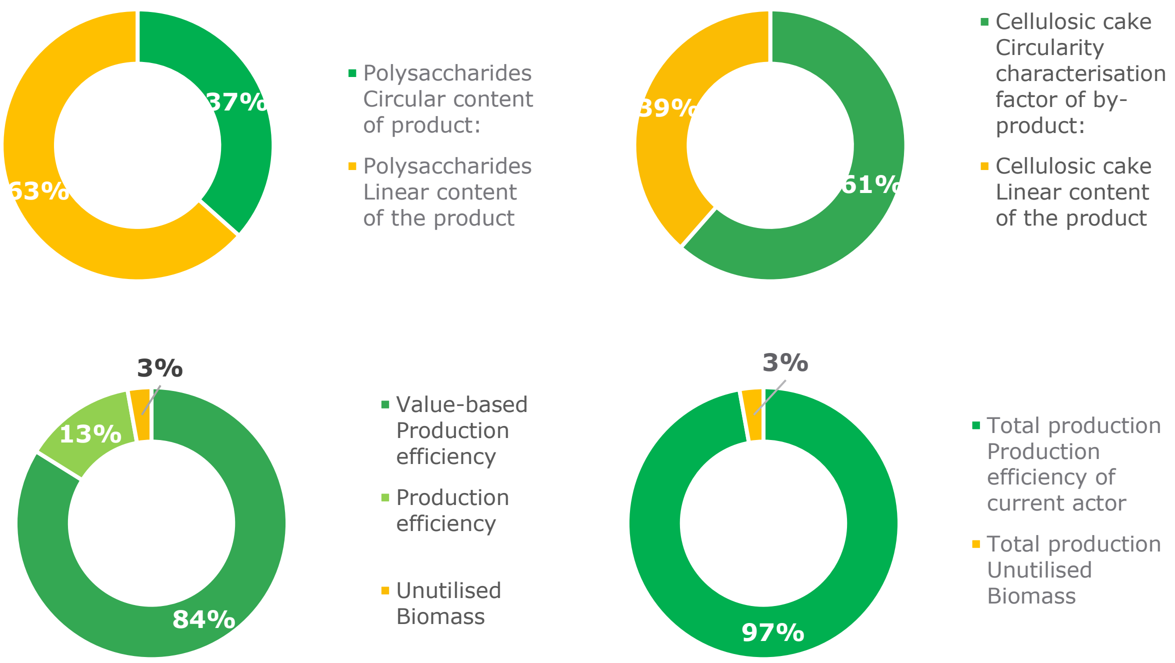


Figure 8. Results of circularity indicators of CS1

The circular content of the polysaccharide product reaches 37%, while 63% is classified as linear content. This proportion mirrors the upstream split observed in the primary production stage, where only part of the biomass could be considered verified renewable.

Regarding the side-stream, the cellulosic cake generated during extraction shows a circular characterisation factor (CCF) of 61%, with 39% classified as linear. This result highlights that a substantial portion of the by-product can be valorised in downstream applications. Nevertheless, the valorisation of this by-product represents a key contribution to improving the circularity of the overall system.

The value-based production efficiency of 84% indicates that the majority of inputs are converted into economically valuable outputs, although some losses occur due to process inefficiencies, non-recoverable fractions, or moisture content. Finally, the total production efficiency of the intermediate producer reaches 97%, demonstrating that nearly all the input biomass is recovered as either main product or usable by-product. Only a marginal fraction remains unutilised.

Production indicators

Table 4 presents energy-related production circularity indicators for the intermediate producer. The intermediate producer operates the preprocessing, fractionation, and extraction stages, which represent the main energy consumers of the chain. They contribute substantially to the total energy inflow (46.3 kWh during the reference period) and determine most of the Energy Intensity (EI = 0,8 kWh/unit). Because this stage frequently uses electricity and thermal energy from mixed sources, its contribution increases the Energy Intensity Performance indicator (EIP = 0,9), but it shows a slightly lower energy demand than typical industrial benchmarks.

Table 4. Circularity indicators related to energy production for the intermediate producer

Energy related indicators	Value	Unit
Renewable energy for production process (REC)	46,3	%
Energy Intensity to produce the product (EI)	0,8	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	0,9	

Table 5 presents water-related production circularity indicators for the intermediate producer. Extraction processes require washing, soaking, and dilution of water, increasing the total water inflow (TWI = 697,223 m^3/year). This actor also contributes to the total water used and consumed (TWU = 1,700 m^3/year). Circular water discharge (CWD = 270 m^3/year) is influenced by the recovery and reuse of process water in washing steps, while the Water Intensity indicator (WI = 43 m^3/unit) reflects the high water dependence of fractionation operations.

Table 5. Circularity indicators related to water for the intermediate producer

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	31	%
Circular water discharge for the total production process for the generated product (CWD)	270	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	0.66	m^3/year
Water Intensity to produce the product (WI)	43	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	2.5	

Although extraction processes may use acids, alkalis, or flocculants, the available data indicate no recycled, reused, or renewable chemicals in the system (REU = REC = BBR = 0 kg). Therefore, CPFC/M and PFC/MI remain 0, in line with the chain-level results. The absence of circular chemical inputs means the intermediate stage does not contribute positively to chemical circularity, and performance (PFC/MIP = 0) remains below the industry benchmark.

- **Use of cellulosic cake as biofertiliser (Final producer)**

The last stage of the value chain considers the utilisation of the cellulosic cake as a biofertilizer. In this case, the cellulosic fraction, originally considered a residue, becomes the main product, contributing to circularity through resource valorisation.

This actor is defined as a final producer, since the cellulosic cake enters the biofertilizer industry as a biological feedstock. This material is transformed into biofertiliser, representing the main bio-based product of this stage. No additional co-products are generated, and the feedstock is entirely biological, derived from the intermediate processing of algal biomass. This actor is classified as a final producer, as it valorises a side-stream into a marketable product, contributing to the circularity of the overall value chain. All flows were quantified and characterised, taking into account that 100% of the cellulosic cake is directed to biofertilizer production, while minor losses from handling or moisture removal are excluded. The application of circularity indicators at this stage highlights the potential of residual biomass to reduce waste and generate sustainable alternatives to conventional fertilizers.

The results obtained show the distribution of biomass flows and the efficiency of the overall value chain, from algae harvesting to the final valorisation step. Figure 9 illustrates the calculated indicators for this stage.

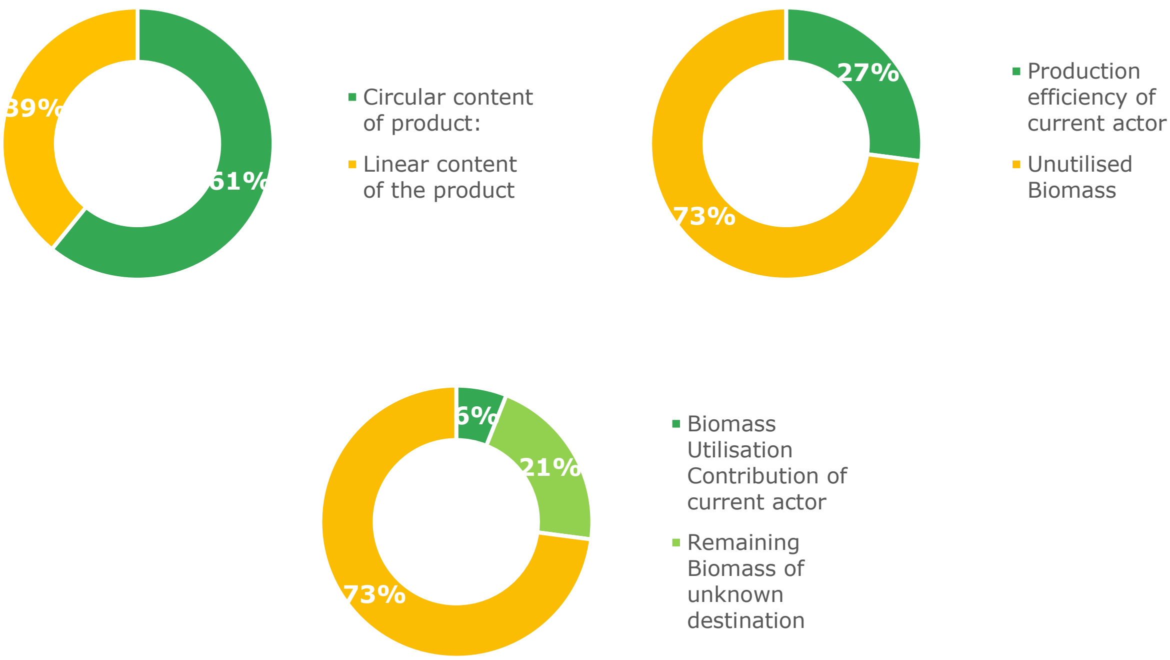


Figure 9. Results of circularity indicators of final producer in CS1

The obtained circularity indicators reflect the performance of this last transformation step. The circular content of the final product reaches 63%, consistent with the characterisation of the cellulosic cake in the intermediate stage. This confirms that the majority of the biomass entering the biofertilizer process is of renewable and valorised origin.

The production efficiency of the current actor, however, is relatively low (27%). This indicates that only a fraction of the incoming biomass is effectively transformed into the final usable product. The low efficiency is likely linked to operational factors such as moisture content, preprocessing losses, stabilisation steps, or the presence of non-functional fractions within the cellulosic cake. While this does not undermine the circularity potential of the material, it highlights opportunities for optimisation in handling, conditioning, and conversion processes.

Similarly, the biomass utilisation contribution of this actor is 7%, meaning that only a small proportion of the total biomass originally harvested is ultimately valorised at this stage.

Production indicators

Table 6 presents energy-related production circularity indicators for the intermediate producer. The final producer performs concentration, purification, drying, and final formulation. These operations consume a smaller share of energy compared with extraction but still contribute to the overall energy profile. As no renewable energy is exported (outflow = 0 kWh), this actor does not modify the chain's renewable energy balance but adds to the cumulative EI.

Table 6. Circularity indicators related to energy for the final producer.

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	46.3	%
Energy Intensity to produce the product (EI)	0.10	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	0.11	

Table 7 presents water-related production circularity indicators for the intermediate producer. At this stage, small volumes of additional water may be used for final purification. The discharge of treated process water (300 m^3/year) corresponds largely to the final producer and contributes to the circular water discharge (CWD indicator). However, as most recirculation is carried out upstream, the final producer contributes less to IWR but is still part of the integrated chain performance.

Table 7. Circularity indicators related to water for the final producer.

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	31	%
Circular water discharge for the total production process for the generated product (CWD)	15	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	0.04	m^3/year
Water Intensity to produce the product (WI)	2.4	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	140	

The final processing steps do not introduce new process-function chemicals (TPFC/M = 41,819 kg for the full chain, but all associated with upstream stages). Therefore, the final producer also yields CPFC/M = 0% and PFC/MI = 0.

2.1.1.3 Sewage sludge

This case study focuses on the production of Volatile Fatty acids (VFA) from sewage sludge generated in urban and industrial wastewater treatment plants, which are subsequently concentrated and purified to obtain high-purity acetic, butyric, and propionic acids.

For the qualitative assessment under the BioReCer framework, the questionnaire was completed by the regional wastewater utility company, which is responsible for managing the most significant treatment plants in Galicia. However, as the downstream processes in this value chain are still at the pilot stage and not yet operationally implemented by other companies, it was not possible to collect responses for those stages.

The results of the questionnaire are presented in Figure 10. They show that the wastewater utility company is fully compliant with the BioReCer framework, and they have a high degree of implementation of sustainability and circularity measures.

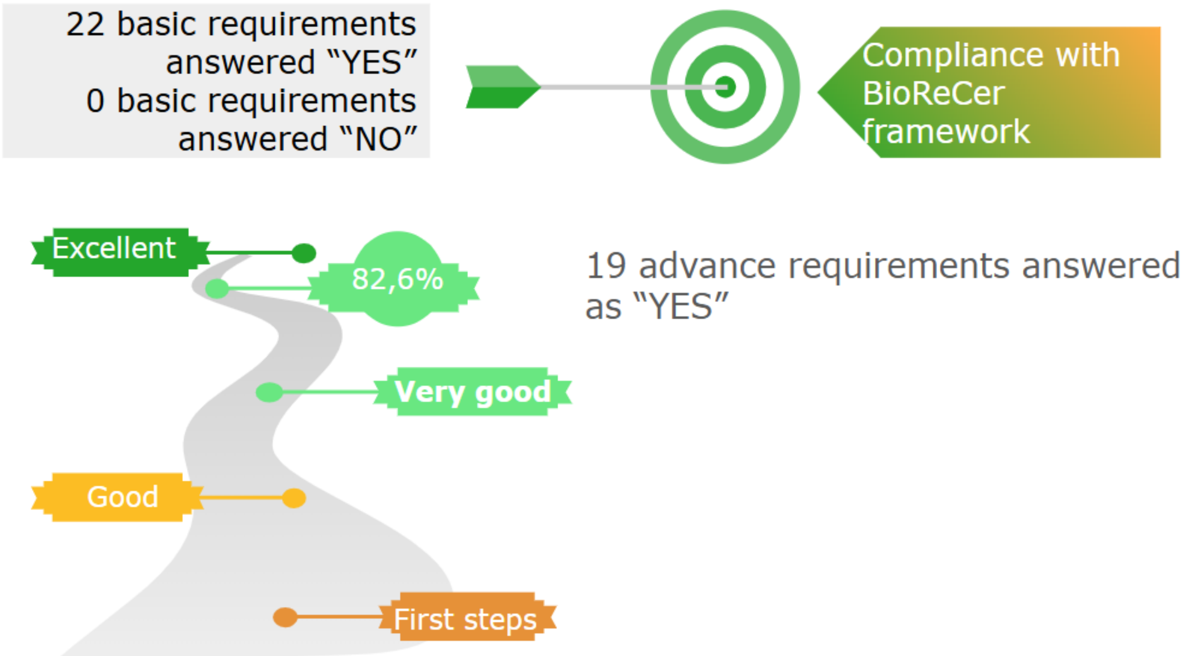


Figure 10. Analysis of requirements in CS1 - Sewage Sludge.

Of the 29 basic requirements listed in the BioReCer framework, the analysed urban wastewater operation company complies with 21. The remaining eight are not applicable to this type of organisation. As a result, the company fully complies with the BioReCer framework. Table 8 shows the 9 requirements that are not applicable and the reason why.

Table 8. Requirements that are not applicable in CS1 -Sewage sludge

Non applicable requirement	Comment
The company shall provide the most updated Environmental Impact assessment (EIA) of the area before starting its operations	The requirement to provide an EIA for a wastewater treatment plant depends on its size and capacity; large plants require an EIA, while smaller ones may be exempt.
The company has some kind of treatment technology to prevent emissions to the environment	The fundamental role of a WWTP is to treat emissions to the environment.
The company characterizes the introduced genetically modified species	Wastewater treatment is carried out through conventional physical, chemical, and biological processes, which do not involve the use or introduction of genetically modified organisms (GMOs).
The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	The wastewater treatment plant does not utilise non-indigenous, invasive species, or pathogens as part of its operational processes.
The company considers the resilience of the ecosystem to ensure sustainability	WWTP is required to comply with environmental regulations to control the quality of treated water and protect receiving ecosystems, it is not specifically obligated to assess or quantify ecosystem resilience or long-term environmental impacts, since its primary function is the treatment and purification of wastewater according to established parameters, rather than direct management of ecological status or biodiversity.
The company has good management of the unsold finished goods, prevention of generation of waste	The operation focuses on the efficient management of sludge and by-products generated during wastewater treatment, optimising processes to minimise waste generation.
The company identifies whether action has been addressed to ensure food security in biomass production systems	Since the biomass generated by the company is directly derived from residual water, no food systems are exposed.

Figure 11 presents a schematic diagram of VFA production from sewage sludge, highlighting the main inputs and outputs along the value chain (for further details, see D2.4 and D6.1). It also identifies the three key actors in the CS1 value chain, which are described below:

1 **Waste producers**: In this case, the actors are the WWTPs, which generates sewage sludge. Four WWTPs were considered: three of them are the largest facilities in the Galicia region (WWTP I, II and, IV), while the fourth is a fictitious plant included to represent the total amount of sludge generated at regional level (WWTP IV).
2 **Post-consumer intermediate producers**: The actors involved in the intermediate step include the production of VFAs and their concentration. The VFA mixture is then supplied to the next actor in the value chain. This stage also involves waste treatment generated during the process, such as biogas production and the spent sludge treatment.
3 **Post-consumer final producers**: Actors responsible for the downstream purification of VFAs into the final products: acetic, propionic and butyric acid.

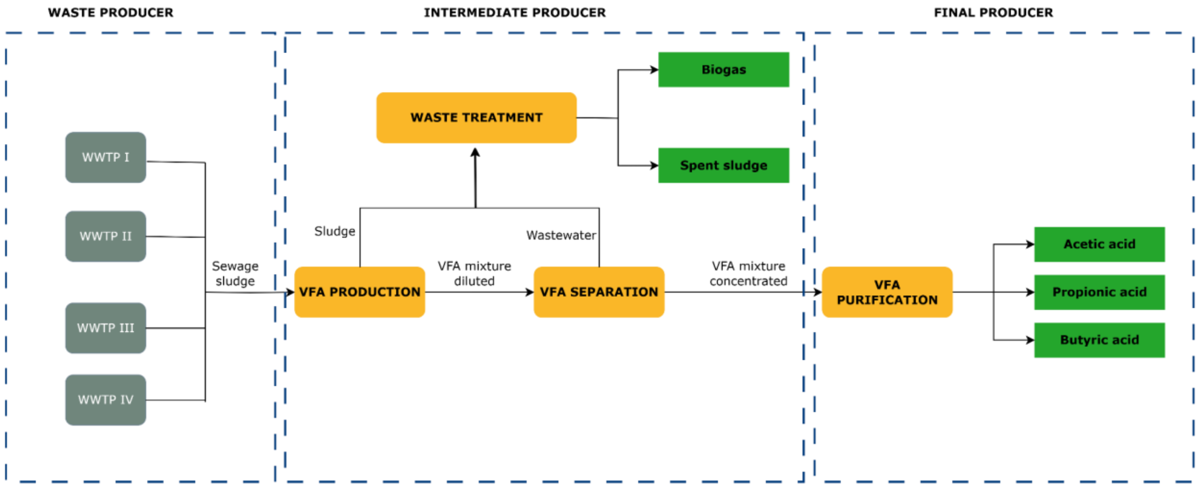


Figure 11. Position of each actor in the CS1 (sewage sludge) value chain.

Circularity indicators are calculated for each of the aforementioned actors, as well as for every type of product, residue, or by-product involved in the value chain.

For the **waste producer**, sewage sludge is generated from urban and industrial wastewater, entirely of biological origin; it was assumed that 100% of the sludge from WWTP I–III is directed to VFA production, whereas WWTP IV allocates 15.6% to landfill and 84.4% to agricultural application (INE, 2024). The **intermediate producer** converts this sludge into a VFA mixture as the main product, while also generating biogas and spent sludge as co-products; the feedstock for this stage is therefore exclusively biological. Finally, the **final producer** fractionates the VFA mixture into acetic, butyric, and propionic acids, which constitute the main products and are obtained solely from the biologically derived VFA feedstock, with no additional co-products.

Because VFAs are not durable, long-life products, use-phase and end-of-life indicators were not calculated for this value chain; accordingly, only material input and production indicators are considered relevant for assessing its circularity.

- **Wastewater producer (waste producer)**

Figure 12 shows the verified virgin renewable content of sewage sludge. The VVREN is considered zero because sludge is a post-consumer waste generated as an unavoidable residue of human activity derived from wastewater treatment. So, VVREN is not applicable.

Regarding the CCF for sewage sludge, a Sustainable Removal Rate (SSR) of 100% is assumed for WWTP I to III, as all the generated sludge is destined to VFA production. In contrast, the WWTP IV is assigned an SSR of 88%, since a part of the sludge is disposed of in landfill. The unavoidable residue is considered to be 100% across all WWTP, as sludge is a waste generated by human food consumption and derived from the treatment of wastewater. Consequently, the CCF for WWTP I to III is 100%, while WWTP IV leads a CCF of 94%, as Figure 12 shows. In order to improve the circularity performance of WWTP IV, all generated sludge should be redirected towards valorisation pathways.

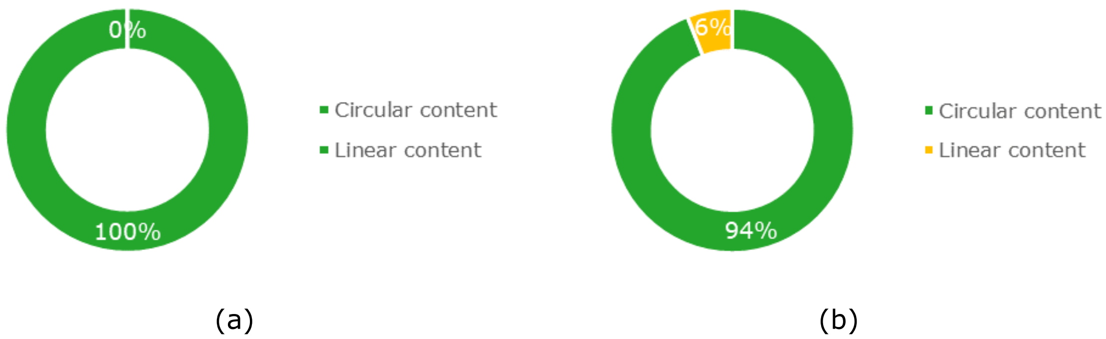


Figure 12. Circular content of the sludge

Regarding the Material Biomass Utilisation Factor (MBUF), WWTP I to III reaches a value of 100%, as all the sewage sludge generated is valorised into bulk chemicals (Figure 13, a). In contrast, the WWTP IV shows a lower MBUF of 88%, since not all the sludge produced is valorised, since a part of it is disposed of in landfill (Figure 13, b).

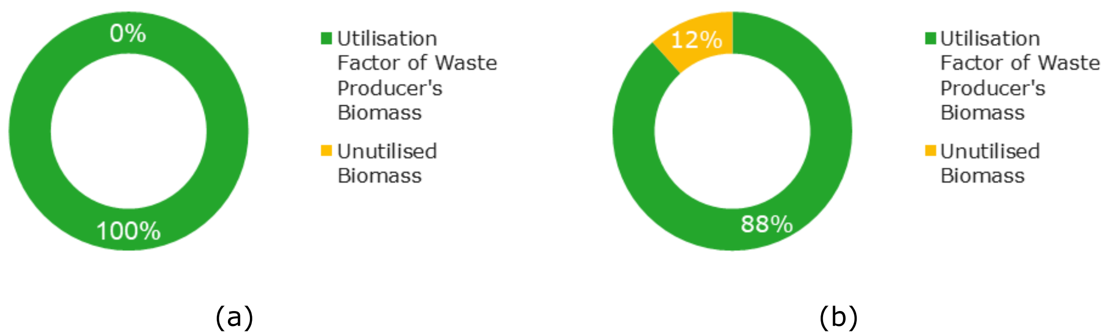


Figure 13. Total biomass utilisation factor for the mixed waste

The Value-based Biomass Utilisation Factor (VMBUF) takes into account the biomass value pyramid by applying specific coefficients based on the final use of the feedstock, as outlined in Deliverables D2.3 and D2.5. For WWTP I to III, the VMBUF is 80%, with a coefficient of 0.8 associated with the valorisation of sludge into bulk chemicals. In contrast, the WWTP IV shows a lower VMBUF of 58%, as it accounts for the portion of sludge that is landfilled, which is assigned a lower coefficient in the calculation.

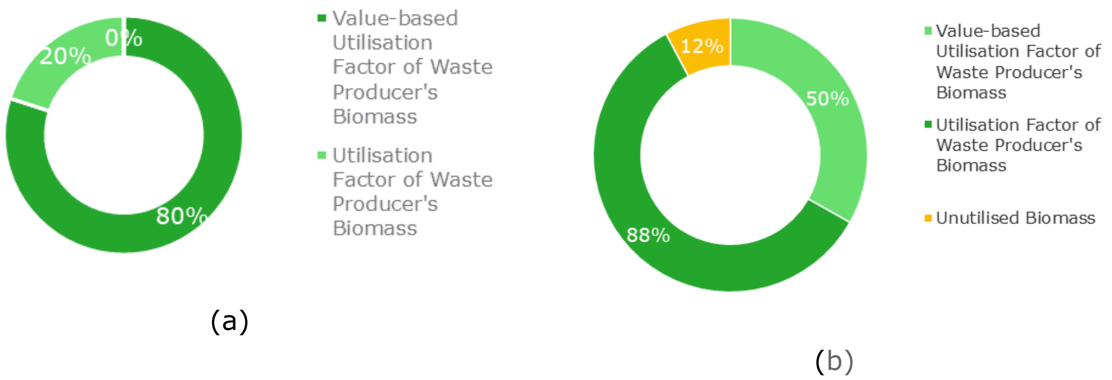


Figure 14. Value-based biomass utilisation factor for the sewage sludge

As the sewage sludge leaves the WWTP and becomes raw material for the next actor in the value chain (intermediate producer), the percentage of the output used as input by the next actor relative to the total input received was 100% for WWTP I to III and 26% for WWTP IV. The VMBUF, which reflects the added value of the portion of the output utilised by the following actor, reaches 80% for WWTP I to III and 20% for WWTP IV. This indicator takes into account the biomass valorisation coefficient, which is set at 0.8, as the sludge is valorised into bulk chemicals.

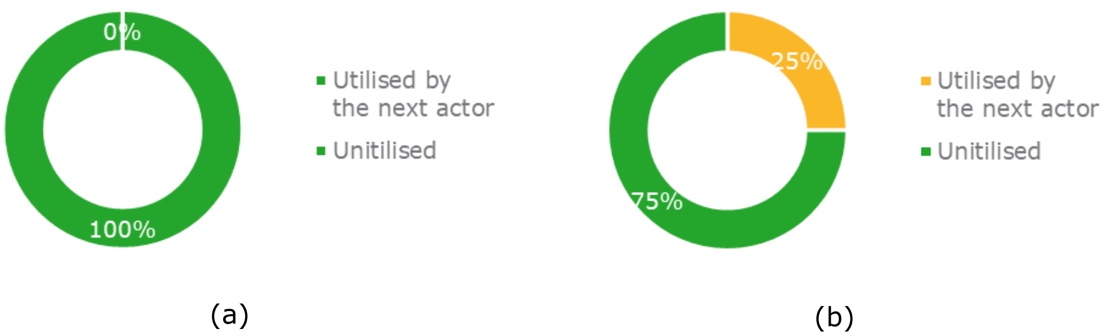


Figure 15. Sewage sludge that will be utilised as input by the next actor as a percentage of the total received input.
In total mass (a) and as value-added (b)

Production indicators

Table 9 presents energy-related production circularity indicators for the waste producer. As shown, REC was calculated for the different WWTP. For WWTP I and II, apart from the electricity supplied from the grid, both facilities generate heat and electricity through a cogeneration process powered by the biogas produced from anaerobic digestion of sludge generated in the wastewater treatment process. In the case of WWTP I, REC indicator is negative due to the energy generated from biogas valorisation. However, WWTP III relies exclusively on grid electricity and, since no renewable energy is utilised, its REC indicator value is zero.

Regarding *EI indicators*, energy consumption per cubic meter of treated water is presented. WWTP I shows the highest energy demand and corresponds to the plant with the largest treatment capacity.

The reported energy intensity values for the WWTPs are based on industrial-scale operational data obtained from wastewater treatment plants in the region. When compared with values reported in the scientific literature for the sector, the average specific energy consumption typically ranges between 0.5 and 1.5 kWh/m³ of treated water.

Table 9. Circularity indicators related to energy for the waste producer.

Energy related indicators	WWTP I	WWTP II	WWTP III	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	-71.78	19.58	0	%
Energy Intensity to produce the product (EI)	0.50	0.47	0.21	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	-	-	-	-

Table 10 presents the results of the water-related circularity indicators for the WWTPs. As can be observed, all of them show similar values. In the case of CWW, it reaches a value of 100%, since treated water is considered circular, being regarded as a raw material that contains contaminants that can be valorised into products. It should be noted that it was not possible to obtain data on the water consumed in cleaning operations; therefore, this consumption has not been included. For the same reason, the IWR indicator reaches a value of 1. Similarly, the WI indicator also shows a value of 1, as the unit considered corresponds to the cubic meter of treated water.

Table 10. Circularity indicators related to water for the waste producer.

Water related indicators	WWTP I	WWTP II	WWTP III	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	100	100	100	%
Circular water discharge for the total production process for the generated product (CWD)	0	0	0	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	1	1	1	m^3/year
Water Intensity to produce the product (WI)	1	1	1	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	-	-	-	-

Regarding the circularity indicators related to chemical consumption, the results are presented in Table 11. For the CPFC/M indicator, all WWTPs show a value of zero, as no recycled or reused chemicals are used. The PFC/MI indicator values are also shown, representing the kilograms of chemicals used per m^3 of treated water.

Table 11. Circularity indicators related to chemical consumption for the waste producer.

Process-function material indicators	WWTP I	WWTP II	WWTP III	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	0	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	0.09	0.13	0.04	kg/unit
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-	-	-

- **VFA production and concentration (intermediate producer)**

In CS1, the post-consumer intermediate producer is responsible for processing the waste generated by the previous actors (the waste producers) through fermentation and anaerobic digestion. The products and by-products generated by this actor are the spent sludge, which is either landfilled or applied to agriculture; the biogas produced during anaerobic digestion; and the VFAs obtained through fermentation, which are subsequently used by the next actor in the value chain.

This section presents the results of the material input circularity indicators for the post-consumer intermediate producer. Unlike for the waste producer, the virgin renewable, reused, and recycled content indicators are all considered to be zero. This is because the process solely involves the transformation of sludge and does not require the addition of any external raw materials, whether virgin renewable, reused, or recycled inputs.

The circular content of both the spent sludge and the biogas produced in this stage of the value chain was determined. This indicator is fed from the content of waste producers' circular residue in product (PPRESC(P)), which is 96%, according to the value of the CCF(R) from the previous actor. Taking into account an allocation mass of the CCF(R) for all wastes produced by the waste producer, the resulting CCF(P) for both sludge and biogas is 96%. Since the production of the VFA mixture requires no additional raw materials, the circularity level (CCF) remains unchanged from that of the previous actor.

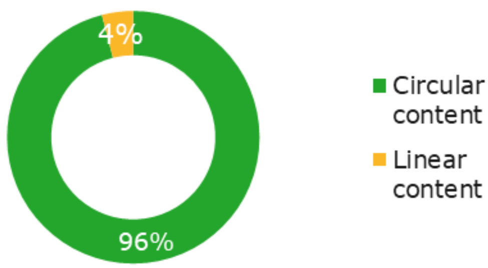


Figure 16. Circular content for sludge and biogas.

For the VFA mixture, the post-consumer CCF was calculated, with the result shown in Figure 16. For this calculation, the unavoidable residue was defined as the inert solids plus 40% of the volatile solids, considering that the target for anaerobic digestion is a 60% destruction.

The MBUF was calculated in the same way as for the waste producer section, following the mass allocation criteria for the different end uses. As shown in Figure 17, the MBUF is 91%, since part of the spent sludge is disposed of to landfill and landfarming, while the remainder is used for biogas and VFA production.

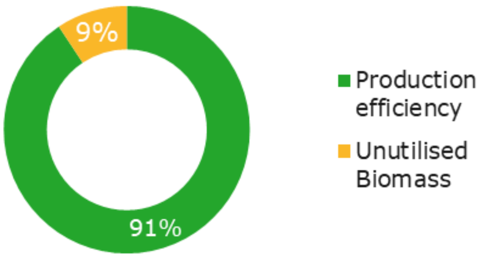


Figure 17. Total biomass utilisation factor.

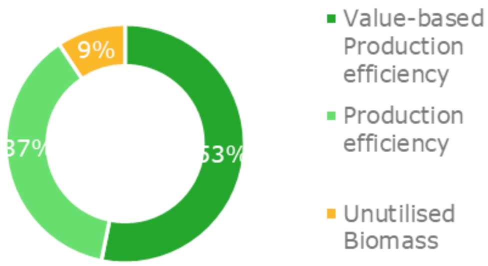


Figure 18. Value-based biomass utilisation factor.

The VMBUF, as with the previous actor, was calculated based on the biomass value pyramid by applying different coefficients depending on the end use of the biomass, as detailed in Deliverables D2.3 and D2.5. The VMBUF reaches 53% (Figure 18). To improve circularity performance in both the MBUF and VMBUF indicators, a greater proportion of the biomass should be directed toward higher-value valorisation pathways, prioritising applications with higher resource efficiency, in accordance with the biomass value pyramid.

Production indicators

Table 12 presents the energy-related production circularity indicators for the intermediate producer. Similar to the waste producer, the REC indicator accounts for the energy generated through the valorisation of biogas, which is produced via anaerobic digestion of the sludge generated during the solid–liquid separation and membrane train stages. This recovered energy is internally consumed in the fermentation and anaerobic digestion processes (considered as renewable energy input), resulting in a REC value of 80.3%. Regarding *EI indicators*, it is expressed as the energy consumed per ton of VFA produced, with a value of 3,495.1 kWh/ton.

It is important to note that the calculation of these indicators is based on pilot-scale operational data, and data at an industrial scale are not publicly available, thereby the calculation and its comparison with the performance industry average is not possible.

Table 12. Circularity indicators related to energy production for the intermediate producer.

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	80.3	%
Energy Intensity to produce the product (EI)	3,495.1	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	-	-

Table 13 also shows the water-related indicators for the intermediate producer. For the calculation of CWW, water present in the raw material is considered as the circular inflow. Total water inflow includes both the water in the sludge (circular) and the water used in the process (linear), primarily during anaerobic digestion and membrane cleaning in the VFA concentration stage. CWW reaches a value of 52.9%.

Regarding CWD indicator, only permeate from the reverse osmosis stage is considered circular, as it is reused within the process due to it constitutes a better quality stream, resulting in a value of 25.8%; whereas IWR is expressed in m³ of water per ton of VFA produced, is 0.43 m3/ton, similarly to the energy-related indicators. IWR indicator is 1 m3/year, as the total volume of water used and consumed equals the overall water inflow from all sources.

Table 13. Circularity indicators related to water for the intermediate producer.

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	52.9	%
Circular water discharge for the total production process for the generated product (CWD)	25.8	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	1	m^3/year
Water Intensity to produce the product (WI)	0.4	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	-	-

The results of the chemical-related indicators for the intermediate producer are presented in Table 14. As shown, CPFC indicator equals zero, as no reused, recycled, or bio-based chemicals are used in this stage of the process. PCF/MI indicator measures the chemicals consumed for VFA production, with a value of 1229.7 m³ per ton of product. Meanwhile, consistent with the other intensity performance indicators, could not be determined due to the lack of available industrial-scale data.

Table 14. Circularity indicators related to chemical consumption for the intermediate producer.

Process-function material indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	1229.64	kg/unit
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-

- **VFA purification (final producer)**

In CS1 the post-consumer final producer uses the concentrated VFA mixture generated by the previous actor in the value chain (post-consumer intermediate producer) as feedstock for the purification of VFA, into acetic, butyric and propionic acids.

Similar to the previous actors, the VVRENcontent is 0%, since no additional materials, virgin renewable, reused, or recycled, are incorporated during the process.

The circular content of the product was calculated for acetic, butyric, and propionic acids, with the results shown in Figure 19. All three acids show identical values, each reaching a circular content of 96%. This result is based on the PPRESC(P) indicator, which takes a value of 96%, derived from the CCF(POB)n of the previous actor in the value chain, as previously indicated in earlier sections. Although a solvent is needed to extract the acids from the fermentation broth. In the final distillery step the solvent is almost completely separated from the individual acids. Because of this, the circularity level (CCF) remains unchanged from that of the previous actor.

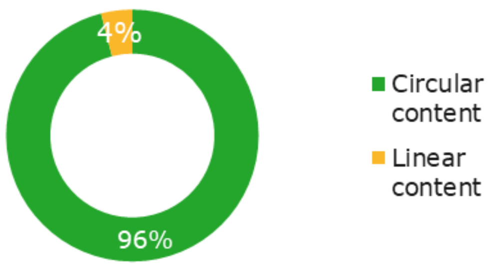


Figure 19. Circular Content of Product (%) for the acetic, butyric and propionic acid.

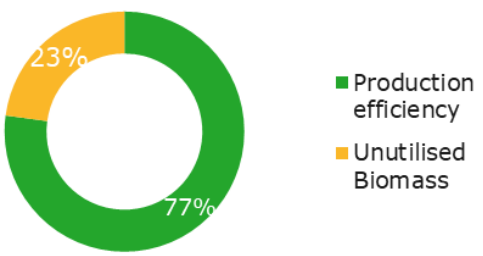


Figure 20. Total biomass utilisation factor for the acetic, butyric and propionic acid.

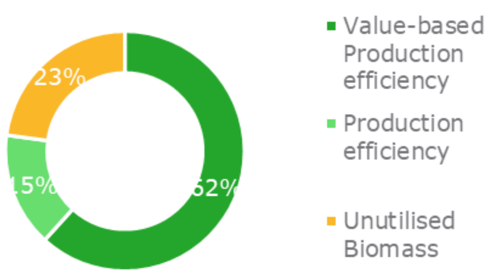


Figure 21. Value-based biomass utilisation factor.

Energy-related indicators have also been calculated for the final producer (Table 15). At this stage, no renewable energy is generated during the VFA purification; however, a part of the heat recovered from biogas valorisation in the prior stage is utilised. Similar to the previous actor, EI indicator is expressed as kWh consumed per ton of VFA produced. Moreover, since only pilot-scale operational data are available, comparison with industry-average energy performance is not feasible.

Table 15. Circularity indicators related to energy for the final producer.

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	4.9	%
Energy Intensity to produce the product (EI)	70.3	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	-	-

As shown in Table 15, and similarly to the preceding producer, for the calculation of the water-related indicators, the water contained in the raw material is also considered as circular (CWW). However, CWD value is zero, as the discharged water is not regarded as circular, since the generated effluents are returned to the WWTP. WI is expressed as m3 per ton VFA produced

Table 16. Circularity indicators related to water for the final producer.

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	100	%
Circular water discharge for the total production process for the generated product (CWD)	0	m3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	1	m3/year
Water Intensity to produce the product (WI)	0.1	m3/unit
Water Intensity performance in comparison to industry average (WIP)	-	-

Finally, chemical-related indicators were also assessed for the final producer. As shown in Table 17, the CPFC indicator accounts for the recycled solvent recovered during the VFA purification stage, representing the contribution of reused chemicals within the process. The PCF/MIP indicator is likewise expressed per ton of VFA produced, whereas the PCF/MIF indicator could not be determined due to the unavailability of industrial-scale data required for its calculation.

Table 17. Circularity indicators related to chemical consumption for the final producer.

Chemical consumption related indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	43.02	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	161.53	kg/unit
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-

Improving circularity performance across the entire value chain would require redirecting biomass valorisation towards end uses with higher coefficients in the biomass value pyramid, such as the production of pharmaceuticals and fine chemicals or food and feed, all of which have a valorisation coefficient of 1. However, due to the nature of sewage sludge and VFAs applications, these applications are not feasible. Therefore, the only viable option to improve the circularity of all actors of the value chain would be its conversion into bioplastics, which also have a coefficient of 1. This would represent an improvement over alternatives like thermal or energy recovery, which are associated with significantly lower valorisation coefficients.

2.1.2 Case study 2: Lombardia, Italy

This case study, conducted in the Lombardy region (Italy), focuses on the valorisation of urban and industrial biowaste through the recovery of struvite and the production of PHAs.

For the qualitative assessment under the BioReCer framework, the questionnaire was completed by CAP HOLDING SPA, operator of the integrated water service in the Metropolitan City of Milan and in several other municipalities of the neighbouring provinces. However, as the downstream processes in the value chain of the Italian case study are still at the pilot stage and not yet operationally implemented by other companies, it was not possible to collect responses from those stages. The results of the questionnaire are presented in Figure 22. They show that the wastewater utility company is fully compliant with the BioReCer framework, and they have a high degree of implementation of sustainability and circularity measures.

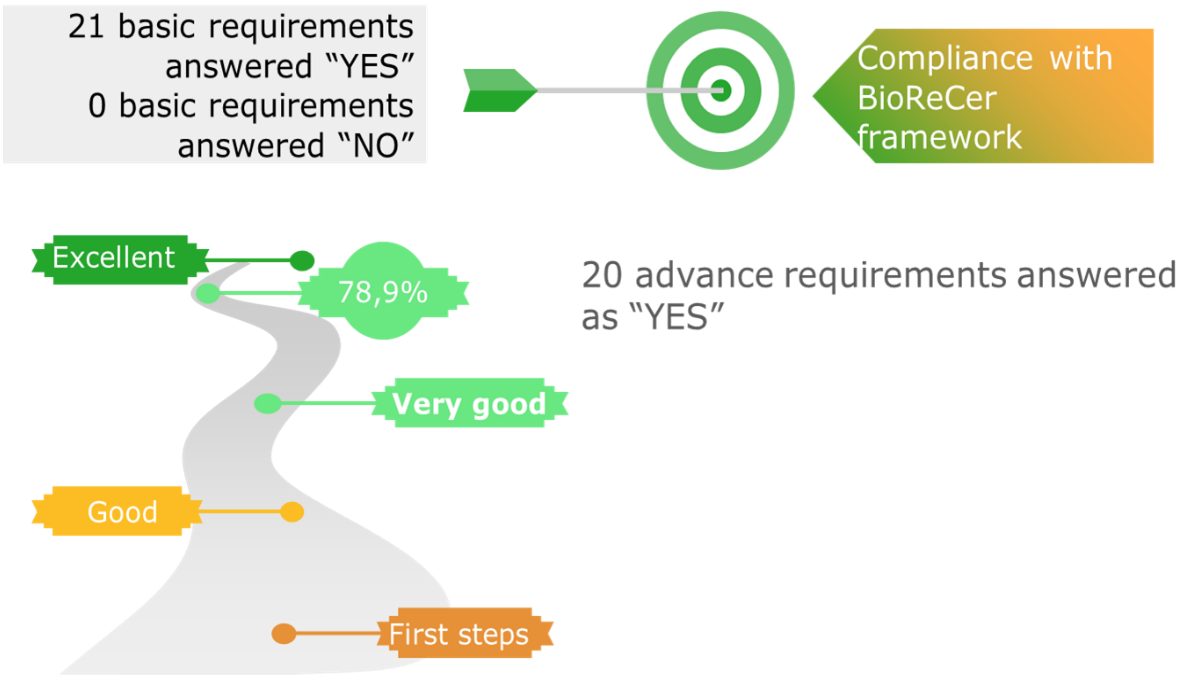


Figure 22. CS 2 – compliance with BioReCer framework.

Of the 29 basic requirements listed in the BioReCer framework, the analysed urban wastewater operation company complies with 21. The remaining 8 are not applicable to this type of organization. As a result, the company fully complies with the BioReCer framework.

Additionally, of the 23 advanced requirements, the analysed urban wastewater operation company complies with 20. Table 18 shows the 8 basic requirements that are not applicable and the related justification.

Table 18. Non-applicable requirements and related justifications.

Non applicable requirement	Comment
The company identifies the water sources affected by runoffs and discharges	The primary objective of the WWTP is to discharge uncontaminated water into the identified and regulated receiving water body.
The company shall provide the most updated Environmental Impact assessment (EIA) of the area before starting its operations	EIA is only required for the WWTP in specific cases, based on its size and treatment capacity.
The company shall have evaluations about the state of the biodiversity within the area and a plan to maintain and improve biodiversity	An initial impact assessment was carried out which highlighted no significant dependencies of biodiversity and ecosystem service as well as on communities. Thus, this criterion is not applicable. However, WWTP, by treating wastewater, actively contributes to preventing the contamination of aquatic ecosystems and, consequently, protecting biodiversity.
The company has some kind of treatment technology to prevent emissions to the environment	The purpose of the WWTP is to prevent emissions to the environment.
The company applies the waste hierarchy to reduced and valorised its waste	The requirement is not easily demonstrable, although the company adheres to it.
The company characterizes the introduced genetically modified species	No genetically modified species are intentionally used or introduced to WWTPs.
The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	No non-indigenous or invasive species are intentionally used or introduced to WWTPs.
The company considers the resilience of the ecosystem to ensure sustainability	The WWTP does not manage, maintain, or restore an ecosystem. Its purpose is to prevent urban wastewater from compromising the resilience of aquatic ecosystems, thereby indirectly contributing to their sustainability.
The company identifies whether action has been addressed to ensure food security in biomass production systems	Food security is not threatened by the activities of the WWTP.

Three actors of the CS2 value chain were identified:

- **Waste producers**: the actors generating sewage sludge, OFMSW and agri-food waste

- **Post-consumer intermediate producers**: the actors of the intermediate step treating the wastes and producing sludge, biogas and the liquid streams which will be further treated by the next actor of the value chain (fermentation supernatant) or used for diluting the incoming waste (AD supernatant)
- **Post-consumer final producers**: the actors of the final step of the value chain further treating the liquid streams generated by the previous actor and producing struvite and PHA-rich sludge

Figure 23 shows the position of each actor in the value chain.

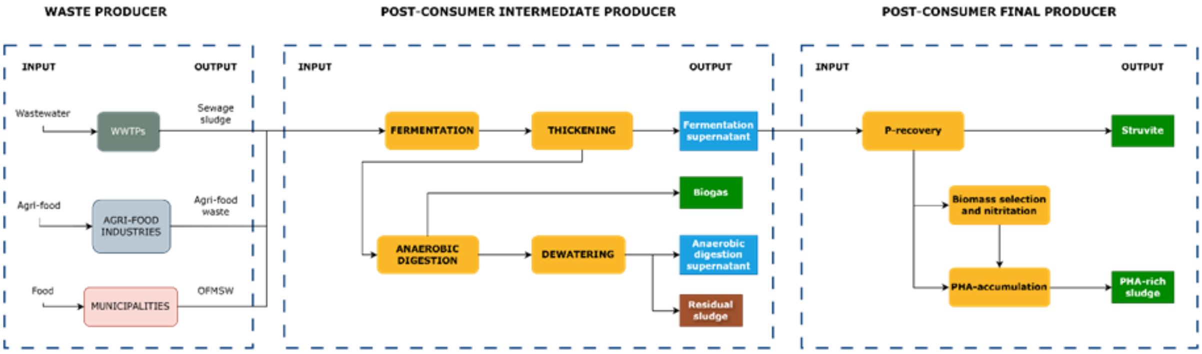


Figure 23. Position of each actor in the CS2 value chain.

All bio-based products are derived from biological feedstocks, including wastewater for sludge producers, food and beverage residues from agro-industrial production, and household and canteen food waste for OFMSW producers. For intermediate producers, the feedstock consists of the biological wastes generated by the waste producers, while for final producers it is the biological liquid stream from the fermenter of the previous step. Several assumptions were made to support the calculation of circularity indicators: for sludge, the unavoidable residue was was estimated considering to the sludge production rates from the literature (Metcalf & Eddy, 2014) and the percentage of residue that is validated as renewable was not applicable; for agri-food waste, the renewable fraction was estimated based on the organic content of food biomass and the share of PDO/PGI certified products, while unavoidable residues were estimated from literature on process waste (Mahro and Timm, 2007) and BOD removal rates (Britz et al., 2006; Zhao et al., 2020); for OFMSW, the biodegradable organic fraction was considered as 86%, according to the composition of the EER 20 01 08 and unavoidable residues were calculated by comparing target per capita production with actual regional production. For all actors, the circularity indicators used for validation are those defined and numbered in Deliverable D2.3.

- **Waste producers (primary producer)**

In CS2 the waste producers are the wastewater treatment plants, the agri-food industries and the municipalities producing OFMSW.

In the case of waste, the VVREN content is 0% as it is 100% a residue.

For sludge, the percentage of residue sustainably removed for further use, in accordance with SSR, is 100%, as none of the sludge is sent to landfill. In six out of the seven wastewater treatment plants assessed, sludge production does not exceed the expected rate reported in the literature (Metcalf & Eddy, 2003); therefore, the unavoidable residue is 100%, resulting in a total circular content of 100% (Figure 24, a). The only exception is the San Giuliano Milanese

Ovest WWTP, where sludge production exceeds the expected rate. In this case, 84% of the sludge is classified as avoidable, leading to a circular content of 79% (Figure 24, b).

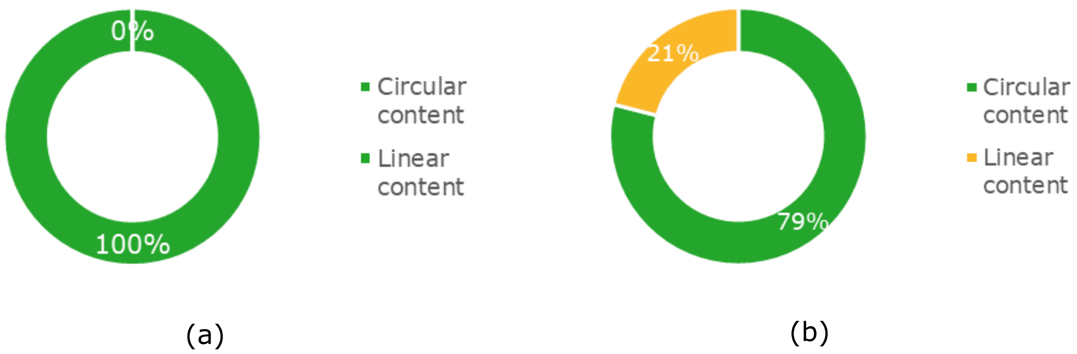


Figure 24. Circular content of the sludge

Referring to the agri-food waste, the circular content was calculated for each specific EER code. The results are shown in Figure 25. As specified before, for the calculation of this indicator for the agri-food waste, some assumptions (organic fraction from food biomass) and literature data (inlet renewability, avoidable and unavoidable residues) were necessary.

For the EER 02 02 01 (sludge from washing and cleaning from the preparation and processing of meat, fish and other foods of animal origin) the circular content is 40%. This value derives from 8% of residue that is validated as renewable (RENR), considering 50% of organic content in the waste stream and 15% of inlet renewability, and a 45% of unavoidable residue, according to the percentage of waste from fish and meat production process indicated by Mahro and Timm (2007).

Regarding the EER 02 02 04 (sludges from on-site effluent treatment from the preparation and processing of meat, fish and other foods of animal origin) the circular content is 86%. This value is due to 100% of residue that is sustainably removed for further utilisation in line with the sustainable removal rate (SSR) (as none of this waste is landfilled) and 44% of residue that is characterised as unavoidable residue, considering a generic sludge production rate of 0.45 kg TSS/kg BOD and a BOD removal rate of 98% (Britz et al., 2006; Zhao et al., 2020).

For the EER 02 03 01 (sludges from washing, cleaning, peeling, centrifuging and separation from fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production, molasses preparation and fermentation) the circular content is 41%. This value derives from 8% of residue that is validated as renewable (RENR), considering 50% of organic content in the waste stream and 15% of inlet renewability, and a 50% of unavoidable residue, according to the percentage of waste of vegetables production process indicated by Mahro and Timm (2007).

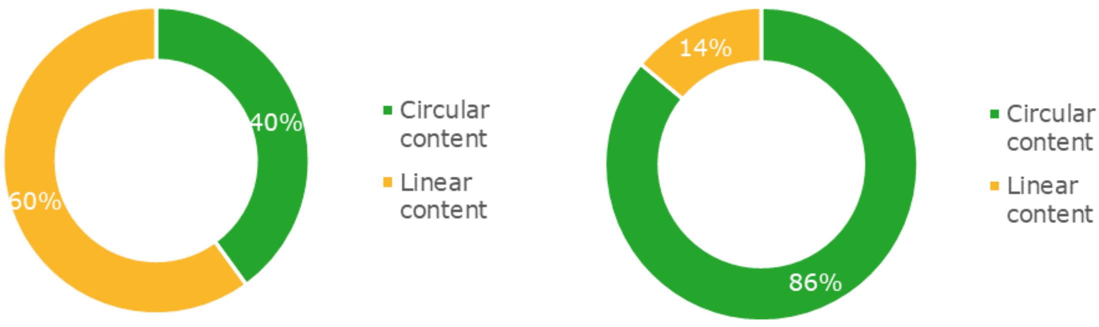
Regarding the EER 02 03 04 (materials unsuitable for consumption or processing from fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production, molasses preparation and fermentation) the circular content is 33%. This value derives from a 15% of residue that is validated as renewable (RENR), considering 100% of organic content in the waste stream and 15% of inlet renewability, and a 0% of unavoidable residue, cautiously assuming the fraction corresponding to batch changes or production ends equal to 0% due to the lack of data.

Regarding the EER 02 03 05 (sludges from on-site effluent treatment from fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production, molasses preparation and fermentation) the circular content is 86%. This value is due to 100% of residue that is sustainably removed for further utilisation in line with the SSR (as none of this waste is landfilled) and 44% of residue that is characterised as unavoidable residue, considering a generic sludge production rate of 0.45 kg TSS/kg BOD and a BOD removal rate of 98% (Britz et al., 2006; Zhao et al., 2020).

For the EER 02 05 01 (materials unsuitable for consumption or processing from wastes from the dairy products industry) the circular content is 33%. This value derives from a 15% of residue that is validated as renewable (RENR), considering 100% of organic content in the waste stream and 15% of inlet renewability, and a 0% of unavoidable residue, cautiously assuming the fraction corresponding to batch changes or production ends equal to 0% due to the lack of data.

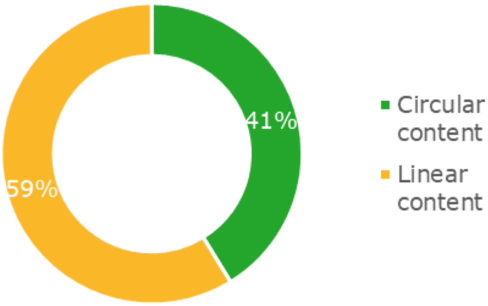
For the EER 02 06 01 (materials unsuitable for consumption or processing from the baking and confectionery industry) the circular content is 33%. This value derives from a 15% of residue that is validated as renewable (RENR), considering 100% of organic content in the waste stream and 15% of inlet renewability, and a 0% of unavoidable residue, cautiously assuming the fraction corresponding to batch changes or production ends equal to 0% due to the lack of data.

For the EER 02 07 01 (wastes from washing, cleaning and mechanical reduction of raw materials from the production of alcoholic and non-alcoholic beverages (except coffee, tea and cocoa)) the circular content is 35%. This value derives from 8% of residue that is validated as renewable (RENR), considering 50% of organic content in the waste stream and 15% of inlet renewability, and a 25% of unavoidable residue, according to the percentage of waste from wine production process indicated by Mahro and Timm (2007).

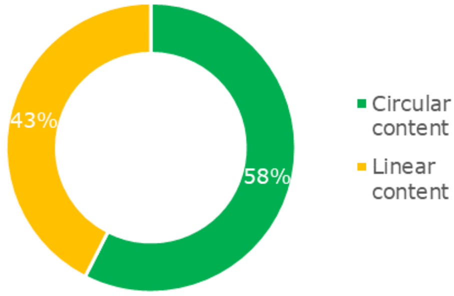


(a) EER 02 02 01

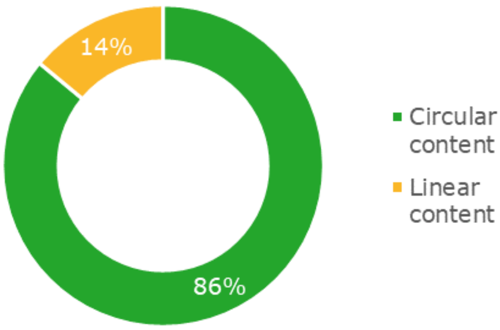
(b) EER 02 02 04



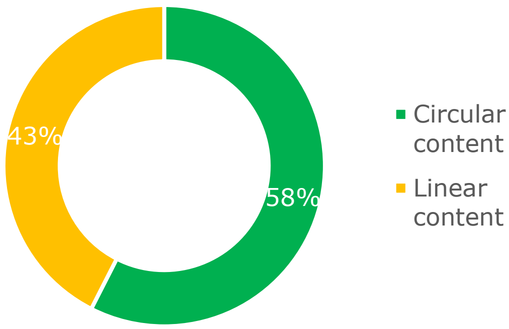
(c) EER 02 03 01



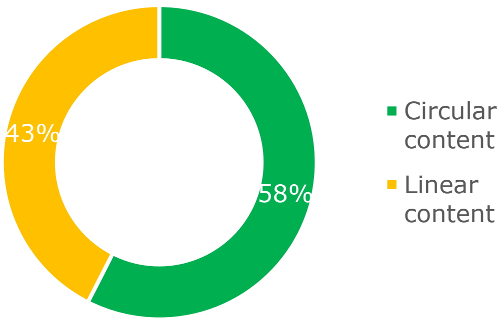
(d) EER 02 03 04



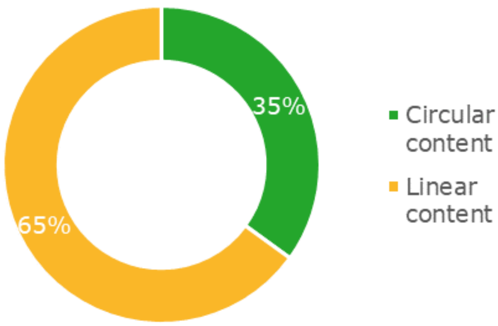
(e) EER 02 03 05



(f) EER 02 05 01



(g) EER 02 06 01



(h) EER 02 07 01

Figure 25. Circular content of each EER code of agri-food waste

The circular content of the OFMSW is 83% (Figure 26), considering that 73% of the OFMSW production could be avoided, the biodegradable organic content is 86% and the SSR is 100%, as all of the OFMSW considered is valorised.

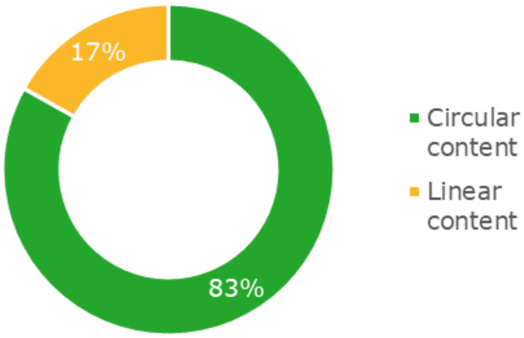


Figure 26. Circular content of OFMSW

The total produced MBUFof the mixed waste (sludge, agri-food waste and OFMSW) is 65% (Figure 27). This indicator has the same value for all the wastes considered due to the application of a mass allocation for the different uses, as these wastes are mixed prior to their management in the biorefinery. In particular, 1% of the waste is used for biopolymers recovery, 11% for biogas production, 0.1% for struvite recovery and 52% for incineration. The remaining 35% corresponds to material losses.

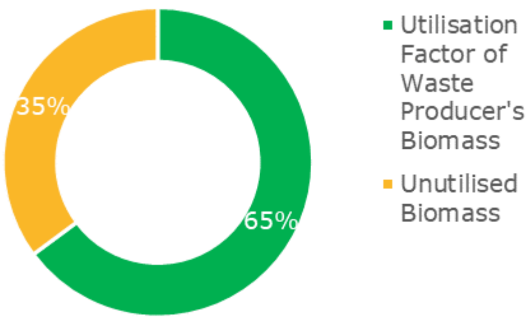


Figure 27. Total biomass utilisation factor for the mixed waste

The VMBUF takes into account the biomass value pyramid (D2.3) including a different coefficient for each usage of the biomass. These sets of coefficients vary if the waste is produced before the consumer usage (pre-consumer, such as agri-food waste) or after the consumer usage (post-consumer, such as sewage sludge and OFMSW). For this reason, the indicator for the agri-food waste has a different value than the ones for sewage sludge and OFMSW. The results are shown in Figure 28 (sewage sludge), Figure 29 (agri-food waste) and Figure 30 (OFMSW).

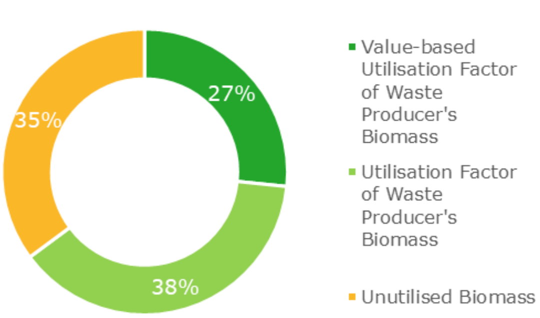


Figure 28. Value-based biomass utilisation factor for the sewage sludge

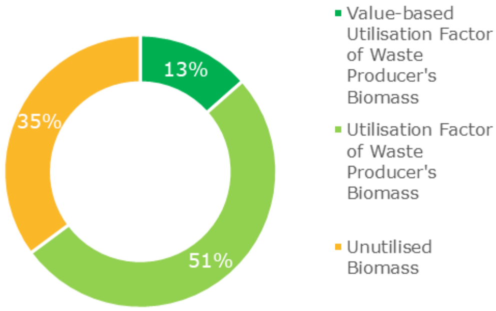


Figure 29. Value-based biomass utilisation factor for the agri-food waste

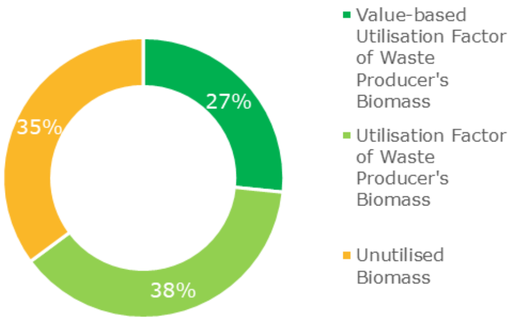


Figure 30. Value-based biomass utilisation factor for the OFMSW

The VMBUF is part of the MBUF. For the sewage sludge and the OFMSW, the VMBUF was 27%, considering that the majority of the waste (in mass) is incinerated at the end of the process value chain, and the related coefficient (mass of generated residue used for energy, heat and fuel - m(RtEHF)) is 0.4 in the case of post-consumer wastes. In the case of the agri-food waste, the VMBUF was 13.5%, considering that the majority of the waste (in mass) is incinerated in the process value chain, and the related coefficient (mass of generated residue used for energy, heat and fuel - m(RtEHF)) is 0.2 in the case of pre-consumer waste.

Production indicators

The production indicators for the waste producers were not validated in CS2 for the following reasons. For WWTPs, validation was considered unnecessary as these indicators had already been verified within CS1. In the case of agro-waste, no information could be collected because the specific agro-industries generating these waste streams were not disclosed by the waste handlers for confidentiality reasons; consequently, no data on chemical, energy or water consumption could be obtained. Finally, for OFMSW, the generation of the waste stream is not directly linked to the use of energy, chemicals or reagents, and therefore no production indicators were applicable.

- **Post-consumer intermediate producers**

In CS2 the post-consumer intermediate producers are those treating the wastes generated by the previous actor in the value chain (waste producer) through fermentation and anaerobic digestion. The "products" and by-products generated by this actor are the residual sludge (to be incinerated), the biogas, the fermentation supernatant (used by the next actor in the value chain) and the anaerobic digestion supernatant (used for diluting the wastes before the fermentation process).

Similar to the VVREN for the waste, the VVREN of the product is 0% as all the mass of the products is generated from residues.

The circular content of the product was calculated for the residual sludge and the biogas generated in this section of the value chain and are shown in Figure 31 and Figure 32 respectively. These results are coming from the content of waste producers' circular residue in product - PPRESC(P), which is 93.5%, according to the value of the CCF(R) from the previous actor. In fact, the waste managed by this actor in the value chain is mostly sewage sludge, which has a CCF(R) of 99%. Consequently, considering a mass allocation for the CCF(R) of all the wastes produced by the previous actor in the value chain (waste producer) the CCF(P) for the sludge and the biogas result equal to 93.5%.

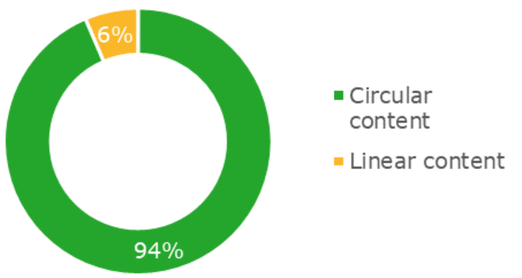


Figure 31. Circular Content of Product (%) for the residual sludge.

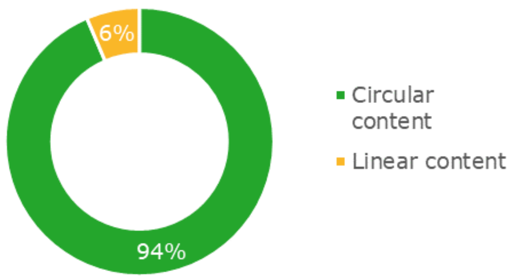


Figure 32. Circular Content of Product (%) for the biogas.

The CCF of post-consumer by-product was calculated for the fermentation and anaerobic digestion supernatants and the results are shown in Figure 33 and Figure 34, respectively.

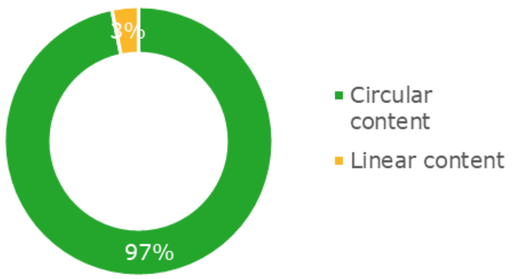


Figure 33. Circularity characterisation factor of post-consumer by-product for the fermentation supernatant.

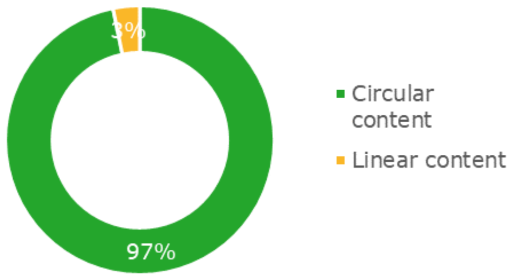


Figure 34. Circularity characterisation factor of post-consumer by-product for the anaerobic digestion supernatant.

The MBUF was calculated in the same way as for the waste producer section, following the mass allocation criteria for the different uses. This indicator resulted in 68.4% of total biomass use.

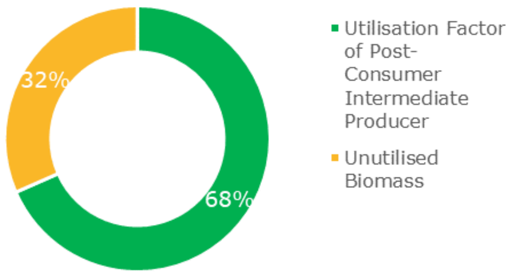


Figure 35. Total biomass utilisation factor.

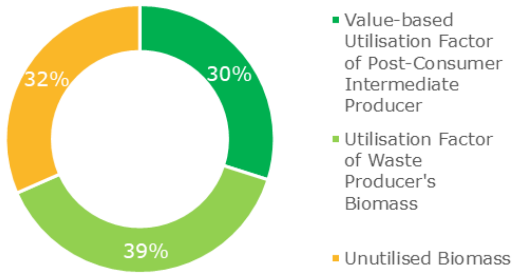


Figure 36. Value-based biomass utilisation factor.

The VMBUF, as explained in the waste producer section, takes into account the biomass value pyramid (D2.3), including a different coefficient for each usage of the biomass. For the post-consumer intermediate producers, the set of coefficients for pre- and post-consumer were combined following a mass allocation. Consequently, since most of the waste (in mass) is represented by sewage sludge, this combination of coefficients resulted basically equal to the post-consumer related coefficients. The result for the Value-based Biomass Utilisation Factor is presented in Figure 36.

Production indicators

Table 19 presents the energy-related production circularity indicators for the intermediate producer. The REC indicator was not calculated because the biorefinery corresponds to a future prospective scenario that has not yet been implemented. As a consequence, the type and share of renewable energy that will be used to operate the process cannot be established at this stage, making the calculation of the REC indicator not meaningful within the current validation. Regarding the EI indicator, it is expressed as the energy consumed per ton of products, including struvite and PHA-rich sludge, with a value of 47980 kWh/ton.

As mentioned for CS1, also in this case it is important to note that the calculation of these indicators is based on pilot-scale operational data, and data at an industrial scale are not publicly available, thereby the calculation and its comparison with the performance industry average is not possible.

Table 19. Circularity indicators related to energy production for the intermediate producer.

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	-	%
Energy Intensity to produce the product (EI)	47,980	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	-	-

Table 20 shows the water-related indicators for the intermediate producer. For the calculation of CWW, the water used for waste dilution before fermentation was considered as total water inflow. Since this water includes the total flow of the anaerobic supernatant (140,793 m^3/y) and a portion of the WWTP effluent (332,526 m^3/y), the water used for diluting the waste before the fermenting unit is also considered as circular inflow. For this reason, CWW reaches a value of 100%. Regarding CWD indicator, there is no water discharged at this stage of the value chain leading to a value of 0%. IWR indicator is 1 m^3/year, as the total volume of water used and consumed equals the overall water inflow from all sources. WI is expressed in m^3 of water per ton of products, including struvite and PHA-rich sludge, and is equal to is 4,056 m^3/ton. EIP, consistent with the other intensity performance indicators, could not be determined due to the lack of available industrial-scale data.

Table 20. Circularity indicators related to water for the intermediate producer.

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	100	%
Circular water discharge for the total production process for the generated product (CWD)	0	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	1	m^3/year

Water Intensity to produce the product (WI)	4056	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	-	-

The results of the chemical-related indicators for the intermediate producer are presented in Table 21. As shown, CPFC indicator equals zero, as no reused, recycled, or bio-based chemicals are used in this stage of the process. PCF/MI indicator measures the chemicals consumed for biogas purification and dewatering, with a value of 2,695 kg per ton of product. PCF/MIP, consistent with the other intensity performance indicators, could not be determined due to the lack of available industrial-scale data.

Table 21. Circularity indicators related to chemical consumption for the intermediate producer.

Process-function material indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	2695	kg/unit
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-

- **Post-consumer final producers**

In CS2 the post-consumer final producers are those using the fermentation supernatant generated by the previous actor in the value chain (post-consumer intermediate producer) as feedstock for the recovery of struvite and PHA-rich sludge, which represent the final products of the value chain.

Similar to the VVRENt for the waste and the post-consumer intermediate products, the virgin renewable content of product is 0%, as all the mass of the products is generated from residues.

The circular content of the product was calculated for the struvite and the PHA-rich sludge, and the results are shown in Figure 37 and Figure 38, respectively. The results are the same for both struvite and PHA-rich sludge and derive from the content of waste producers' circular residue in product - PPRESC(P), which is 97%, according to the value of the $CCF(POB)_n$ of the fermentation supernatant from the previous actor.

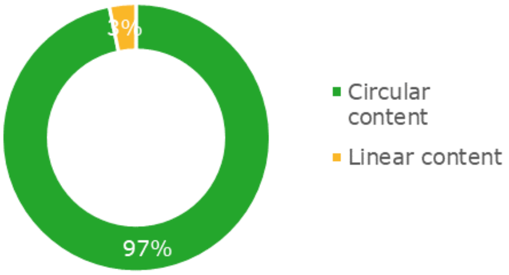


Figure 37. Circular Content of Product (%) for the struvite.

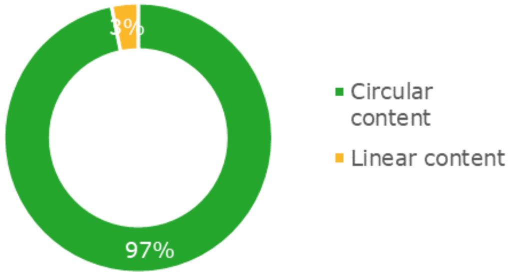


Figure 38. Circular Content of Product (%) for the PHA-rich sludge.

The MBUF was calculated in the same way as for the waste producer and post-consumer intermediate producer sections, following the mass allocation criteria for the different uses. In the case of the post-consumer final producer, the uses were biopolymers (PHA-rich sludge) and biosphere (struvite). This indicator resulted in 25% of total biomass use (Figure 39).

The VMBUF, as explained in the waste producer and post-consumer intermediate producer sections, takes into account the biomass value pyramid (D2.3), including a different coefficient for each usage of the biomass. The set of coefficients used for the post-consumer final producers were the same applied for the post-consumer intermediate producer (pre- and post-consumer coefficients combined following a mass allocation). The result of the Value-based Biomass Utilisation Factor is presented in Figure 40.

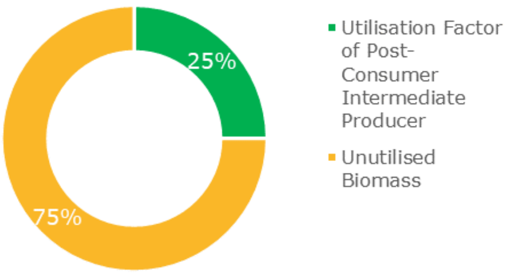


Figure 39. Total biomass utilisation factor.

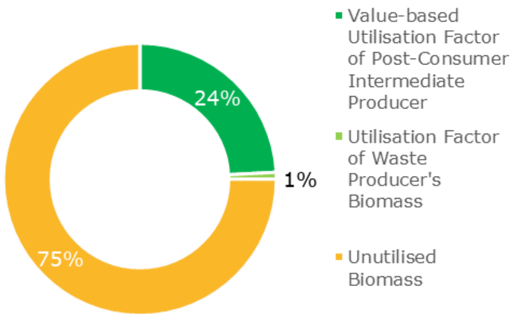


Figure 40. Value-based biomass utilisation factor.

Additionally, as this is the final step of the value chain, the product/by-product that will be utilised as input by the next actor as a percentage of the total received input and the value-added of the product/by-product that will be utilised by the next actor as a percentage of the total received input were also calculated for the struvite (Figure 41) and the PHA-rich sludge (Figure 42). For the PHA-rich sludge, the percentage of the product utilised by the next author as value-added is approximately 0.1 %.

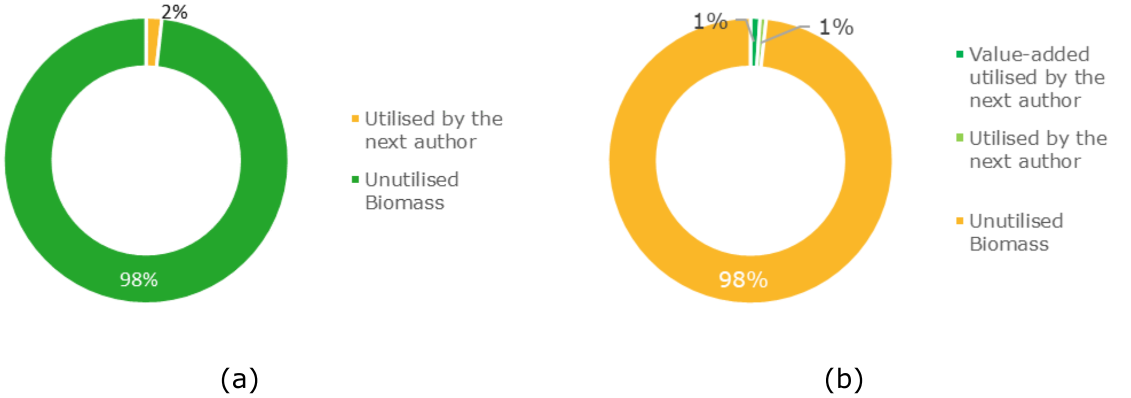


Figure 41. Struvite that will be utilised as input by the next actor as a percentage of the total received input.
In total mass (a) and as value-added (b).

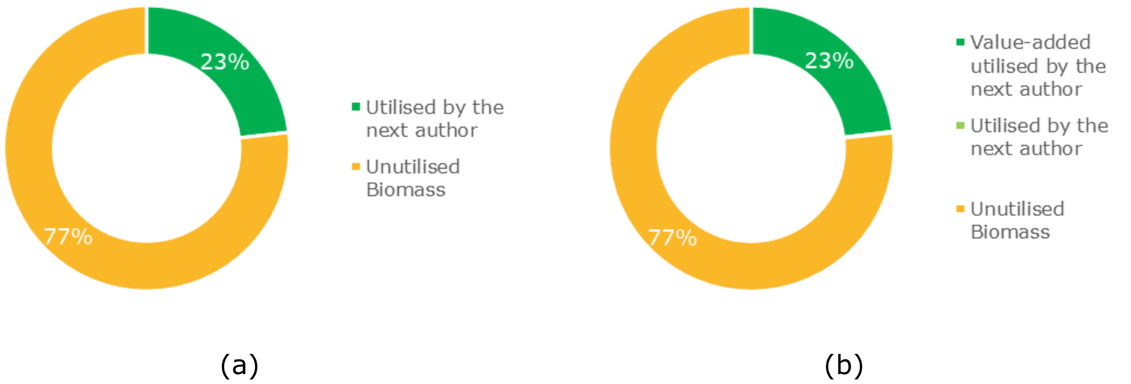


Figure 42. PHA-rich sludge that will be utilised as input by the next actor as a percentage of the total received input.
In total mass (a) and as value-added (b).

Production indicators

Energy-related indicators have also been calculated for the final producer (Table 22). Similarly to the previous actor, the REC indicator was not calculated for the final producer because the biorefinery corresponds to a future prospective scenario that has not yet been implemented. As a consequence, the type and share of renewable energy that will be used to operate the process cannot be established at this stage, making the calculation of the REC indicator not meaningful within the current validation. EI indicator is expressed as kWh consumed per ton of products, including struvite and PHA-rich sludge. Moreover, since only pilot-scale operational data are available, comparison with industry-average energy performance is not feasible.

Table 22. Circularity indicators related to energy for the final producer.

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	-	%
Energy Intensity to produce the product (EI)	1469	kWh/unit
Energy Intensity performance in comparison to industry average (EIP)	-	-

The water-related indicators are shown in Table 23. For the final producer, the volume of water inflow is the fermentation supernatant, coming from the previous actor, also considered as circular (CWW). However, CWD value is zero, as the discharged water is not regarded as circular, since the generated effluents are returned to the WWTP. IWR indicator is 1 m3/year, as the total volume of water used and consumed equals the overall water inflow from all sources. WI is expressed as m^3 per ton of product.

Table 23. Circularity indicators related to water for the final producer.

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	100	%
Circular water discharge for the total production process for the generated product (CWD)	0	m^3/year
Internal water recirculation or reuse in the total production process of the product (IWR)	1	m^3/year
Water Intensity to produce the product (WI)	718	m^3/unit
Water Intensity performance in comparison to industry average (WIP)	-	-

Finally, chemical-related indicators were also assessed for the final producer and are presented in Table 24. Similarly to the previous actor, CPFC indicator equals zero, as no reused, recycled, or bio-based chemicals are used in this stage of the process. The PCF/MIP indicator is likewise expressed per ton of product, whereas the PCF/MIF indicator could not be determined due to the unavailability of industrial-scale data required for its calculation.

Table 24. Circularity indicators related to chemical consumption for the final producer.

Chemical consumption related indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%

Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	1177	kg/unit
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-

Final considerations

When evaluating the CS2 value chain, certain hotspots in circularity performance become evident. One major bottleneck is the reliance on incineration for residual sludge, which reduces the VMBUF across the chain. While 65 – 68.4% of total biomass is utilised, the value-based utilisation is lower (as low as 13.5 – 27% depending on waste type), reflecting the low valorisation potential of incineration compared to recovery routes like bioplastics or fine chemicals.

Exploring alternative applications for digested sludge could enhance circularity indicators. One promising route is its use in the production of construction materials such as bricks or ceramics. The incorporation of sludge into clay-based products can immobilise contaminants and reduce the need for virgin raw materials. Another emerging option is pyrolysis, which can convert digested sludge into biochar, syngas, or oil. Biochar can be used as a soil amendment or for carbon sequestration, offering a higher-value circular outlet than incineration. Implementing these pathways could increase value-based biomass utilisation and support new forms of resource recovery.

The struvite and PHA-rich sludge generated in the final step show high circular content and are promising feedstocks for external actors (such as fertiliser and bioplastics manufacturers) who could integrate these inputs to improve the circularity of their own production lines.

2.1.3 Case Study 3: Central Macedonia, Greece

The Greek case study focuses on agricultural waste and its associated by-product streams. For the calculation of circularity indicators, two value chains are considered: the production of biofertilizer (compost) using wheat straw, peach tree prunings, and peach pulp, and the production of particle boards using wheat straw. Both value chains have been described in detail, both qualitatively and quantitatively, in Deliverables D6.1 and D2.4.

The qualitative validation of the BioReCer framework has been conducted by addressing a structured questionnaire to the biofertilizer and particle board companies. Each company was assessed against the full set of the 29 basic and 23 advanced requirements of the BioReCer framework. The biofertilizer company demonstrated compliance with 25 criteria considered applicable, while 4 basic requirements were identified as outside the scope of its operational context. Similarly, the particle board manufacturer fulfilled 26 basic requirements, with 3 being considered as non-applicable. Therefore, in both cases, the organizations showed a sufficient score in terms of compliance with the BioReCer framework as demonstrated in Figure 43 and Figure 44 for the biofertilizer and particle board production respectively.

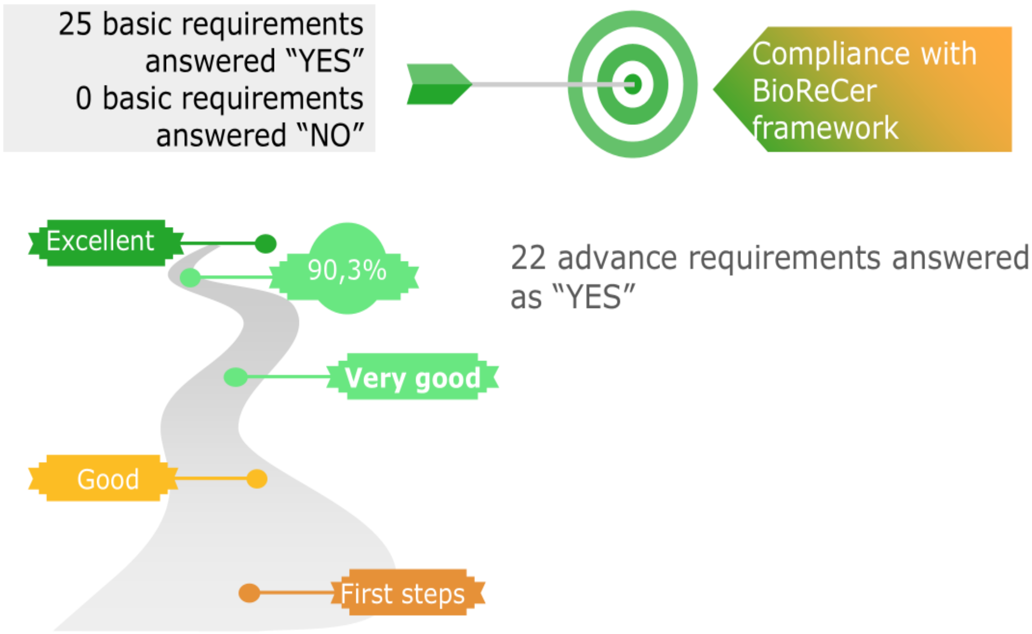


Figure 43. Analysis of requirements in CS3 – Biofertilizers.

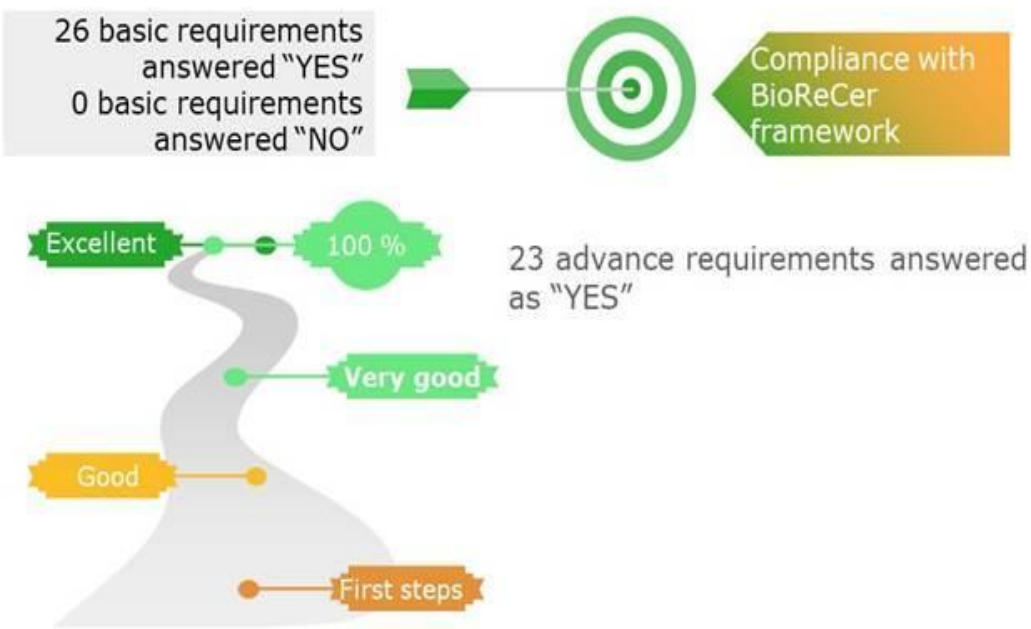


Figure 44. Analysis of requirements in CS3 – Particle Boards.

Additionally, of the 23 advanced requirements, the biofertilizer production company complies with 22 and the particle board industry with 23. To complement the assessment, an explanatory table is created for each company (Table 25 and Table 26), providing clarifications on requirements that were either not applicable or not fulfilled.

Table 25. Requirements that are not applicable in CS3 – biofertilizers company.

Non applicable requirement	Comment
The company characterizes the introduced genetically modified species	This requirement is not applicable because the company does not introduce or work with any genetically modified species in its composting process. The raw materials are ordinary agricultural byproducts already present in the supply chain.
The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	The composting activity does not release any new species or pathogens into the natural environment, as the process occurs in a controlled facility. Therefore, monitoring invasive or harmful species is unnecessary.
The company considers the resilience of the ecosystem to ensure sustainability	The company's operations do not modify or interact directly with natural ecosystems, so measuring the resilience of surrounding habitats is not relevant. The process only transforms existing organic residues without altering environmental balances.
The company identifies whether action has been addressed to ensure food security in biomass production systems	This requirement is not applicable because the company does not manage or operate biomass production systems, but only processes existing agricultural byproducts such as straw and pomace. Since it does not influence crop production or food supply chains, no specific actions related to ensuring food security are required.

Table 26. Requirements that are not applicable in CS3 – particle board company.

Non applicable requirement	Comment
The company characterizes the introduced genetically modified (GM) species	Such operations do not involve the introduction of genetically modified species—activities where this is relevant include agriculture, aquaculture, laboratory biotechnology, and import/export of GM organisms
The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	Such operations do not introduce non-indigenous species or pathogens into the ecosystem—activities where this is relevant include agriculture, aquaculture, import/export of live organisms, and biotechnology
The company identifies whether action has been addressed to ensure food security in biomass production systems	This requirement is not applicable because the company does not manage or operate biomass production systems, but only processes existing agricultural byproducts such as straw. Since it does not influence crop production or food supply chains, no specific actions related to ensuring food security are required.

2.1.3.1 Biofertilizer production

As it can be observed in the simplified flow diagram presented in Figure 45 of the biofertilizer value chain, the main actors are the wheat grain producer and the peaches producer (cultivation and harvesting stage), the peach canning industry (peach processing) and the biofertilizer industry (biofertilizer production). For the calculation of the circularity indicators, a detailed flow diagram (Figure 46) is generated (based on the diagrams provided in Deliverables D6.1 and D2.4) which shows the inputs, outputs, and flows throughout the value chain, as well as the position of each actor within it.

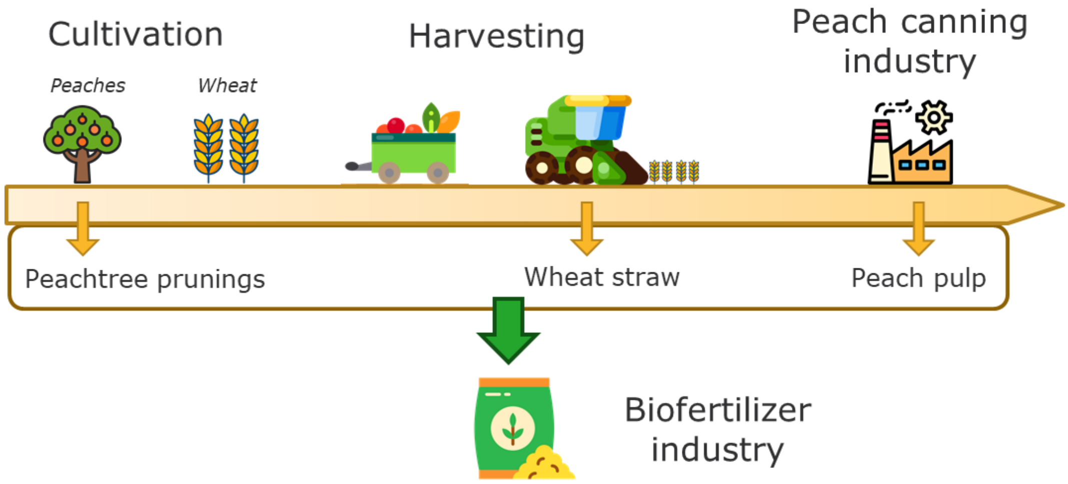


Figure 45. Schematic representation of the CS3 value chain (Biofertilizer production)

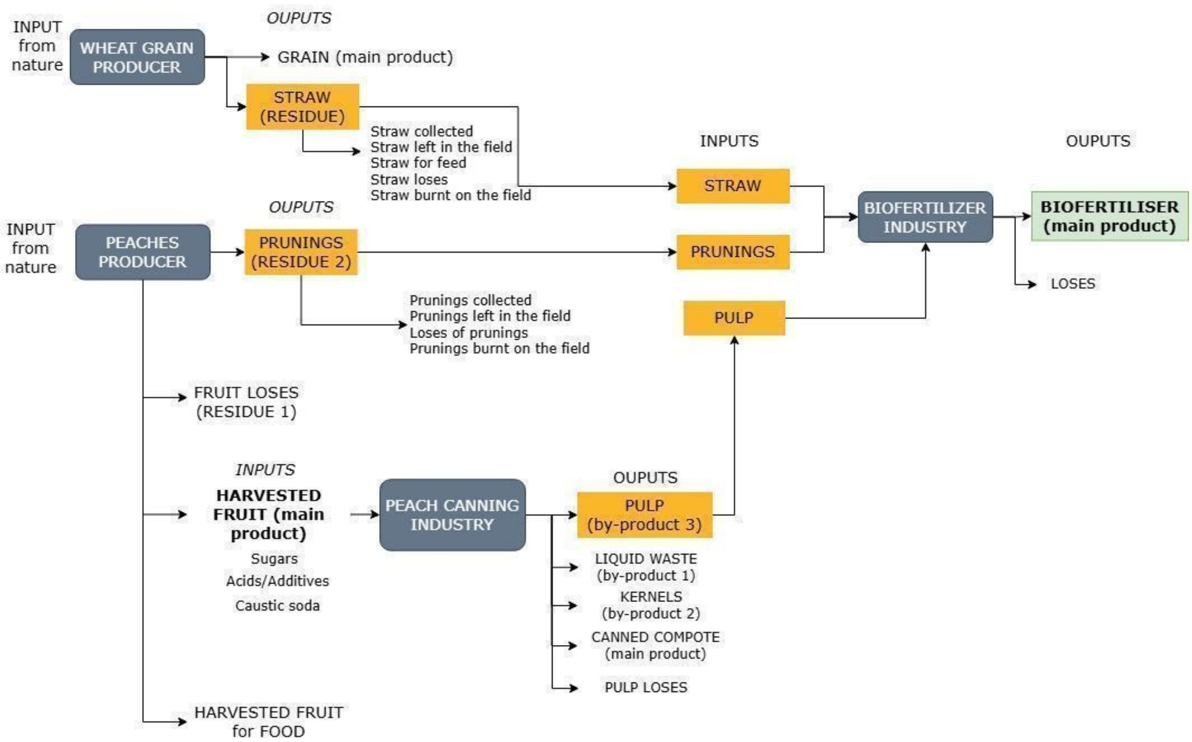


Figure 46. Detail flow diagram of the biofertilizer value chain.

The biofertilizer value chain in the Region of Central Macedonia (Greece) includes two primary producers, one intermediate pre-consumer producer, and one final producer. The first primary producer is the wheat grain producer, who generates wheat as the main bio-based product and straw as a co-product. The second primary producer is the peaches producer, who produces peaches as the main product, with prunings as co-products. For both producers, outputs originate directly from natural capital rather than processed inputs and the distinction between biological and fossil-based feedstocks is not applicable. The intermediate producer, the peach canning industry, produces peach compote as the main product, with peach pulp and kernels as residues; in this case, additional inputs such as sugars, citric acid, and additives are used. Finally, the final producer, the biofertilizer facility, produces biofertilizer (compost) as the main product, with no other co-products or additional feedstocks, either biological or fossil based.

For the quantification and characterization of flows, the input/output tables presented in Deliverables D6.1 and D2.4 were considered. However, based on more recent and reliable data from the case study's field experts, the following scenarios were applied: for wheat straw, 45% remains on the field, 45% is recovered, and 10% is burnt as it is considered unsuitable for use; of the recovered portion, 10% is utilized in the biofertilizer value chain, while the remaining 90% is employed in husbandry. For peach prunings, 20% is either burnt or lost during shredding or transportation, 45% remains on the field, and the recovered fraction is allocated to energy, material, and biofertilizer applications.

For all actors, the circularity indicators were calculated using the equations described in D2.3 and assigned to each actor according to D2.5. However, in addition to the data provided in D2.4, it was considered necessary to acquire data on sustainably renewable production. For wheat, data on organic farming production were obtained from the Hellenic Statistical Authority and the Greek Ministry of Rural Development and Food for the year 2022, and a Sustainable Removal Rate (SSR) of 40% was applied (White & Oldfield, 2016), based on literature values for similar crops in Greece due to the lack of local data. Similarly, for peaches, data on organic production and an SSR of 40% were used, following the same sources and assumptions. The indicators selected for prunings were analogous to those applied for straw.

- **Wheat grain producer (primary producer)**

The wheat grain producer cultivates wheat and during the harvesting period except for the main product, they produce wheat straw as a by-product, which can be valorised by the biofertilizer industry. For the production of 100 kg^{DM} of biofertilizer, 24.5 kg^{DM} of straw are needed which are produced from the cultivation of 0.20 ha of land.

Figure 47 shows the VVREN of wheat grains, which is attributed to agricultural holdings, which are fully organic. The organic farming levels of wheat in the Region of Central Macedonia (RCM) are low (2.4%), because there is no interest in organic wheat by the Greek market. Farmers which apply such practices for environmental or economic reasons, sell wheat as conventional. The VVREN of wheat grains could increase if certified agricultural crops (with Agro 2.1/2.2 and GLOBAL G.A.P) were taken into account. However, this kind of data is not publicly available. If VVREN was calculated by a wheat grain producer with certified agricultural crops, this indicator would significantly increase.

Concerning straw, the CCFr of residue is 57% (Figure 48), while the remaining percentage is considered noncircular. The factors affecting this indicator are the sustainable renewable production of wheat, the distinction between unavoidable and avoidable residue generation, and the sustainable removal rate of residues from the field.

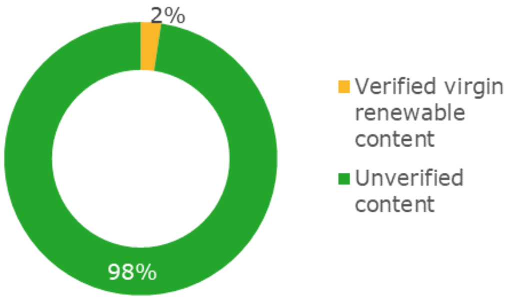


Figure 47. Verified virgin renewable content of wheat grains

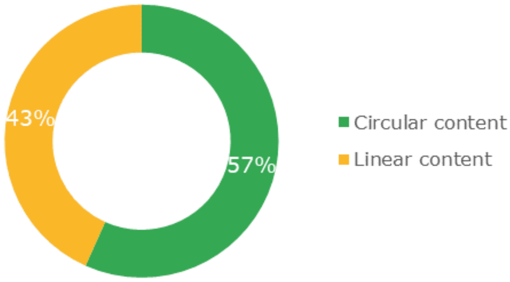


Figure 48. Circular content of straw

As shown in Figure 49 (a), for the total produced biomass, the utilisation factor is 93%, while the remaining 7% consists of unutilized biomass, which is usually burnt or lost during pre-treatment and transportation to the next actor. However, the value-based utilisation factor is slightly lower than the utilization factor – i.e. 87% - since it takes into account the weighted value of the biomass various fates [Figure 49 (b)]. For example, the biomass fraction that is not utilised carries no value.

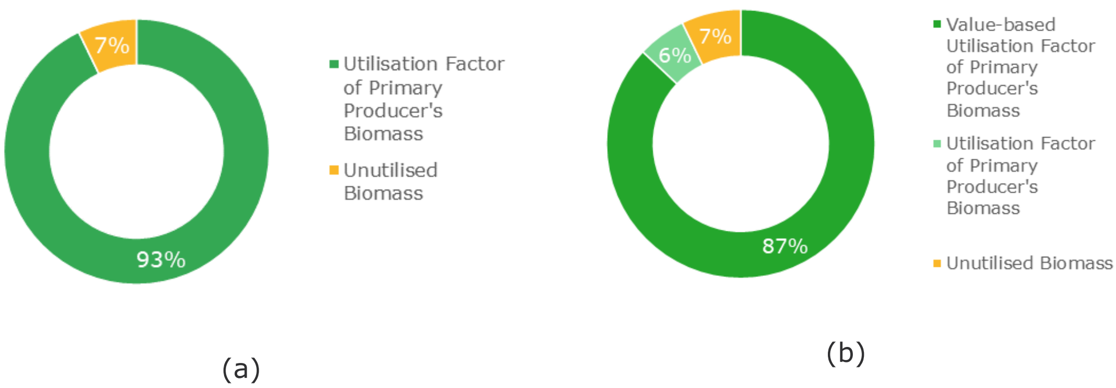


Figure 49. (a) Utilisation Factor and (b) Value-based Utilisation Factor of Wheat Grain Producer's Biomass

Production indicators

Production indicators concerning energy, water and chemicals consumption have been estimated for wheat grain production, based on data given in D2.4. A fraction of the straw generated as by-product in the wheat cultivation stage is used as feedstock both for the biofertilizer and particle board end-products. The calculation of the production indicators of wheat grain production are presented in the context of the biofertilizer value chain, but it is highlighted that the results apply to the particle board value chain as well. The estimation of production indicators has been performed considering land surface (ha) as production unit to facilitate the transferability and comparability of results between the two value chains.

The energy-related circularity indicators for wheat grain producer are presented in Table 27. In this process, the energy source used is diesel fuel. According to the Fuel Quality Directive, up to 7 % of this diesel is fatty acid methyl ester (FAME), i.e. biodiesel, which constitutes a renewable energy component. The average energy intensity for wheat production is reported at 4.47 GJ/ha, based on a critical literature review for EU agriculture (Paris et al., 2022).

Table 27. Circularity indicators related to energy for the primary wheat grain producer

Energy-related indicator	Value	Unit
Renewable energy for production process (REC)	7.03	%
Energy Intensity to produce the product (EI)	1961	kWh/ha
Energy Intensity performance in comparison to industry average (EIP)	1.6	-

Water-related indicators have been estimated for the wheat producer and the results are presented in Table 28. The data used for calculating the indicators were derived from literature sources, as described in Deliverable 2.4. However, the water requirements for wheat cultivation may vary, as they strongly depend on the climatic conditions, soil characteristics, and crop management practices of each region. No reliable value for the average water demand of this crop was identified. As a result, the Water Intensity Performance (WIP) relative to the industry-average could not be calculated. Finally, for the calculation of the Circular Water Discharge for the total production process of the generated product (CWD), it was assumed that 20% of the irrigation water infiltrates and percolates back into the subsurface, contributing to groundwater recharge. This value is considered a reasonable and conservative estimate for the region of Central Macedonia.

Table 28. Circularity indicators related to water for the primary wheat grain producer

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	0	%
Circular water discharge for the total production process for the generated product (CWD)	20	%
Internal water recirculation or reuse in the total production process of the product (IWR)	1	-
Water Intensity to produce the product (WI)	0.9	m^3/ha
Water Intensity Performance in comparison to industry average (WIP)	-	-

Additionally, the process-function materials indicators are estimated for the primary wheat grain producer (Table 29). The raw materials required for wheat cultivation include fertilizers, herbicides, fungicides and lubricants. These raw materials are not considered circular. The average sector intensity in terms of raw materials consumption is reported at 218 kg/ha as derived from the FAO report on "Energy and Agriculture Nexus".

Table 29. Circularity indicators related to material consumption for the primary wheat grain producer

Process-function materials indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	227.4	kg/ha
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	1.04	-

- **Peaches producer (primary producer)**

The peaches producer cultivates peaches. During cultivation, prunings are produced, which consist mainly of woody biomass, such as branches, twigs and shoots. Pruning involves removing dead, diseased, or broken parts to prevent further damage or decay of the tree. During harvesting, peaches are produced, which in RCM are mainly directed to the food industry (80%) and to a lesser extent to direct consumption (20%). For the production of 100 kg^{DM} of biofertilizer, 15 kg^{DM} of prunings are needed.

Figure 50 shows the VVREN of peaches, which is attributed to agricultural holdings, which are fully organic. The percentage of organic farming is low (0.1%) because peach crops in RCM are mainly intended for industrial use where there is no interest in organic products. This indicator could increase if certified agricultural crops (with Agro 2.1/2.2 and GLOBAL G.A.P) were taken into account. However, this kind of data is not publicly available. If VVREN was calculated by a peaches producer with certified agricultural crops, this indicator would significantly increase.

Concerning tree prunings, the circularity characterisation factor of residue is 55% (Figure 51), while the remaining percentage is considered noncircular. The factors affecting this indicator are the sustainable renewable production of wheat, the distinction between unavoidable and avoidable residue generation, and the sustainable removal rate of residues from the field.

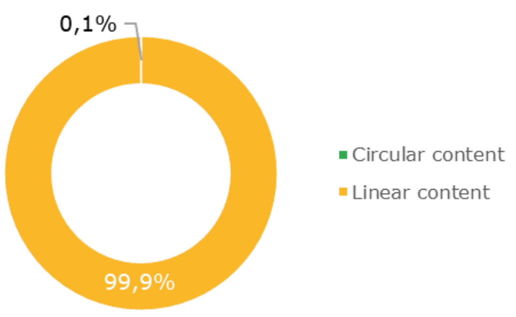


Figure 50. Verified virgin renewable content of peaches

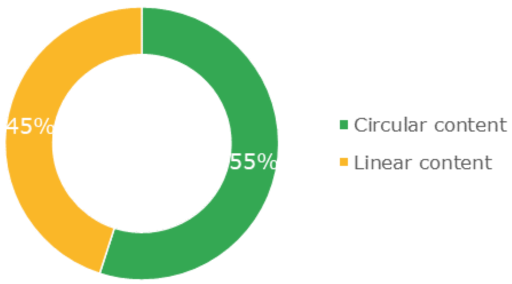


Figure 51. Circular content of prunings

As shown in Figure 52(a) for the total produced biomass the utilisation factor is 84%, while the 16% is unutilized biomass which is usually burnt or lost during pre-treatment and transportation to the next actor. The value-based utilisation factor is slightly lower than the utilization factor – i.e. 69% - since it takes into account the weighted value of the biomass various fates which is based on the bio-based value pyramid [Figure 52(b)]. For example, the biomass fraction that is not utilised carries no value.

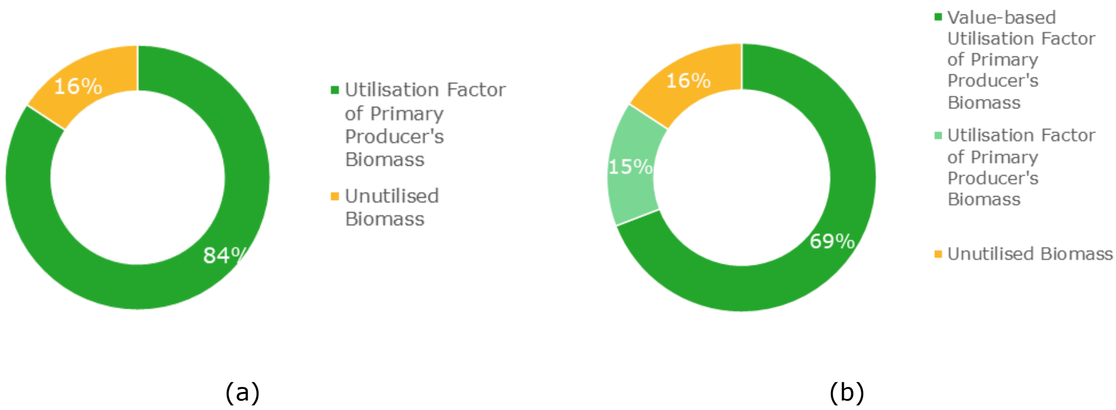


Figure 52. (a) Utilisation Factor and (b) Value-based Utilisation Factor of Peaches Producer's Biomass

Production indicators

Production indicators concerning energy, water and chemical consumption have been estimated for the primary peach producer. Part of the tree prunings derived from peach cultivation are used as feedstock for the biofertilizer end-product. Additionally, peaches are supplied to the intermediate compote producing facility, which generates peach pomace as a by-product that constitutes also a feedstock for biofertilizer production. The estimation of production indicators has been carried out using land surface area (ha) as production unit. It is highlighted that for peach production, it was not possible to obtain credible data for benchmarking the average intensity of peach cultivation process in terms of energy, water and chemicals consumption, rendering the estimation of corresponding indicators (EIP, WIP, PFC/MIP) unfeasible.

The energy-related circularity indicators for primary peach producer are presented in Table 30. For peach cultivation, both electricity and diesel fuel are required. According to the Greek Ministry of Environment and Energy, 43.8% of the national electricity generation mix came from renewable energy sources in 2023 (IENE, 2024). Moreover, as previously mentioned, 7 % of the fuel blend comes from biodiesel.

Table 30. Circularity production indicators related to energy for the primary peach producer

Energy-related indicators	Value	Unit
Renewable energy for production process (REC)	11.98	%
Energy Intensity to produce the product (EI)	2831	kWh/ha
Energy Intensity performance in comparison to industry average (EIP)	-	-

Water-related indicators have been estimated for the peach producer with the results presented in Table 31. As in the case of straw cultivation, it is assumed that 20 % of the irrigation water infiltrates and percolates into the subsurface, thereby contributing to groundwater recharge.

Table 31. Circularity production indicators related to water for the primary peach producer

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	0	%
Circular water discharge for the total production process for the generated product (CWD)	20	%
Internal water recirculation or reuse in the total production process of the product (IWR)	1	-
Water Intensity to produce the product (WI)	1211	m^3/ha
Water Intensity performance in comparison to industry average (WIP)	-	-

Process-function materials indicators are calculated for the primary peach producer (Table 32). The raw materials consumed at the peach cultivation stage include fertilizers and pesticides. These raw materials are not considered as circular while information regarding the average material consumption intensity tailored for peach cultivation cannot be retrieved.

Table 32. Circularity indicators related to material consumption for the primary peach producer

Process-function materials indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	316	kg/ha
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-

- **Peach canning industry (intermediate producer)**

The peaches produced by the peaches producer are transported to the peach canning industry for the production of peach compote. During peach processing, peach pulp and peach kernels are produced as by-products. Peach pulp consists mainly of peels and inappropriate fruit. To produce 100 kg^{DM} of biofertilizer, 76 kg^{DM} of peach pulp are needed.

Figure 53 shows the circular content of peach compote, which is attributed to the peaches which come from agricultural holdings, which are fully organic. As in the case of tree prunings and straw, this indicator is considered rather low (0.05%), but it could increase if certified agricultural crops (with Agro 2.1/2.2 and GLOBAL G.A.P) were taken into account.

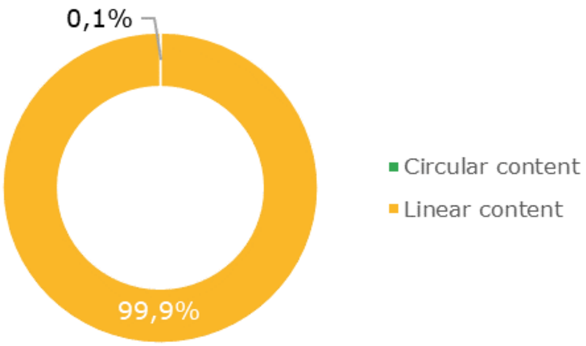


Figure 53. Circular content of peach compote

Figure 54 shows the production efficiency (a) and the value-based production efficiency (b) of the peach canning industry, which utilizes almost all the quantity of peaches and by-products (94%), while only 6% of the biomass remains unutilized due to losses. The value-based production efficiency is less than half lower than the utilization factor – i.e. 42% - since it takes into account the weighted value of the biomass various fates. For example, a significant amount of peach pulp and kernels is utilized for fuel and heat production, respectively.

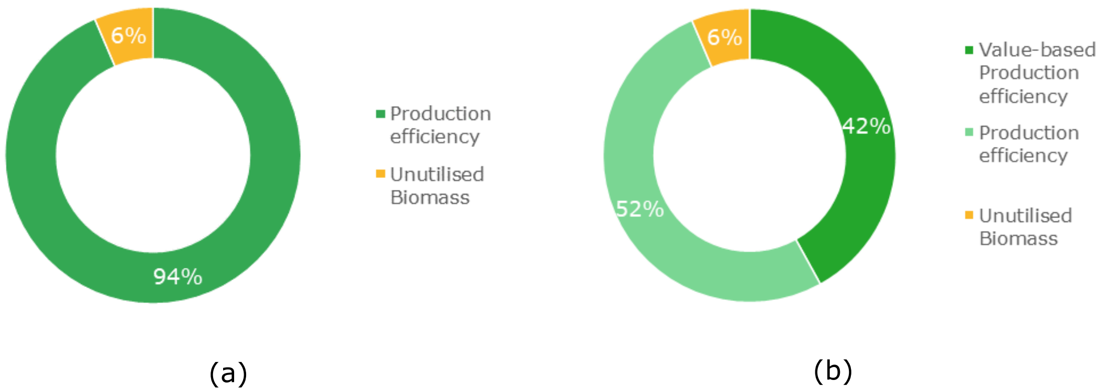
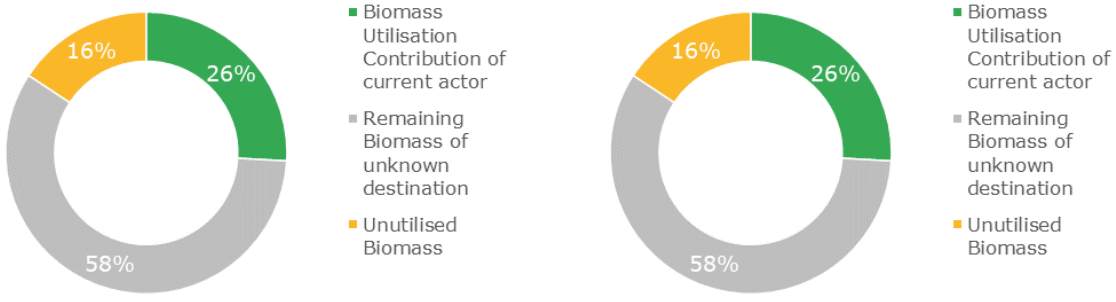


Figure 54. (a) Production efficiency and (b) Value-based Production efficiency of peach canning industry

Figure 55 shows the peach producer's (a) Biomass Utilisation Contribution and (b) Value-based Utilisation Contribution to the peach canning industry. The Biomass Utilisation Contribution is 26% from which and Value-based Utilisation Contribution is 12%. The remaining biomass of unknown destination, produced by the peach producer, is 58% while the unutilized biomass is 16%. The remaining biomass consists of the quantity of peaches and prunings which do not enter the fruit processing industry.



(a) (b)

Figure 55. Peach producer's (a) Biomass Utilisation Contribution and (b) Value-based Utilisation Contribution to peach canning industry

The residues produced by the peach canning industry are peach pulp consisting mainly of peels and inappropriate fruit and peach kernels. Figure 56 shows the circularity characterisation factor of peach pulp, which is 48%, while Figure 57 shows the circular content of peach kernels which is 48%. The main contribution to this indicator is the fact that these residues are considered as 90% unavoidable

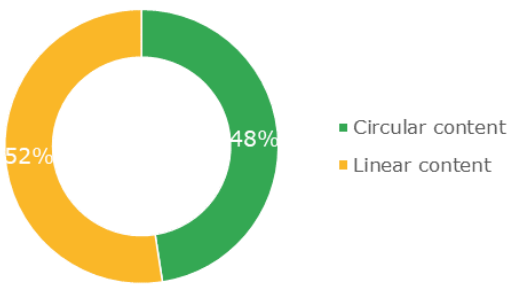


Figure 56. Circular content of peach pulp

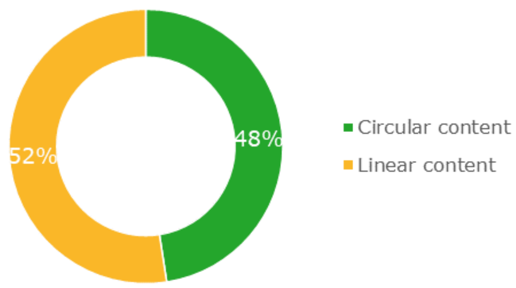


Figure 57. Circular content of peach kernels

Production indicators

Energy-related indicators have been calculated for the intermediate peach canning industry with the results being presented in Table 33. The production unit considered is 1 kg of final peach compote product in wet mass. In the peach canning industry, electricity is used to operate the mechanical equipment, while fuel is used to meet the heating and pasteurization requirements. In Greece, as previously mentioned, 43.8 % of the national electricity generation mix in 2023 was derived from renewable energy sources. For heating fuel, however, it is assumed that no portion comes from renewable sources, as there is currently no legislation mandating renewable content for this type of fuel. Furthermore, a small fraction of the peach pulp produced is sent to anaerobic digestion and peach kernels could be sold as fuel while there is no outflow of energy from the production site. The average energy intensity of peach compote industries is difficult to be defined due to the large variability of data reported in literature. As a result, the estimation of EIP indicator could not be sufficiently representative and reliable.

Table 33. Circularity indicators related to energy for the intermediate peach compote producer

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	3.81	%
Energy Intensity to produce the product (EI)	0.454	kWh/kg (WM) canned compote
Energy Intensity performance in comparison to industry average (EIP)	-	-

The results of the water-related indicators are demonstrated in Table 34, considering 1 kg of final peach compote product in wet mass as production unit. The wastewater produced from the peach compote production process is subjected to wastewater treatment. The wastewater outflow is sufficiently treated in order to be safely discharged to the environment and therefore it can be categorized as "water discharges considered as circular". The average water intensity for this type of industry is reported equal to 0.0069 m^3/kg (UNIDO, 2024).

Table 34. Circularity indicators related to water for the intermediate peach compote producer

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	0	%
Circular water discharge for the total production process for the generated product (CWD)	95.48	%
Internal water recirculation or reuse in the total production process of the product (IWR)	1.00	-
Water Intensity to produce the product (WI)	0.017	m^3/kg (WM) canned compote
Water Intensity performance in comparison to industry average (WIP)	2.41	-

The process-function materials indicators are calculated for the intermediate compote producer (Table 35). Also in this case, the production unit is 1 kg of final peach compote product in wet mass. The raw materials consumed during the production process include sugar, glucose, caustic soda, tinplate cans and paper boxes. The benchmark material requirements are retrieved from Drosou et al, 2023, which report a range of 0.15-0.35 kg raw materials (excluding fruits)/kg canned compote.

Table 35. Circularity indicators related to material consumption for the intermediate peach compote producer

Process-function materials indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	0.201	kg/kg (WM) canned compote
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	1	-

- **Biofertilizer industry (final producer)**

Wheat straw, peach tree prunings and peach pulp are transported to the biofertilizer industry to produce 100kg^{DM} of compost. Figure 58 shows the circular content of biofertilizers which is 50%. This indicator is the sum of the following indicators: reused content of product [REUC(P)], virgin renewable content of product [VRENC(P)], primary producers' residue content of product [PPRESC(P)], pre-consumer recycled content of product [PRRECBBC(P)] and post-consumer recycled content of product [PORECC(P)].

Figure 59. Primary producers' residue content and pre-consumer recycled content of biofertilizer shows the content in the final product, i.e. the biofertilizer: 19% is the primary producers' circular residue, 31% is the pre-consumer recycled content coming from the peach canning industry, while 50% is linear.

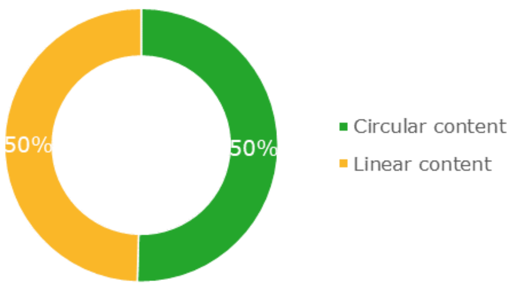


Figure 58. Circular content of biofertilizers

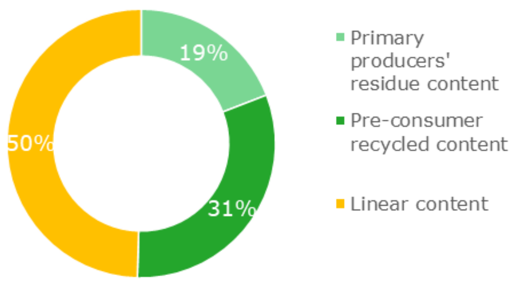
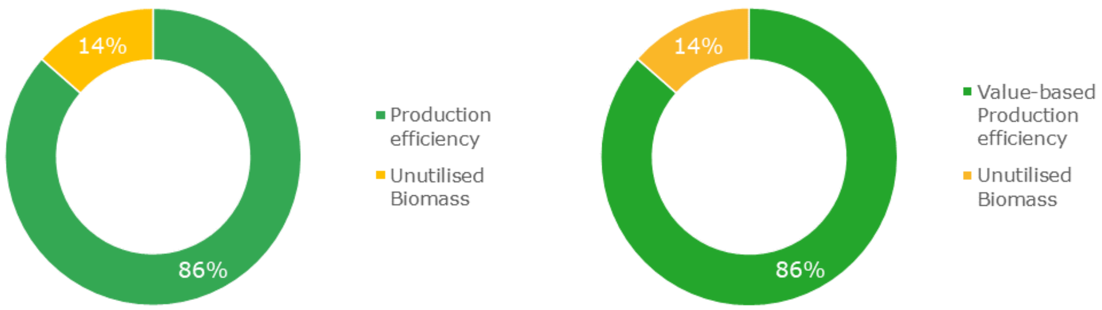


Figure 59. Primary producers' residue content and pre-consumer recycled content of biofertilizer

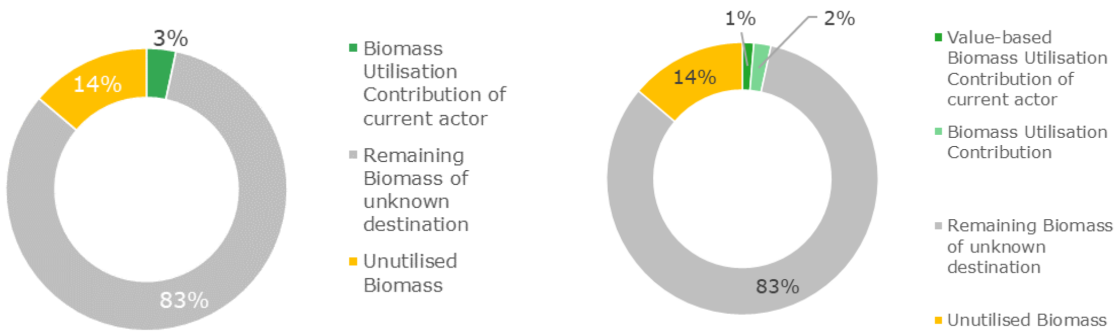
Figure 60 shows the production efficiency and the value-based production efficiency of the biofertilizers industry. Both of them are 86% because the facility utilizes almost all the quantity of feedstocks, while only 14% of the biomass remains unutilized due to losses.



(a) (b)

Figure 60. (a) Production efficiency and (b) Value-based Production efficiency of the biofertilizers industry

Figure 61 shows the biomass utilisation contribution of primary producers to the final product, which is 3%, while the value-based utilisation contribution is 1%. The remaining biomass of unknown destination is 83%, while the unutilised biomass is 14%.



(a) (b)

Figure 61. (a) Biomass Utilisation Contribution and (b) Value-based Utilisation Contribution of the biofertilizers industry

Production indicators

Energy-related circularity indicators have been calculated for the biofertilizer production process (Table 36) considering 1 kg (DM) biofertilizer as final product. In this case both electricity and diesel fuel are required. As already mentioned, 43.8% of the national electricity generation mix came from renewable energy sources in 2023[AK1], while 7 % of the fuel blend comes from biodiesel (IENE, 2024). The average energy intensity for windrow composting (open system) has been reported at 29 kWh/tonne waste (Waste Control, n.d.).

Table 36. Circularity indicators related to energy for the biofertilizer final producer

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	33.61	%
Energy Intensity to produce the product (EI)	0.064	kWh/kg (DM) biofertilizer
Energy Intensity performance in comparison to industry average (EIP)	0.807	-

Water-related indicators are not applicable for the case of biofertilizer production as the manufacturing process does not require the addition of water at any stage. Water is utilized only for indirect and auxiliary purposes, such as equipment cleaning and general facility hygiene and therefore were excluded from the analysis. The raw materials consumed in this process include the polyethylene films used for product packaging. As there were no available data for raw material consumption that could be representative of the industry, the PFC/MIP indicator has not been estimated.

Table 37. Process-function materials indicators for biofertilizer final producer

Process-function materials indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	0.004	kg/kg (DM) biofertilizer
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	-	-

2.1.3.2 Production of particle boards

As it can be observed in the simplified flow diagram presented in Figure 62 of the particle boards value chain, the main actors are the wheat grain producer (cultivation and harvesting stage) and the particle board industry (particle board production). For the validation of this value chain the use phase and end of life (EoL) steps have also been added. Furthermore, with the help of the flow diagrams outlined in deliverables D6.1 and D2.4, a detailed flow diagram (Figure 63) is generated, which indicates the inputs, outputs and flows throughout the value chain as well as the position of each actor in it.

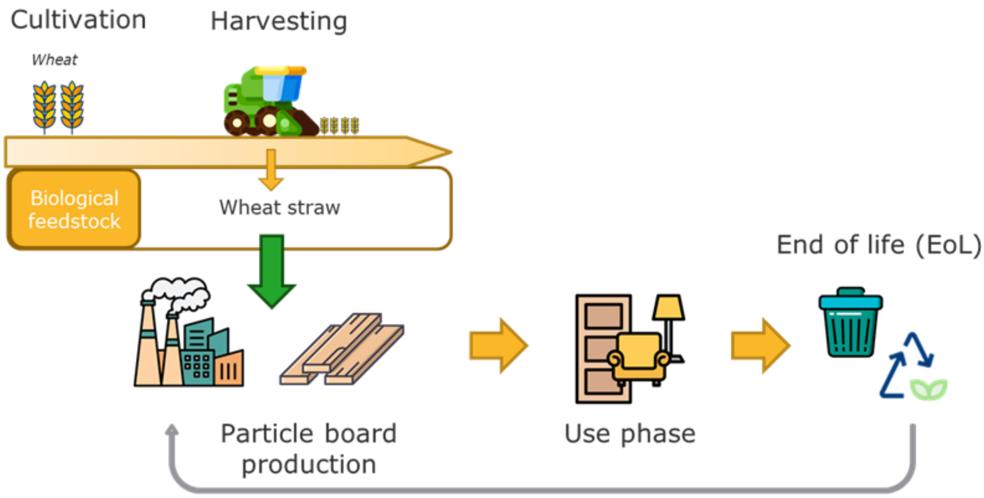


Figure 62. Schematic representation of the CS3 value chain (production of particle boards)

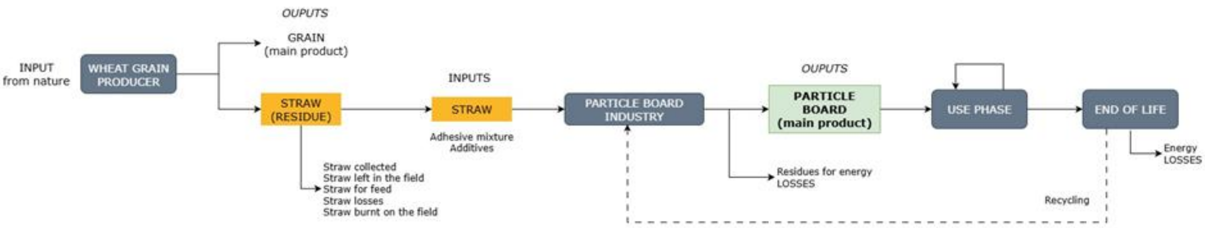


Figure 63. Detail flow diagram of the particle boards value chain

For the particle board value chain, flow quantification and characterization were based on the input/output tables in Deliverables D6.1 and D2.4, with adjustments made according to data provided by case study field experts. Wheat straw serves as the main bio-based feedstock, with 45% left on the field, 45% recovered, and 10% burnt due to unsuitability for use. Of the recovered straw, 10% is directed to particle board production, while the remaining 90% is used in husbandry. Particle boards are produced using the recovered straw along with adhesive mixtures and additives and are sold in cubic meters, with a density of 650 kg/m³ and a moisture content of 6.5%. Circularity indicators, as indicated in Deliverable D2.5, were calculated using the equations described therein and in D2.3. For the calculation of circularity indicators, the sustainably renewable production and the SSR of wheat straw were aligned with literature values and organic farming practices in Central Macedonia, with SSR set at 40%. Given that particle boards are durable products, their circularity assessment incorporates material circularity indicators, as well as use-phase and end-of-life (EoL) circularity indicators.

- **Wheat grain producer (primary producer)**

The straw produced as a by-product from the wheat grain producer can be also valorised by the particle board industry. For the production of $1m^3$ (moisture content equal to 6.5%) of finished uncoated particle board 639 kg^{DM} of straw are needed, which are produced from the cultivation of 5.1 ha of land. The wheat grain producer is considered a primary producer, and the answers to steps 1–4 for calculating the circularity indicator, as described in Figure 1, are identical to those for the biofertilizer producer.

Figure 64 shows (a) the Verified virgin renewable product [VVREN(P)] for grains, (b) the circularity characterisation factor [CCF(R)] of straw, (c) the modified biomass utilisation factor of primary producers [MBUF0] for total biomass and (d) the value-based biomass utilisation factor [VMBUF0] following the bio-based value for total biomass. As it can be seen the results are the same as in the biofertilizers value-chain.

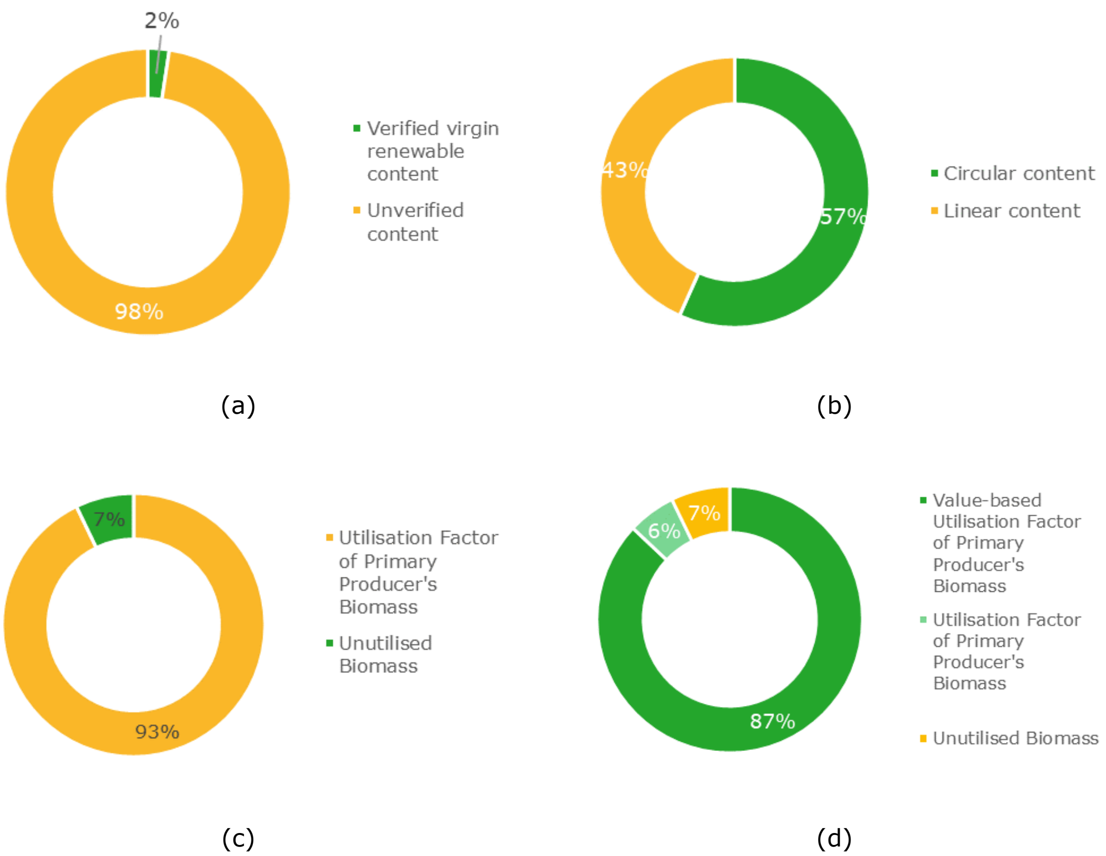
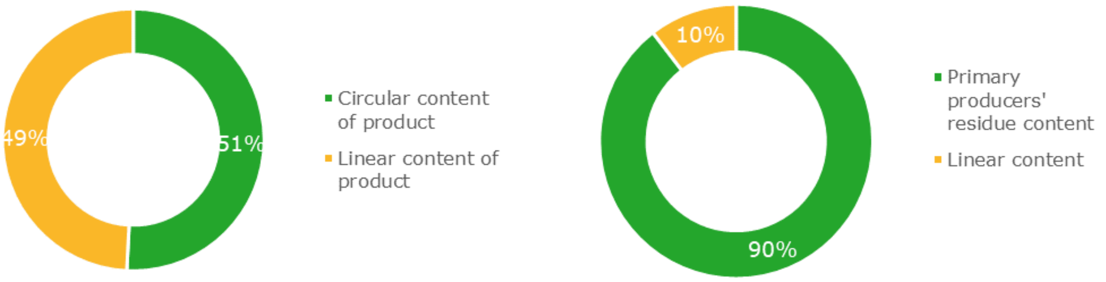


Figure 64. (a) Verified virgin renewable content of wheat grains (b) Circular content of straw (c) Utilisation Factor and (d) Value-based Utilisation Factor of Wheat Grain Producer's Biomass

- **Particle boards industry (intermediate producer)**

Wheat straw is transported to the particle board industry to produce 1 m^3 of finished uncoated particle board. In Figure 65 the circular content and the primary producers' residue content of particle boards are shown.



(a) (b)

Figure 65. (a) Circular content of particle boards and (b) primary producers' residue content of particle boards

Production indicators

Energy-related indicators have been calculated for the particle board production site, with the results being presented in Table 38. The calculations have been performed based on 1 m^3 particle board end-product for a facility operating at a production capacity of 600 m^3/day. Within the production site, straw residues generated throughout the processing stages are used for on-site energy generation, constituting a renewable energy source. Additionally, the average energy intensity has been obtained from FAO report on "Energy conservation in the mechanical forest industries" (appendix V) which indicates a value of 1000 kWh for particleboard manufacturing in a standard, well-operated plant of 100 m^3/day capacity.

Table 38. Circularity indicators related to energy for the particle board final producer

Energy related indicators	Value	Unit
Average renewable energy consumed in the total production process for the generated product (REC)	16.15	%
Energy Intensity to produce the product (EI)	854	kWh/m^3 particle board
Energy Intensity performance in comparison to industry average (EIP)	0.854	-

Water-related indicators have been quantified for particle board production. The results are summarized in Table 39. As a production unit, 1 m^3 particle board is considered. It is feasible to quantify the total water consumption incorporated into the product throughout the production process, while it should be stressed that no water recycling takes place. Finally, regarding the average water intensity of the particle board industry, due to the absence of reliable benchmarking data on average water intensity for the particle board sector, it is not possible to estimate the corresponding WIP indicator.

Table 39. Circularity indicators related to water for the particle board producer

Water related indicators	Value	Unit
Circular water withdrawal for the total production process for the generated product (CWW)	0	%
Circular water discharge for the total production process for the generated product (CWD)	0	%
Internal water recirculation or reuse in the total production process of the product (IWR)	1	-
Water Intensity to produce the product (WI)	0.0124	m^3/m^3 particle board
Water Intensity performance in comparison to industry average (WIP)	-	-

Process-function materials indicators have been also calculated for the particle board production industry and the results are shown in Table 40. For this case as well, 1 m^3 particle board is considered as a production unit. It is highlighted that the raw materials required for the manufacturing of the particle boards comprise the adhesive and additives which do not constitute a recycled raw material. The average industry consumption of materials is reported at 78.16 kg/m^3 (Azman et al., 2021).

Table 40. Process-function materials indicators for the particle board producer

Process-function materials indicators	Value	Unit
Average circular process-function chemical(s)/material(s) input in the total production process of the product (CPFC/M)	0	%
Process-function chemical(s)/material(s) intensity during the reference time period - PFC/MI	70.9	kg/m^3 particle board
Process-function chemical(s)/material(s) intensity performance - PFC/MIP	0.907	-

Regarding the use phase circularity, it is considered that the Average Lifetime of product is no different in comparison to industry average, even though the value chain valorising exclusively agricultural residues has not been commercialized yet. However, if the product is used properly by the user (not damaged, kept away from moisture etc.) this assumption is fair. Figure 66 shows the use phase circularity.

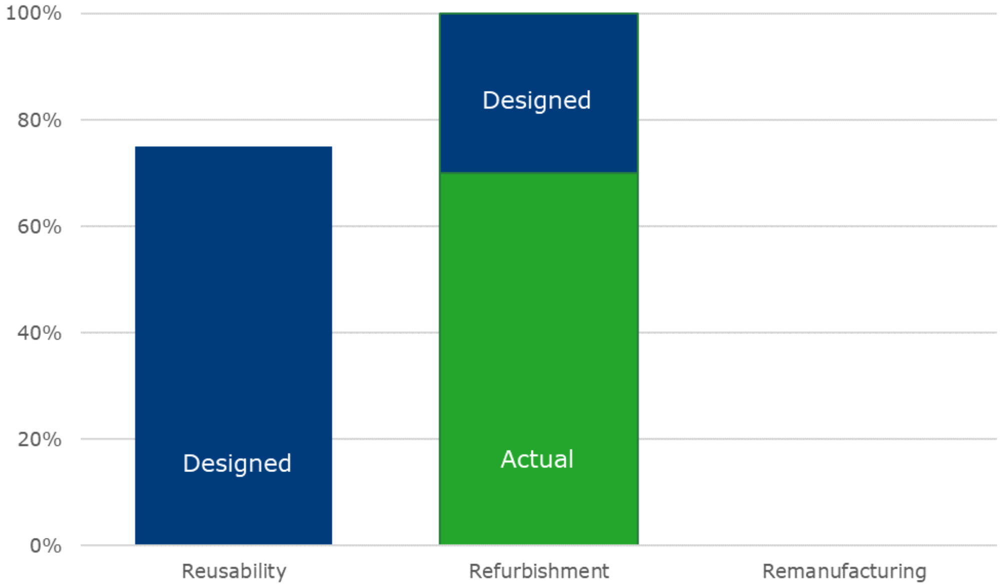


Figure 66. Use phase circularity of particle boards

Figure 67 (a) shows the EoL circularity of particle boards which, by design, is downcycled in the technical cycle to form new particle boards, due to the economic viability of the procedure. The particleboard is crushed as is and new wood chips are formed that also have a small percentage of glue (fully crosslinked polymer) on them. Recycled wood chips are of lower quality than virgin wood chips as part of their cells are already filled with resin and are not available for the development of chemical bonds with the new adhesive mixture that will be used in the production. For the aforementioned reasons the particle board cannot be upcycled according to its design. Even though a significant percentage of particle boards is designed for recirculation, as shown in Figure 67 (b), particle boards are not actually recycled. In Greece, particleboard, at the end of its life cycle, is considered municipal waste and is collected by Local Authority Organizations along with other mixed waste and there is no separate recycling stream specifically for particleboard or fibreboard. Consequently, recycling of these materials is not officially implemented.

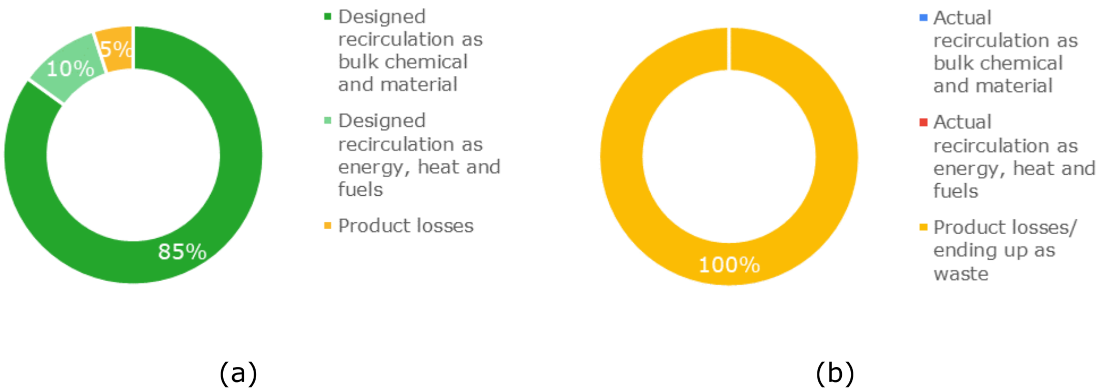


Figure 67. (a) Designed and (b) Actual EoL circularity of particle boards

2.1.4 Case Study 4: Västernorrland, Sweden

The Swedish case study focuses on the forest industry, with the circularity indicators calculated for the value chain involved in the production of bio-oil using sawdust, sawmill bark, GROT, pulp mill bark, and fibre sludge. This value chain has been described both qualitatively and quantitatively in Deliverables D6.1 and D2.4, and a simplified flow diagram is presented in Figure 69.

Of the 29 basic requirements listed in the BioReCer framework, the hypothetical biooil company complies with 24. The remaining 5 are not applicable to this type of organization. As a result, the company fully complies with the BioReCer framework (Figure 68).

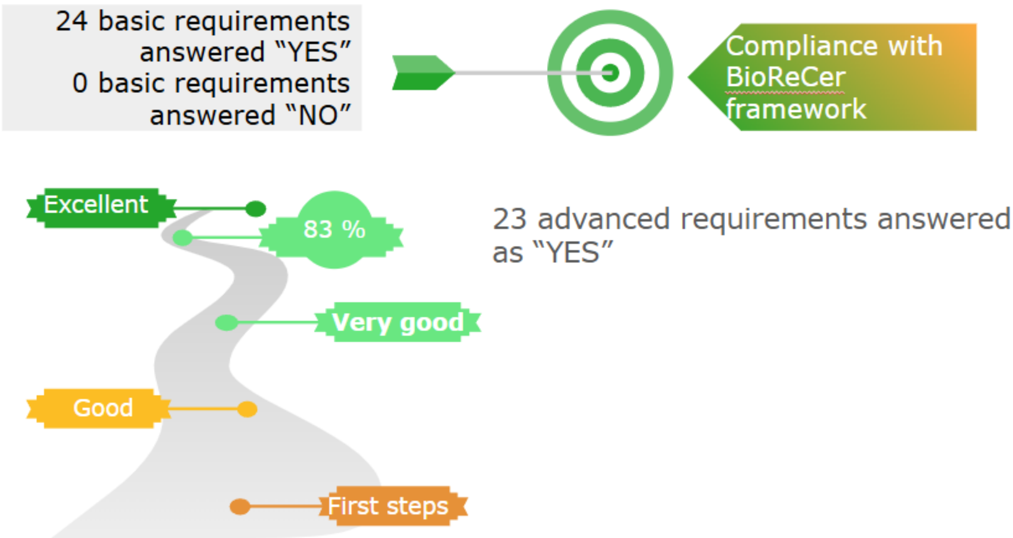


Figure 68. Analysis of requirements in CS4 (bio-oil).

Additionally, the hypothetical biooil company complies with all 23 advanced requirements. Table 41 shows the five basic requirements that are not applicable and the related justification.

Table 41. Requirements that are not applicable in CS4.

Non applicable requirement	Comment
The company shall indicate whether it adopts ecosystem regeneration and rehabilitation measures	This does not apply to this type of company. Its business does not involve cultivation, plantation, harvesting or similar business - it is accounted for by companies situated earlier in the value chain.
The company shall have evaluations about the state of the biodiversity within the area and a plan to maintain and improve biodiversity	This does not apply to this type of company. Its business does not involve cultivation, plantation, harvesting or similar business - it is accounted for by companies situated earlier in the value chain.
The company characterizes the introduced genetically modified species	Biooil production is carried out via hydrothermal liquefaction of residual forestry streams and do not involve the use or introduction of genetically modified organisms (GMOs)

The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	This does not apply to this type of company. Their business does not involve plantation, cultivation, harvesting or other processes which may introduce new species or pathogens to the ecosystem.
The company identifies whether action has been addressed to ensure food security in biomass production systems	This does not apply to this type of company since it utilizes forestry residues and produces intermediates for chemicals and do not compete with or contribute to food applications.

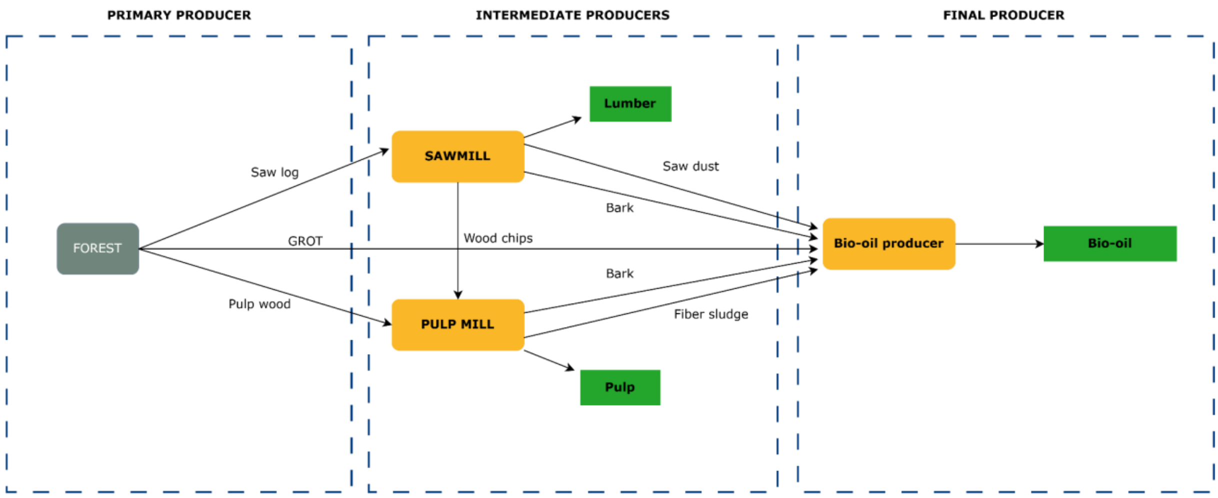


Figure 69. Schematic overview of the CS4 value chain (biooil production).

As illustrated in Figure 69 of the CS4 forestry value chain, the main actors include the forest, sawmills, the pulp mill, and the biooil producer, with the figure also showing each actor's position within the value chain. For the primary producer, the main bio-based products are saw logs and pulp wood, while GROT (tops and branches) is generated as a co-product. The distinction between biological or fossil-based feedstocks is not applicable, as all outputs originate directly from natural capital. Flow quantification and characterization were based on the input/output tables in Deliverables D6.1 and D2.4, with the following assumptions: 45% of the total biomass becomes saw logs transported to the sawmill, 45% becomes pulp wood transported to the pulp mill, and 10% results in GROT, of which 1.03% is removed from the field for valorisation into biooil or other products, while 8.97% remains on the field. Circularity indicators were calculated using the equations described in D2.3 and D2.5

- **Forest (primary producer)**

Logging of the forest results in two main products: saw logs and pulp wood. In addition, a significant fraction of tops and branches, GROT, is produced. This residue may be valorised, e.g. to biooil, but in the CS4 value chain, GROT is co-valorised with several other inputs.

As shown in the figure above, the forest comprises the primary producer and the main products comprise sawlogs and pulp logs, going to the intermediate producers' sawmills and pulp mills, respectively. The utilization factor of primary producer's biomass is 93%, Figure 70a. The remaining 7% represents residual biomass, such as GROT (branches and tops), which is not effectively utilized by the biosphere beyond the sustainable threshold and is therefore considered unutilized. This unutilized portion lowers the overall utilization factor. However, if we consider the value-based utilization factor of the primary producer's biomass, it is slightly lower than the utilization factor of primary producer's biomass (Figure 70a and d), since it takes into account the weighted value of the biomass various fate and e.g. applications like energy, heat and fuel is significantly lowered valued compared with main products, pharmaceuticals and fine chemicals. The model further assumes that the biomass fraction deemed unutilized – based on the sustainable residual mass not actively valorised – carries no value as well. 68% of the sawlogs stem from verified virgin renewable forests, Figure 70b, since only 68% of the forests are certified. The number is the same for the pulpwood, Figure 70c.

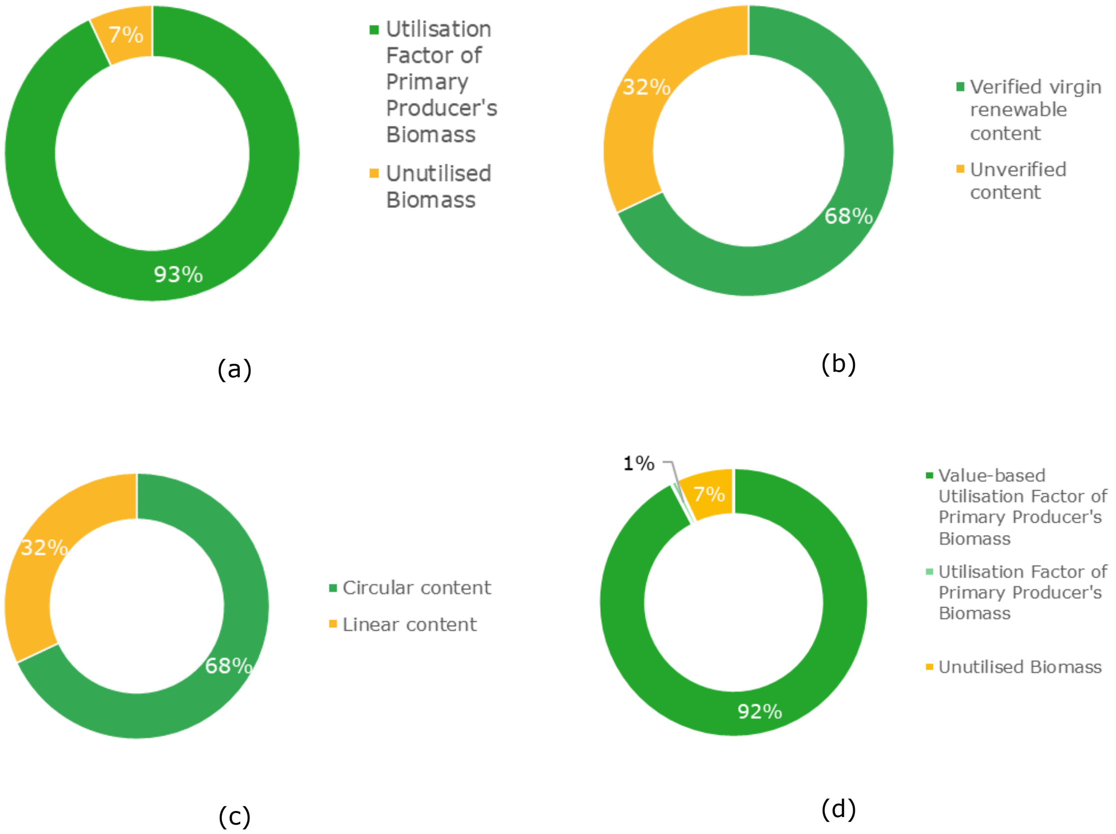


Figure 70. Utilisation factor of primary producer's biomass (a) verified virgin renewable content of the sawlog (b), circular content of pulpwood (c) and the value-based utilization factor of the primary producer's biomass for the pulp wood (d).

The main residue from the primary producer is tops and branches, often called GROT in Swedish. Its CI is 89%, Figure 71, based on the Circularity characterisation factor of residue considering 68% of Swedish forests are validated as renewable, it's fully unavoidable due to its character in combination with requirements from the intermediate producers and its current removal rate is fully sustainable.

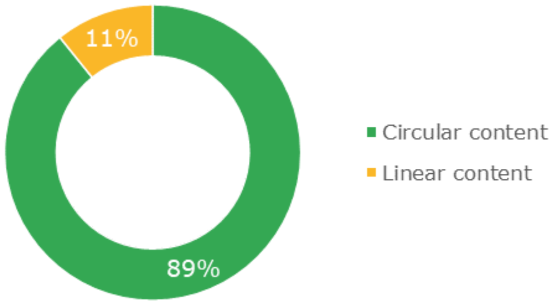
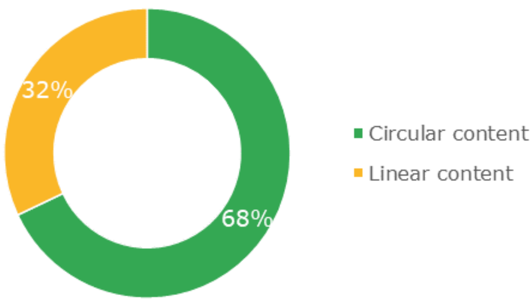


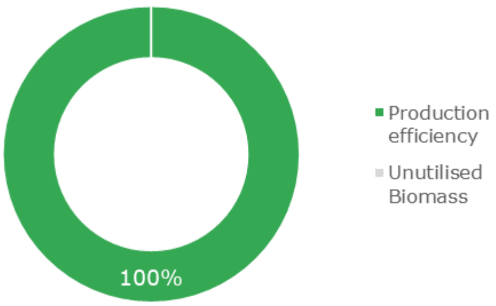
Figure 71. Circular content of GROT, the main residue from the primary producer.

- **Sawmill (intermediate producer 1)**

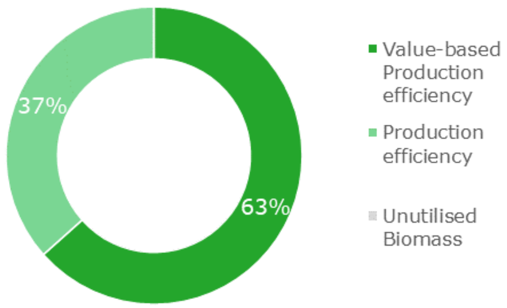
The circular content of the main product from the sawmill equals the virgin renewable content of the product, 68%, Figure 72a. The production efficiency of the sawmill is 100%, i.e. all biomass is utilized, Figure 72b, whereas the value-based production efficiency is 63%, Figure 72c. This is attributed to the low share of higher value applications, e.g. main product and large share of lower value applications like bulk materials, energy, heat and fuel. More specifically, all of the wood chips generated in the sawmill are utilized as feed by the pulp mill. The circular content of that residue, as well as the saw dust generated by the sawmill is 84%, Figure 73.



(a)

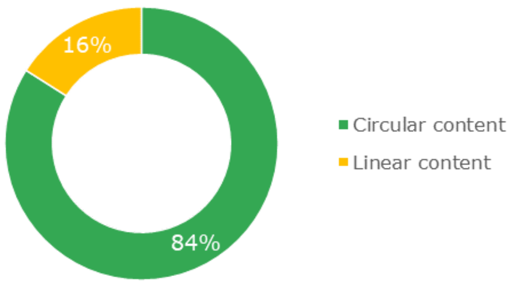


(b)

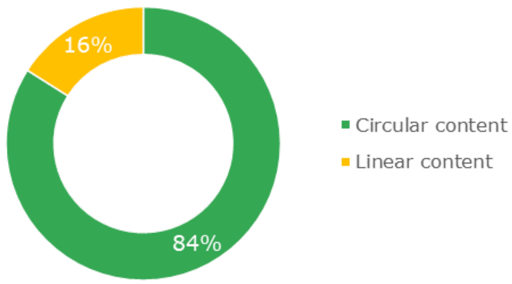


(c)

Figure 72. Circular content of the sawmill main product (a), production efficiency for the total production of the sawmill (b) and value-based production efficiency of the sawmill's total production (c).



(a)

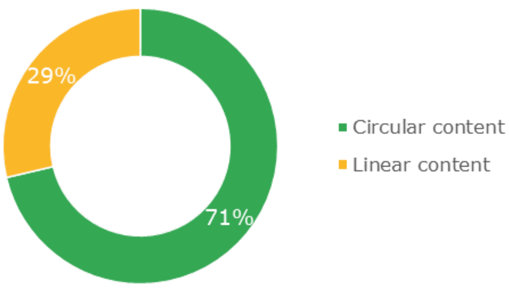


(b)

Figure 73. Circular content of the sawmill residues bark (a) and sawdust and wood chips (b).

- **Pulp mill (intermediate producer 2)**

The circular content of the pulp, i.e. the main product from the pulp mill, is 71% (Figure 74a). It is higher than the corresponding numbers for the primary producer's main products and the sawmill's main product. This is due to the utilization of the sawmill's residue wood chips as feed in addition to the pulp wood from the primary producer. Similar to the other intermediate producers, all biomass is utilized (Figure 74b). The production efficiency of the pulp mill is higher than that of the sawmill (43% vs 37%), but the value-based production efficiency is lower (56% vs 63%), Figure 74c and Figure 74c. The production efficiency is the difference between total production and the value-based production efficiency. The latter one is quite low as more than half of biomass is utilized for low-value applications like energy, heat and fuel. The circular contents of the residue bark and sludge are 84% and 72% respectively, Figure 75. This difference stem from their respective characteristics: the bark stem from virgin renewable material, whereas the sludge also contains a significant fraction of pre-consumer recycled content.



(a)

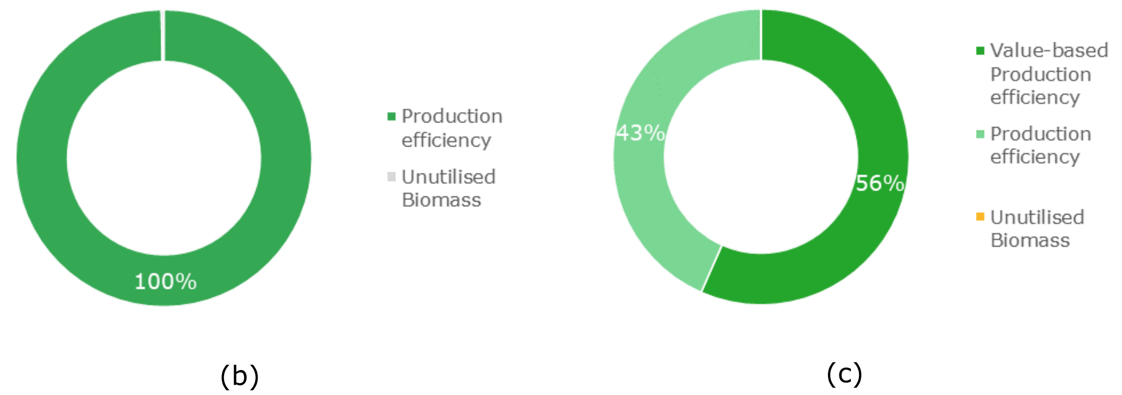


Figure 74. Circular content of the pulp mills main product, pulp (a), production efficiency for the total production at the pulp mill (b) and value-based production efficiency and production efficiency for the total production for the intermediate producer, the pulp mill (c).

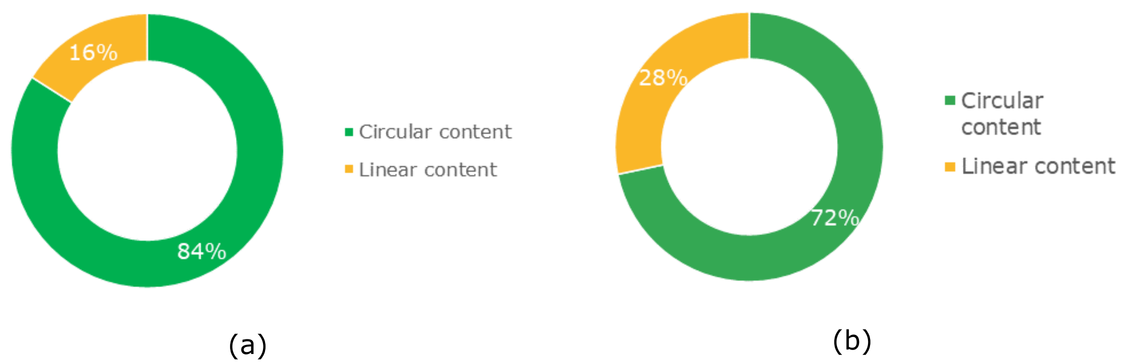


Figure 75. Circular content of the residue bark and fibre sludge from the pulp mill.

- **Bio-oil producer (final producer)**

The circular content of the bio-oil is 86% (Figure 76a) as the main product contain 29,4% of primary producer's residue in the form of GROT and 56,2% of pre-consumer recycled content (bark from sawmill & pulp mill, sawdust, and fibre sludge, Figure 76b). In contrast to the primary and intermediate producers, a significant share of the biomass remains unutilized as the process for producing bio-oil results in water and char fractions which are currently not valorised (Figure 76c). Hence, at this step, the production efficiency equals the value-based production efficiency (Figure 76d).

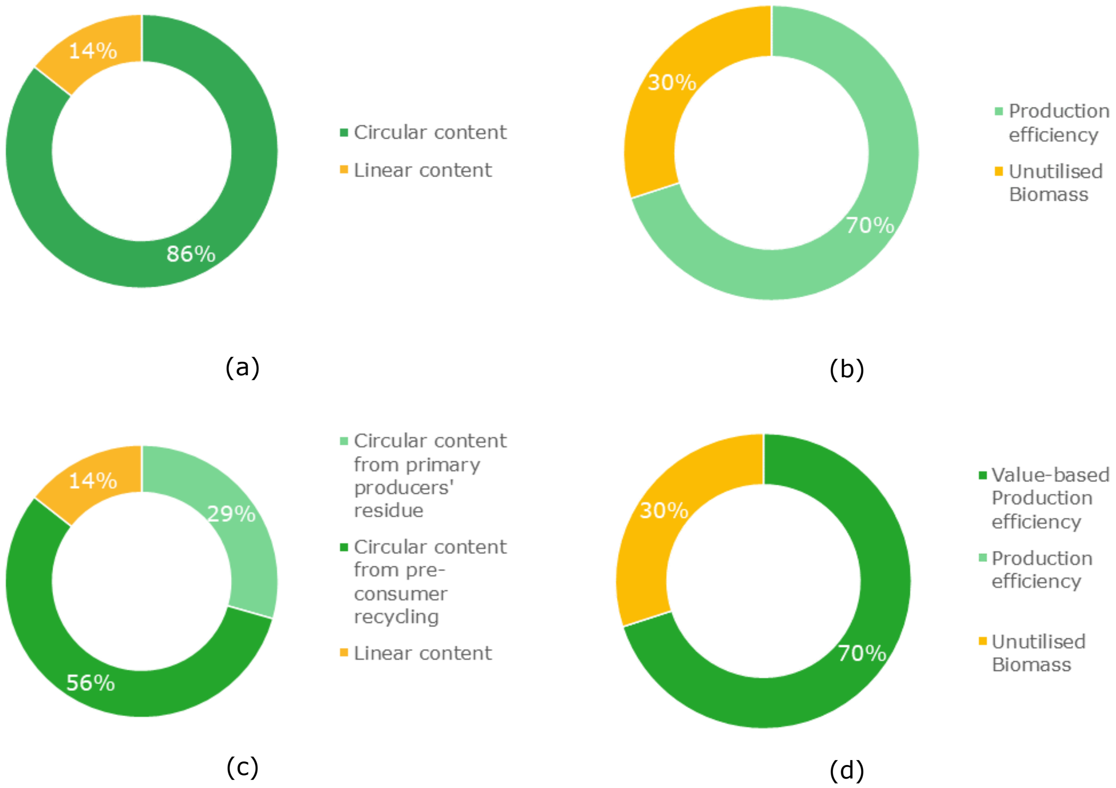


Figure 76. Circular content (a), production efficiency (b), breakdown of circular content (c) and value-based production efficiency for the final producer (d).

No circular production indicators have been calculated since the case study is based on a hypothetical bio-oil producer and therefore detailed industry input data is not available. For a real case scenario, the indicators would be calculated using operational data provided by the company implementing the process.

2.2 Conclusions of the validation of the BioReCer framework

Across all four BioReCer case studies, the applicability and robustness of the circularity indicators proved to be strongly dependent on data availability, quality, and scale of operation. While the indicators developed were conceptually sound and aligned with circular economy objectives, their implementation often required assumptions, data extrapolation, and cross-referencing with literature or regional statistics due to incomplete or heterogeneous datasets.

In the Galician fishery case study (CS1), the applicability of the circularity indicators was closely linked to the availability and quality of data across the three analysed value chains (fish oil, collagen, and polysaccharides). While all processes were conceptually modelled according to the BioReCer framework, the feasibility of calculating the indicators varied significantly. For the polysaccharide value chain, indicators were successfully computed thanks to the availability of real industrial data from algae harvesting and processing stages. This allowed the assessment of energy, water, and chemical consumption indicators with a good level of precision, confirming the robustness of the BioReCer methodology when applied to real operational systems. Conversely, for the fish oil and collagen value chains, it was not possible to calculate the indicators due to the lack of primary data and limited participation of industrial actors. Available information from literature, laboratory data (collagen) and databases were highly variable and not representative of full-scale operations, as production parameters depend on species, extraction methods, and regional practices. Consequently, only conceptual modelling could be carried out, without reliable quantitative validation.

In the Galician sewage sludge case study (CS1), the difficulty of applying each indicator is closely linked to data availability. Regarding the waste producer, it should be noted that this actor is not a real actor, and that the sludge is a post-consumer waste derived from an unavoidable residue of human activity. For this reason, material input indicators do not adequately reflect the circularity of this waste. Data for this actor, specifically those related to sludge characterization, such as organic content and moisture, are the most difficult to obtain. Regarding the availability of data for this value chain, the data required to calculate the production indicators for all actors were the easiest to obtain, as energy, water, and chemical use are routinely monitored in WWTP operations and pilot plants. However, production indicators related to the industry average could not be calculated due to the lack of industrial-scale data, since VFA are produced only at pilot scale and such data are not publicly available.

In the Italian urban biowaste case study (CS2), the main limitation was the heterogeneity of data sources and monitoring practices across sectors (wastewater treatment, agri-food, municipal waste). Reliable datasets were available for sludge production and treatment, but agri-food and OFMSW data required reconstruction from literature, assumptions, and regional statistics. This lack of harmonisation reduced the comparability and reproducibility of the indicators. Despite these challenges, the use of mass balance estimations enabled consistent calculations of the main circularity indicators, although uncertainty remained due to the aggregated nature of the data. The analysis highlighted the need for systematic and standardised monitoring frameworks to improve data accuracy and transparency.

The Greek agro-industrial case study (CS3) faced difficulties primarily at the primary production level, where data on agricultural residues, sustainable removal rates, and renewable production were often unavailable. Farmers typically record only quantities intended for sale; many values had to be estimated using literature or assumptions. Data availability improved significantly for intermediate and final producers, as environmental reporting requirements facilitated access to material input and consumption data. However, the implementation of circular production indicators was limited by the absence of structured input–output monitoring systems. Overall, data completeness and monitoring practices were identified as the main barriers to fully operationalising circularity assessment in the agricultural sector.

In the Swedish forestry case study (CS4), data availability for primary and intermediate producers (forest owners, sawmills, pulp mills) was generally good due to mandatory reporting and industry databases. However, the main challenges arose from the immature nature of the selected value chain, which ends with an intermediate rather than a final commercial product. As a result, circular production and end-of-life indicators could not be applied. Moreover, energy- and water-related indicators were difficult to estimate, since process data are expected to change with future industrial scaling. These limitations underscore the complexity of applying circularity metrics in emerging bio-based value chains that lack commercial benchmarks.

Overall, the cross-case analysis demonstrates that while the proposed circularity indicators are specific, measurable, relevant, and suitable for long-term monitoring, their achievability depends heavily on data availability, consistency, and scale. Reliable indicator calculation requires harmonised reporting practices, improved residue characterisation, and more comprehensive industrial datasets particularly for pilot-scale or emerging technologies.

3 Environmental outcomes of the BioReCer project

This section presents the environmental assessment of the BioReCer case studies, carried out through Life Cycle Assessment (LCA). The objective is to quantify the potential environmental benefits achieved by implementing BioReCer circular valorisation routes compared with conventional linear systems.

An attributional LCA was performed in all four case studies, following ISO 14040 and the Environmental Footprint 3.3 methodology. Each study compares a Baseline scenario (current or conventional practice) with a BioReCer scenario (high value valorisation practice).

The assessment follows a cradle-to-gate approach, including feedstock acquisition, pre-treatment, processing, energy and chemical inputs, transport, and waste management. For multifunctional processes, system expansion was used to ensure fair comparison.

Primary data was collected directly from stakeholder companies and pilot facilities. They are specific to the case being analysed and are obtained through direct measurements, field surveys, or operational data from the companies or producers involved in the process. For example, the amount of energy consumed, greenhouse gas emissions, resource consumption, and waste treatment data generated during the production of a product. The secondary data was sourced from external references and databases like Ecoinvent in the v3.10 and v3.11 versions. Also, secondary data may come from previous studies, databases, scientific literature, public reports, or general environmental data sources. All modelling was performed in SimaPro, using midpoint and single-score indicators. The impact categories selected, climate change, acidification, eutrophication, particulate matter, land use, water use, and fossil resource use, reflect the key environmental dimensions targeted by BioReCer.

This general methodological approach, described in Figure 77, was then adapted to each case study, taking into account regional conditions, specific feedstocks, and process configurations. The following subsections present the LCA results for each case study.

Attribute	Description
Goal of the study	The objective of this study is not to optimize the system, but to provide a comparative evaluation of the scenarios selected by BioReCer in each case study with waste treatment processes and/or counterpart production. Although a product production approach is proposed, rather than a feedstock approach, we may select this approach based on data availability and the first approximation of the environmental impact results for the different case studies. The work now focuses on the BioReCer case study. The following sections provide common guidelines for conducting the LCA analysis.
Strategy to reach the goal	Operational LCA. The infrastructure related to the different life cycle stages considered will be neglected.
Technical system boundaries	Cradle-to-gate. The analysis shall be performed taking into account the valorization of the feedstock/input stream. Indirect impacts of the waste production stages shall not be included within the study (a cut-off or zero-load approach shall be considered). The analysis should incorporate the transport of feedstock/waste to the facility gate. Transport, consumption and end-of-life activities related to the products shall not be part of the analysis.
Scale of the technologies	The valorization strategy should be preferably for industrial scale considering a capacity that envisages a potential future implementation of the technologies. In case sufficient data is not available for the case to be applied on an industrial scale, the scale should be pilot. Case study developers should provide information on the description of the selected case study, including flow chart and identification of the main flows.
Geographical system boundaries	European/Global. The geographical boundaries of the system should be European and only for background data (from databases and for indirect processing) could a global scale be considered. This could occur only when there are data limitations from, for example, Ecoinvent or other LCA databases.
Temporary system boundaries	Hierarchic perspective (H)
Emission accounting approach	Attributional. Avoided emissions are not considered and the analysis should be a reliable snapshot of what is happening for the system at the time of analysis.
Level of implementation	Micro or product-oriented level: Initially all case studies should have a product-based objective. Macro-level or process-oriented will be contemplated in the future depending on the results.
Allocation procedure	Mass allocation. The impact will be distributed between the possible co-products manufactured by the system based on their production in terms of mass (i.e., kg or tons).
LCI inventory perspective	Bottom-up approach. Data will be collected directly for laboratory or industrial processes and not from national or continental scale data.
Functional unit	As first approach, each case study should select a mass-oriented functional unit of the product(s). For example, kg of product A and kg of product B.

Figure 77. Conditions for the LCA study.

3.1 Results of the case studies

3.1.1 Case study 1: Galicia, Spain

3.1.1.1 Polysaccharides

The environmental trade-offs of algae valorisation were analysed by comparing two processing pathways for algal biomass collected along the Galician coast: (i) the extraction of polysaccharides (algae derived compounds), and (ii) the production of cellulose cake as the main co-product.

The functional unit adopted for the assessment was *1 kg of dry algal biomass processed*. The study followed a cradle-to-gate approach, encompassing all stages from algal collection, washing, drying and milling to extraction, purification, and final product (polysaccharide or cellulose cake) recovery.

Both systems include upstream and downstream processes such as reagent and energy production, transport of biomass and chemicals, and waste and wastewater treatment. In the Baseline scenario, the algal biomass is treated using conventional extraction processes with external energy inputs and limited material recovery. In the BioReCer scenario, the system is optimised through improved biomass valorisation strategies, integrating by-product recovery and circular reuse of process water and residual biomass, contributing to a reduction in environmental burden.

Primary data were collected directly from pilot-scale operations, including information on biomass yield, reagent consumption, process temperatures and durations, and energy use. Emissions to air, water, and soil were quantified according to mass balances and standard emission factors. Transport distances for biomass collection and chemical supply were based on local conditions.

The results indicate that the polysaccharide extraction pathway presents higher impacts in energy-related categories such as climate change and fossil resource use, mainly due to the heat demand during extraction and solvent recovery. Conversely, the cellulose cake pathway shows higher impacts in eutrophication and land use, attributed to the larger biomass input and associated upstream activities. The detailed characterisation results for both scenarios are provided in Annex B.

Figure 78 illustrates the relative performance of both valorisation pathways for the selected midpoint categories, where the system with the highest impact is normalised to 100%. This comparative representation highlights the trade-offs between energy intensity and biomass utilisation efficiency. Figure 78 shows clear environmental advantages for the BioReCer scenario. Across most impact categories, in particular climate change, acidification, and fossil resource use, impacts are reduced by 40–60 % compared with the baseline. These improvements stem from lower thermal energy consumption, simplified extraction, and the valorisation of the cellulose cake that would otherwise be discarded.

In the BioReCer scenario, the main contributors to total impact are the energy and transport stages, followed by waste management (wet by-products and biomass residues). Nevertheless, the overall environmental profile is more favourable due to the simplicity of the process and the direct valorisation of the solid residue as a product.

Water use is also significantly lower in the BioReCer scenario (2.39E+01 m³ depriv. vs. 4.22E+01 in the baseline), indicating reduced pressure on water resources.

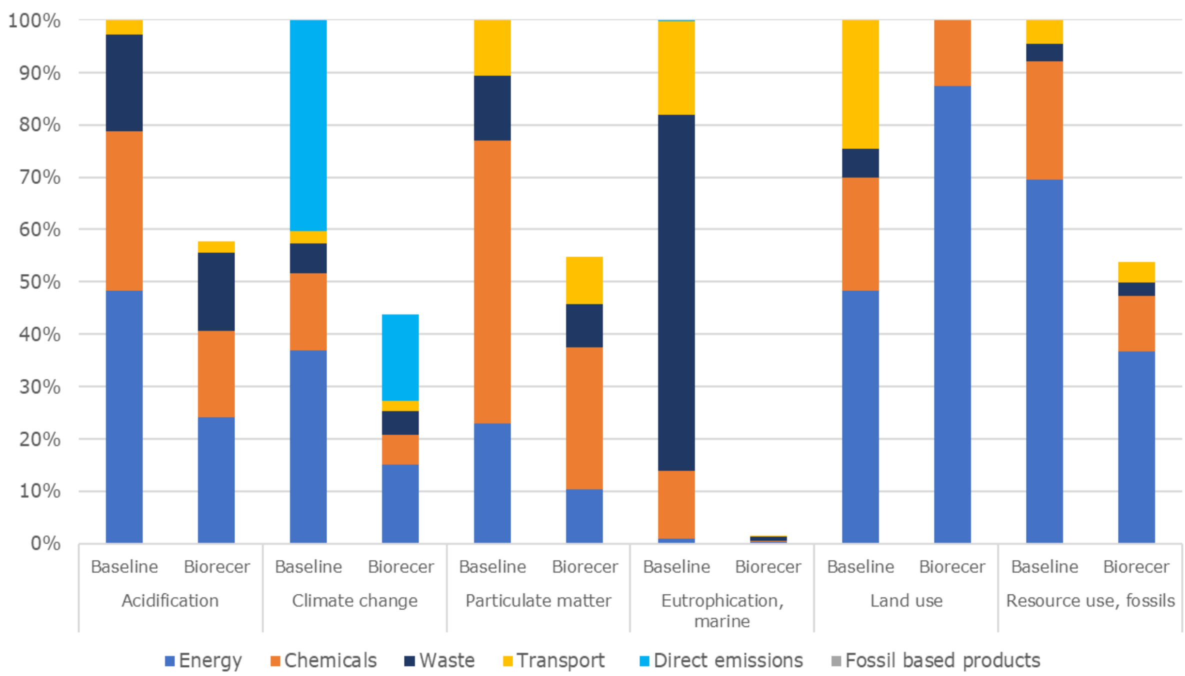


Figure 78. Midpoint impact categories relative comparison.

In contrast, Figure 79 presents the single score results for both pathways, showing that the integrated valorisation system (BioReCer scenario) achieves a significantly lower (40% less impact) overall environmental footprint compared to the conventional process, highlighting better performance in climate change, fossil resource use, and water consumption categories.

This improvement is mainly driven by reductions in external energy demand and chemical use, as well as by the valorisation of process residues.

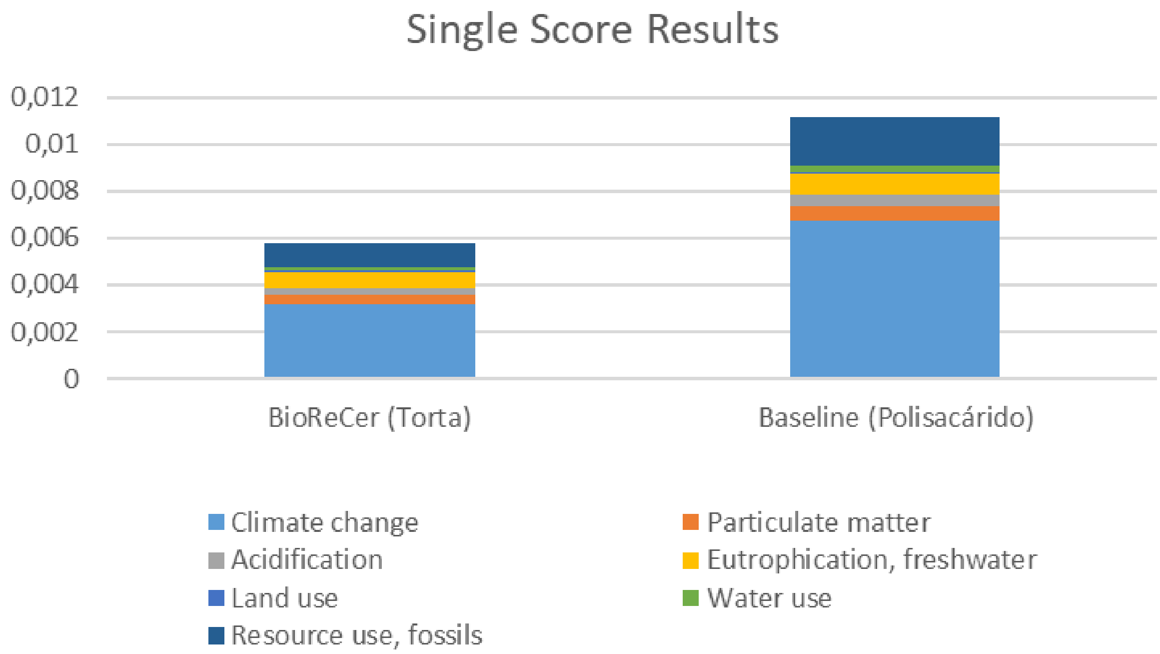


Figure 79. Single score results.

Overall, the analysis demonstrates the environmental benefits of adopting circular valorisation strategies for algal biomass. By transforming marine residues into high-value bioproducts such as polysaccharides and cellulose derivatives, the BioReCer approach contributes to a sustainable blue bioeconomy.

3.1.1.2 3.1.1.2 Sewage sludge

The second Galician assessment examined the environmental implications of urban and industrial sewage sludge valorisation through the production of volatile fatty acids (VFAs), compared with conventional sludge management and fossil-based acid production.

System expansion was used to compare the functions of both scenarios. The BioReCer scenario proposes a novel valorisation pathway that treats the residue while producing high value chemicals. For the baseline scenario these two functions were considered, on the one hand the business-as-usual approach to waste management in a WWTP and on the other hand the production of acetic, propionic and butyric acid from fossil-based sources. Figure 80 and Figure 81 depict the system limits for both analysed scenarios.

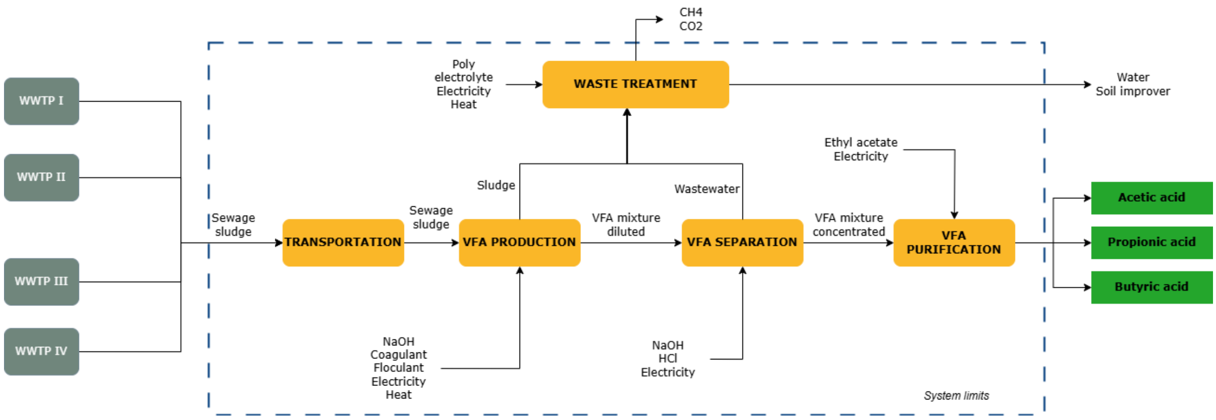


Figure 80. System limits for the BioReCer scenario.

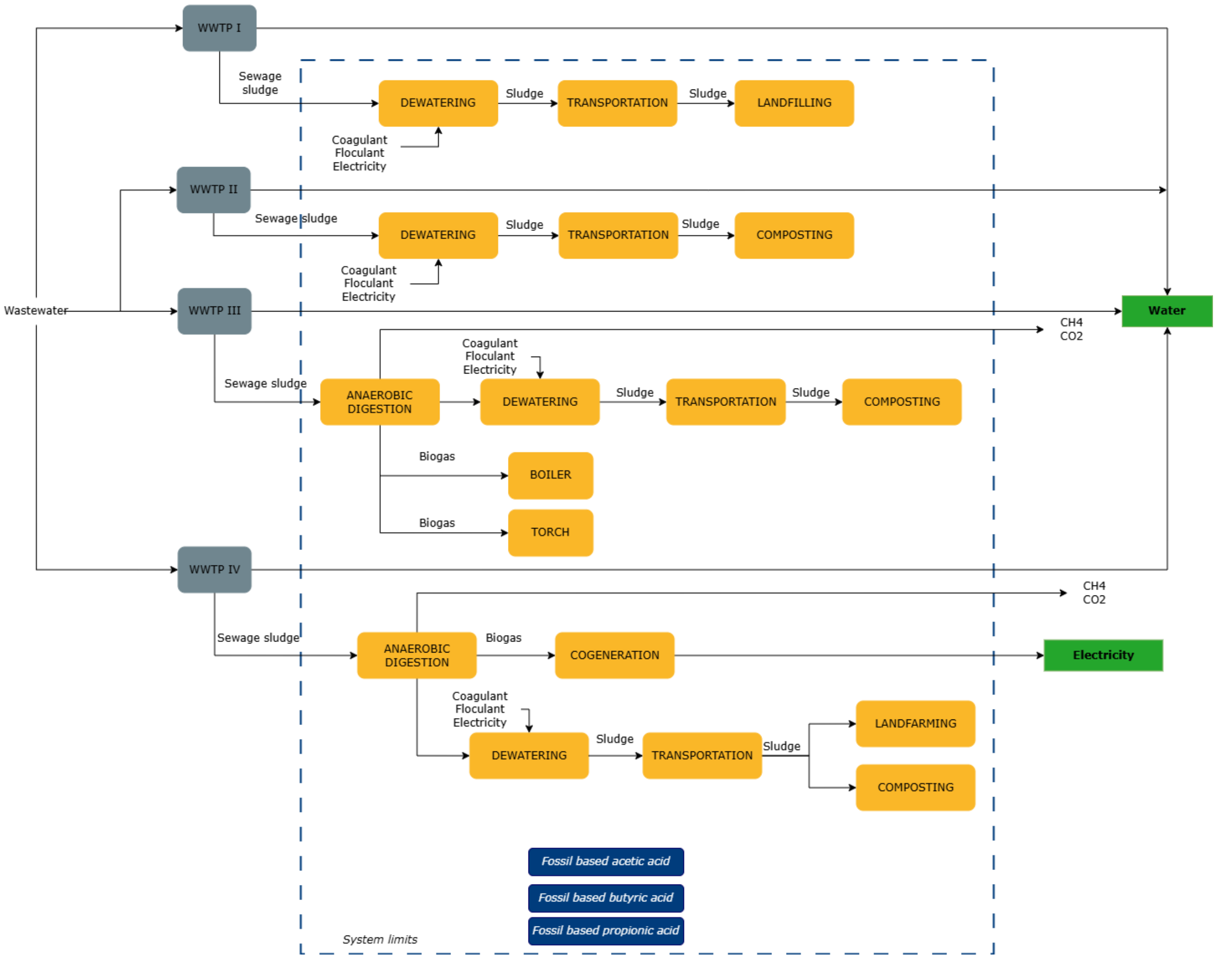


Figure 81. System limits for the baseline scenario. The fossil-based acids are considered as background processes.

For the Baseline scenario, the analysis includes the transport of sludge to the facility gate, the waste treatment process, and the associated emissions. Additionally, acetic, propionic, and butyric acids production was considered following the system expansion approach. Regarding the BioReCer scenario, waste treatment is focused on its valorisation into VFAs through an anaerobic fermentation process. VFAs are subsequently concentrated using a membrane train, after which the concentrated mixture undergoes an extraction process and successive distillation stages to obtain high-purity acetic, butyric, and propionic acids. For this scenario, in addition to the consumption of energy and chemicals, the transport of sludge to the plant was included, assuming the centralization of treatment in a single facility within the study region. Additionally, the treatment of wastewater and sludge generated throughout the process was considered, including the associated emissions.

Regarding inventory data, primary data was mostly obtained from operational data provided by wastewater treatment operators, as well as from internal projects. These data encompassed a wide range of inputs for both processes, including energy consumption, chemical use, transport, and waste generation. Direct emissions linked to biogas combustion were estimated based on the emission factors proposed by the EMEP/EEA air pollutant emissions inventory guidebook.

As shown in Figure 82, the BioReCer scenario demonstrates better environmental performance across all impact categories evaluated. The improvements are mainly attributed to reduced chemical consumption, notably the avoidance of polyelectrolytes required for dewatering in the baseline, and the centralisation of sludge treatment, which decreases transport-related impacts. The characterisation results for both scenarios are presented in Annex B.

Direct emissions are the main contributors to the climate change category in both scenarios, primarily associated with the anaerobic digestion process. However, energy consumption is higher in the BioReCer scenario across all impact categories, due to the high energy demand associated with the purification stage of VFAs.

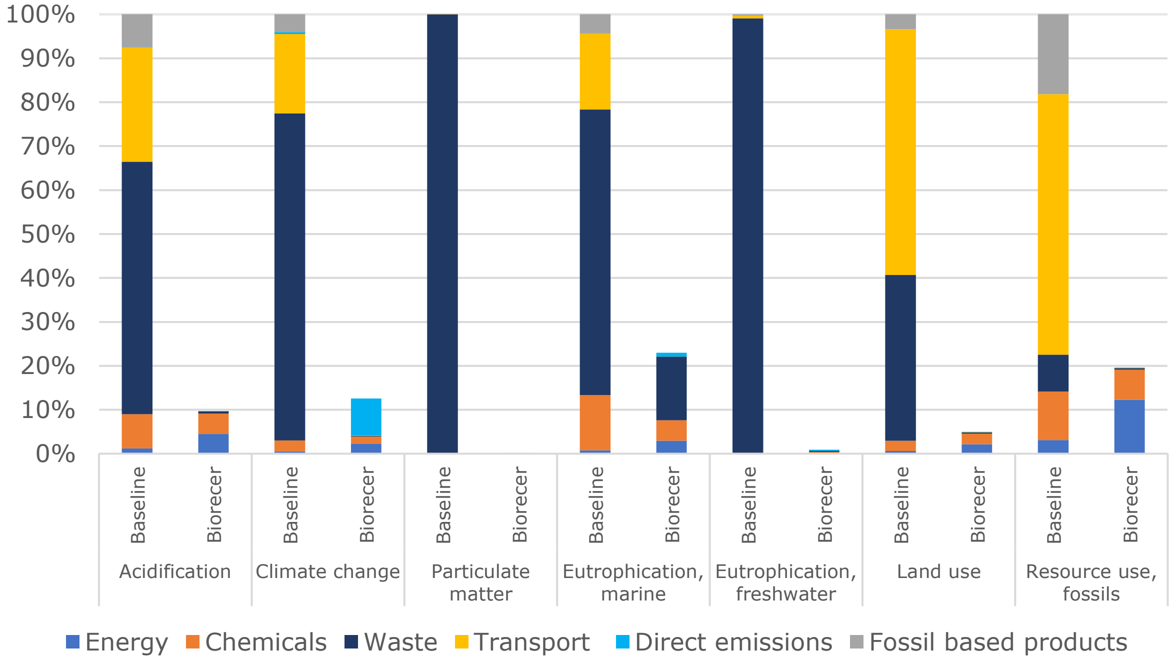


Figure 82. Midpoint impact categories relative comparison.

Figure 83 presents the comparison between both scenarios based on single score values, Pt, which reflect the aggregated contribution of all impact categories evaluated. As shown, the climate change category exhibits the highest contribution in both scenarios, mainly due to direct process emissions, particularly those associated with anaerobic digestion, as previously discussed. This is followed by the resource use, fossils category, which is associated to the production of acetic, propionic, and butyric acids in the Baseline scenario, and to energy consumption in the BioReCer scenario. Nevertheless, the BioReCer scenario shows a lower total environmental impact compared to the Baseline, highlighting its better environmental performance.

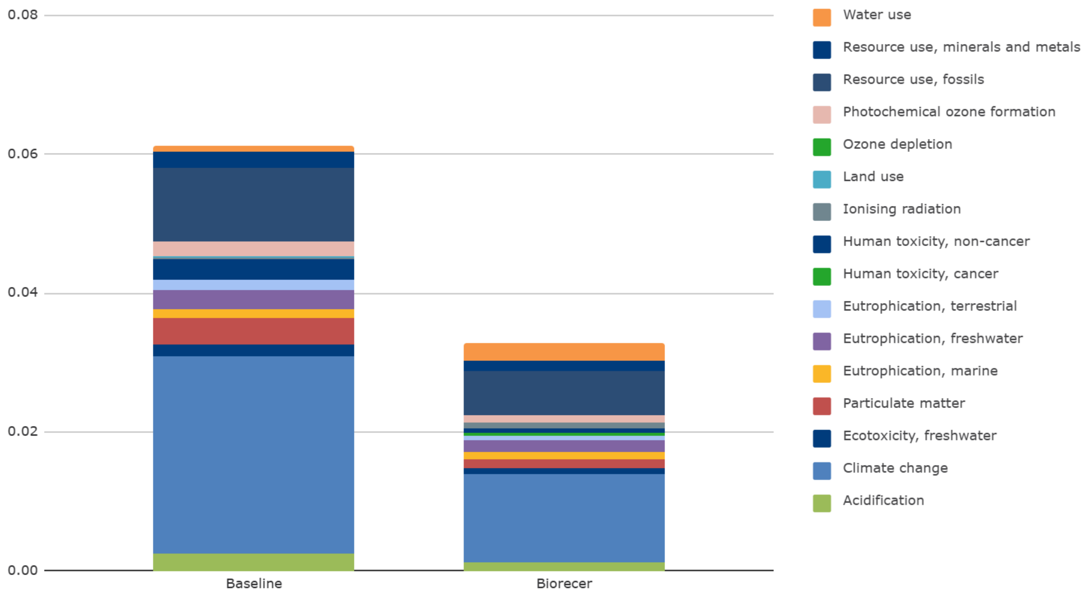


Figure 83. Single score results for both scenarios.

3.1.2 Case study 2: Lombardia, Italy

Urban and industrial waste

In CS2 the environmental performance of urban and industrial biowaste valorisation in the Lombardy region was performed comparing a baseline scenario representing current management practices (considering the years 2016-2022) with a BioReCer scenario integrating circular recovery processes for the production of struvite and polyhydroxyalkanoates (PHA). The analysis quantifies the potential environmental benefits derived from transforming mixed waste streams into value-added bioproducts.

The goal of this analysis was to provide a comparative evaluation of the environmental impacts of the Baseline and the BioReCer scenarios. The functional unit adopted was 1 ton of input waste. The system boundaries of the Baseline scenario are shown in Figure 84, while those of the BioReCer scenario are presented in Figure 85.

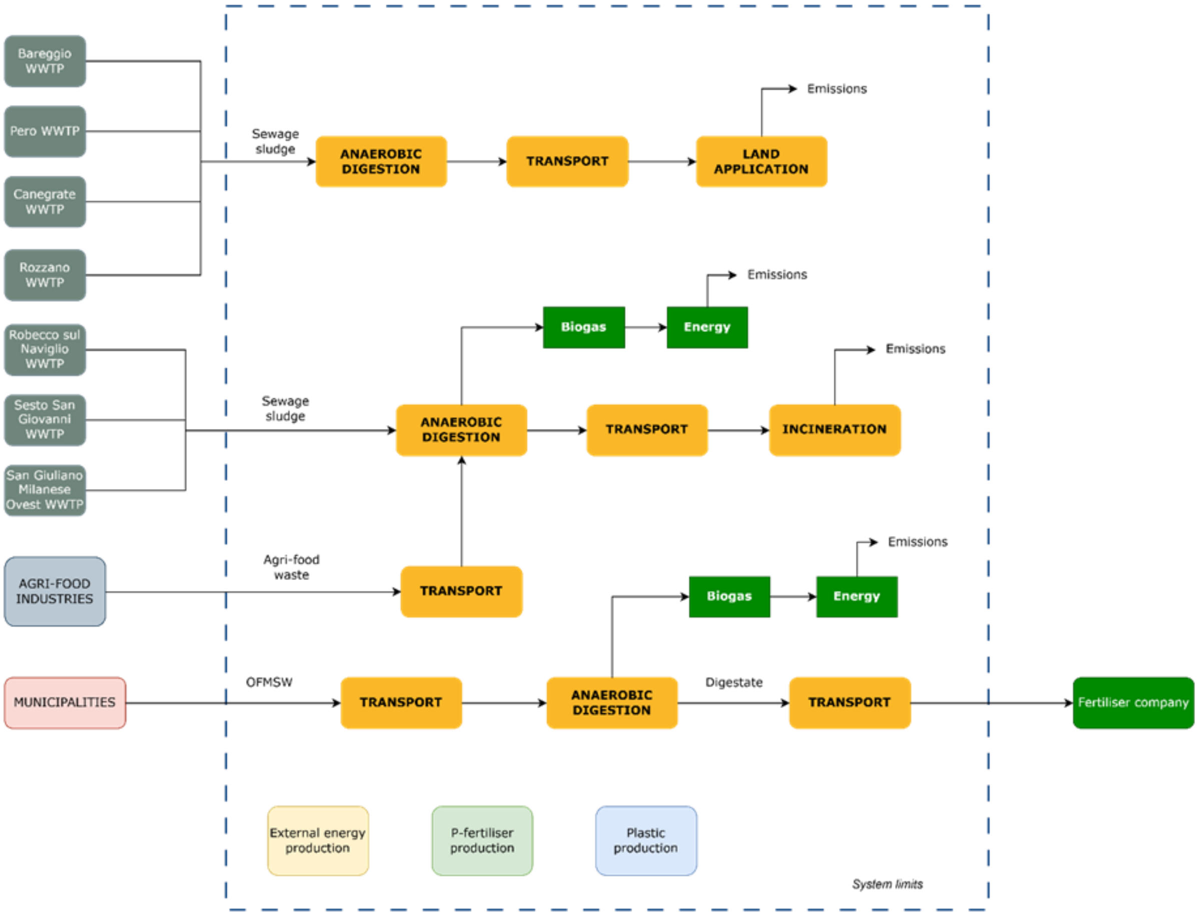


Figure 84. Boundaries of the Baseline scenario.

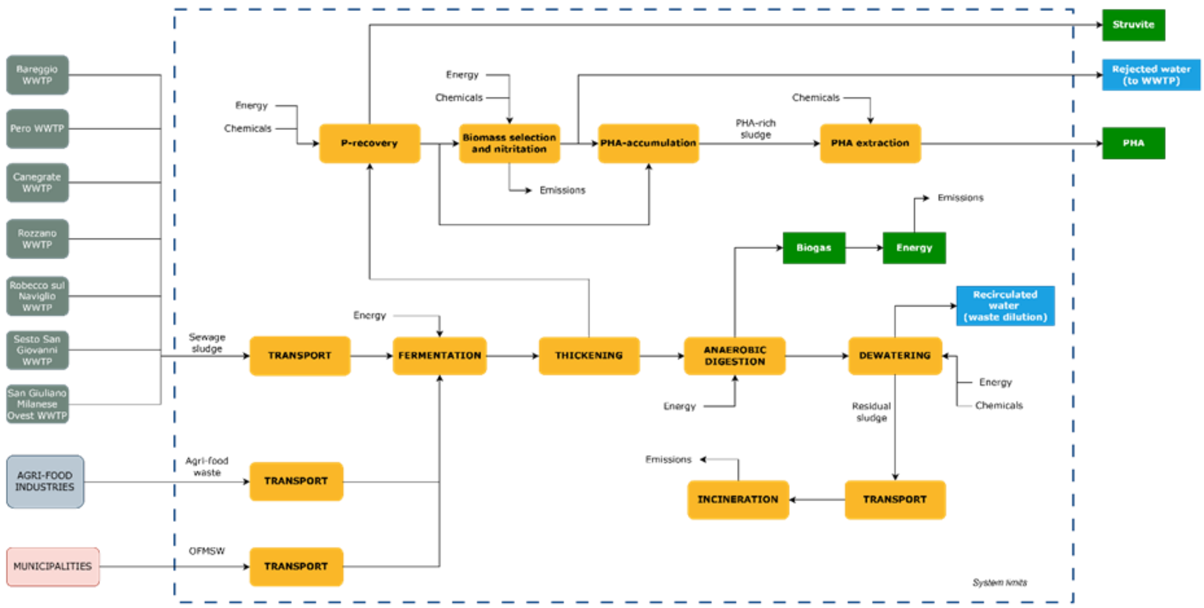


Figure 85. Boundaries of the BioReCer scenario.

In the Baseline scenario, in addition to waste management and the associated emissions, the production of fertilisers, plastic bags, and external energy was included. This approach ensures a fair and meaningful comparison with the BioReCer scenario, where waste treatment is coupled with the recovery of valuable products such as struvite and PHA, enabling the production of fertilisers and bioplastics. Struvite can be used directly as a fertiliser, whereas PHA must first be extracted from the biomass, through chemical digestion, mechanical disruption or solvent extraction (Saavedra del Oso et al., 2021). The comparison between conventional fossil-based plastic bags and biobased alternatives was conducted in accordance with the study of Khoo et al. (2010). The external energy considered in the Baseline scenario corresponds to the difference in biogas-derived energy production between the BioReCer and the Baseline scenarios. It is important to note that the BioReCer scenario includes the recent implementation of a biogas purification system at the Sesto San Giovanni plant. This system is capable of producing biomethane with a methane concentration of up to 99%. Its associated energy and chemical consumption have been accounted for within the BioReCer scenario.

The waste quantities considered for the study represent the average amounts processed between 2016 and 2022 in the selected WWTPs, based on available data. These values served as the basis for both the Baseline and BioReCer scenarios.

Regarding the inventory data, the emissions resulting from biogas combustion were calculated using the methodology outlined by the Environmental Protection Agency (2016). The electrical and thermal energies produced from biogas were estimated based on the approach proposed by Omer (2015).

In the Baseline scenario, nitrous oxide emissions from the via-nitrite process, applied to remove nitrogen from the anaerobic digestion supernatant, were calculated according to the study of Longo et al. (2017). Regarding the agricultural land application of the sludge, the associated N2O emissions (to both air and soil) and NH3 emissions (to air) were calculated using the emission factors provided by the IPCC (2006). The methane emissions to air, as well as the diesel and energy consumption of the machinery involved in sludge application, were estimated based on the study of Hospido et al. (2005). The emissions of heavy metals in the soil were derived from the actual characterisation of the sludge applied to the agricultural soil.

In the BioReCer scenario, the chemical usage and energy consumption for the struvite recovery and PHA production units were estimated based on the results of SMART-Plant (2020). Regarding the PHA extraction, the associated water, chemicals, and energy demand were considered according to the study of Saavedra del Oso et al. (2021) and the patent developed by Simone Begotti (2017).

For the transport of wastes and chemicals, actual distances were used when available. Otherwise, a default distance of 40 km was applied.

The characterisation results for both scenarios are provided in Annex B, and the comparative performance across midpoint categories is illustrated in Figure 86 and Figure 87. In the Baseline scenario, the energy includes also the production of diesel used for land application.

The results indicate that the BioReCer scenario generally performs better than the Baseline scenario, with noticeable reductions in categories such as climate change, freshwater eutrophication, and acidification. These reductions are largely driven by decreased contributions from energy use, direct emissions, and waste management. In contrast, for particulate matter, the BioReCer scenario performs worse than the Baseline in this specific category. This can be primarily attributed to the increased use of chemicals, specifically magnesium chloride, employed in the struvite recovery process. Magnesium chloride production is associated with emissions that contribute to particulate matter formation, offsetting the benefits observed in other impact categories. To mitigate this drawback, alternative sources of magnesium with lower environmental burdens could be explored, such as by-products from industrial processes or natural brines. Additionally, optimising the dosage or recovery efficiency of magnesium in the struvite precipitation step could help reduce overall consumption and related emissions, thereby improving the performance of the BioReCer scenario in this impact category.

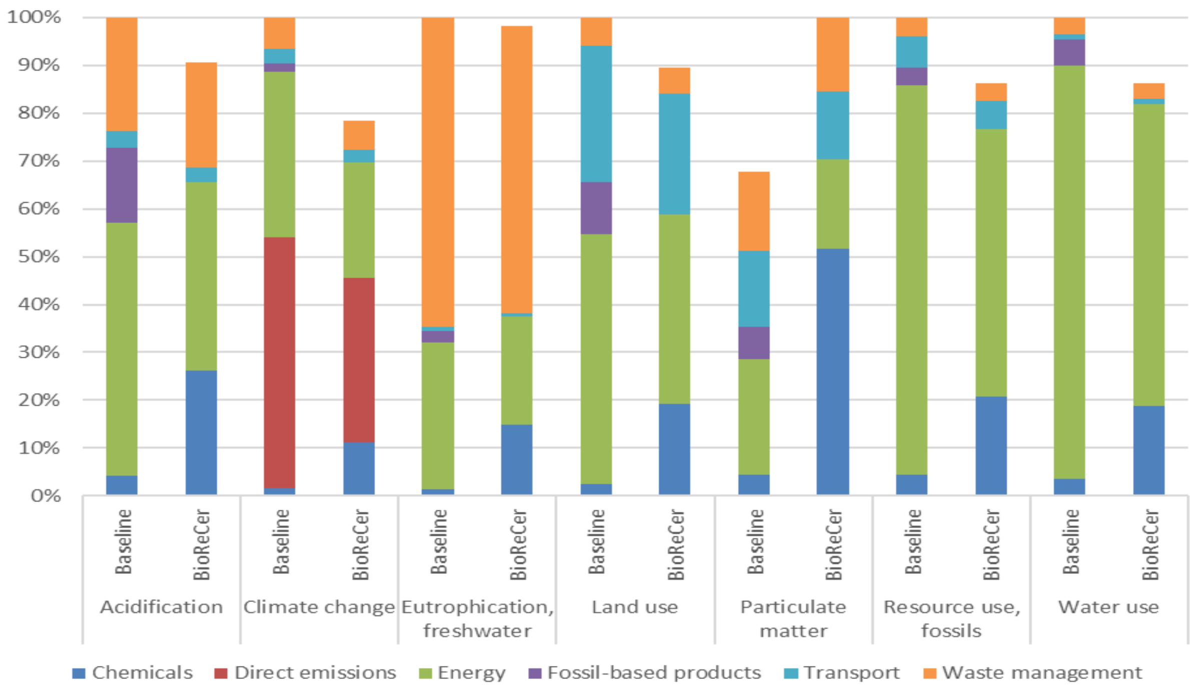


Figure 86. Midpoint impact categories relative comparison.

The overall environmental impacts of the Baseline and the BioReCer scenarios, expressed in normalised single-score values (Pt) and broken down by impact category are shown in Figure 87. Each bar represents the aggregated environmental impacts, with segments indicating the contribution of the categories. The comparison reveals that, although the BioReCer scenario shows a slight increase in particulate matter impacts, it achieves a significantly lower total environmental impacts than the Baseline scenario. This reduction is driven by substantial improvements in key categories such as climate change, resource use, and land use.

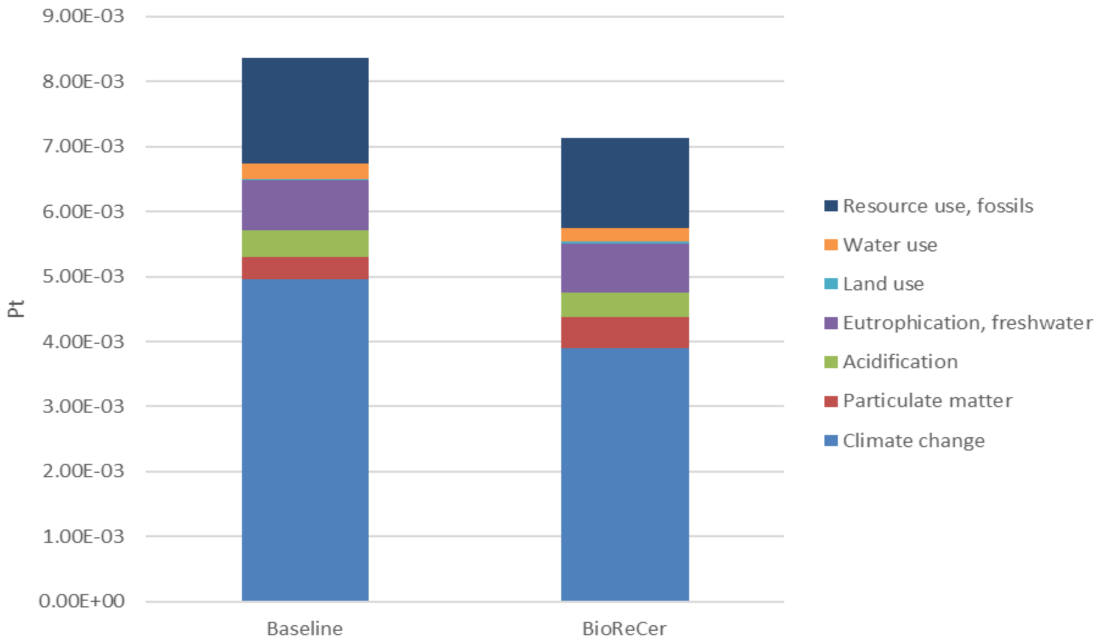


Figure 87. Single score results for both scenarios.

3.1.3 Case study 3: Region of Central Macedonia, Greece

3.1.3.1 Particleboards value chain

The first assessment in the Region of Central Macedonia focused on the environmental performance of bio-based particleboard production, comparing a baseline scenario representing conventional wood-based panel manufacturing with a BioReCer scenario that incorporates lignocellulosic agricultural residues like straw as a substitute raw material. The aim was to evaluate how integrating agricultural by-products into the particleboard value chain can enhance environmental performance while contributing to the regional circular bioeconomy

The functional unit for the assessment was 1 m3 of finished particleboard. The study followed a cradle-to-gate approach, covering all operations from raw material acquisition to the product at the factory gate. In the baseline scenario, particleboards are produced from virgin wood chips. In the BioReCer scenario, the virgin wood is substituted by residues derived from residual straw, which are pre-treated and incorporated into the board manufacturing process. Upstream processes, including resin and energy production, transport of raw materials, and waste management, were included in both systems. The system boundaries and main process flows are shown in Figure 88 and Figure 89.

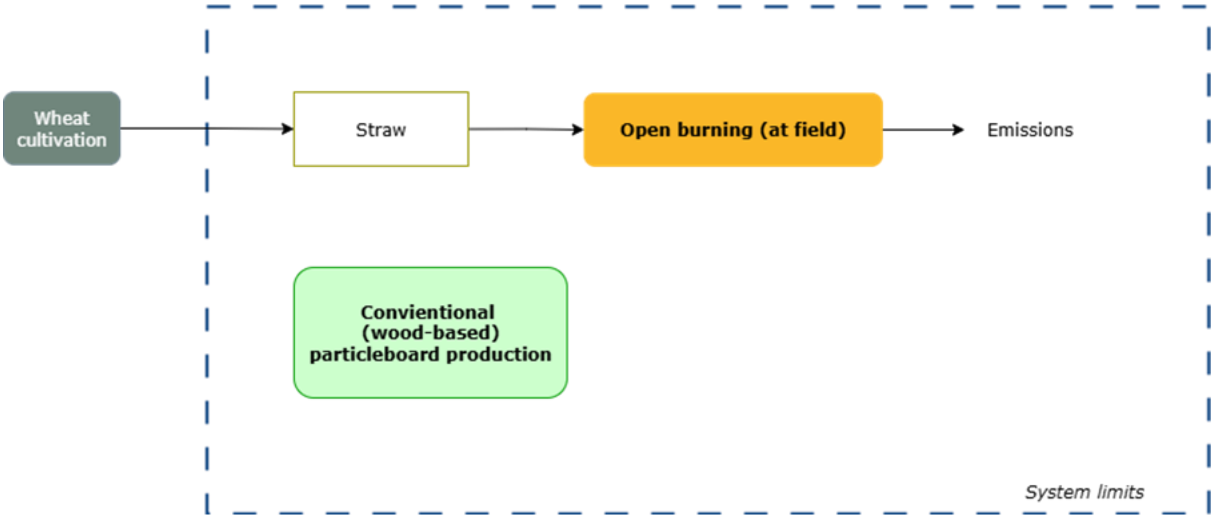


Figure 88. System limits for the particleboards baseline scenario

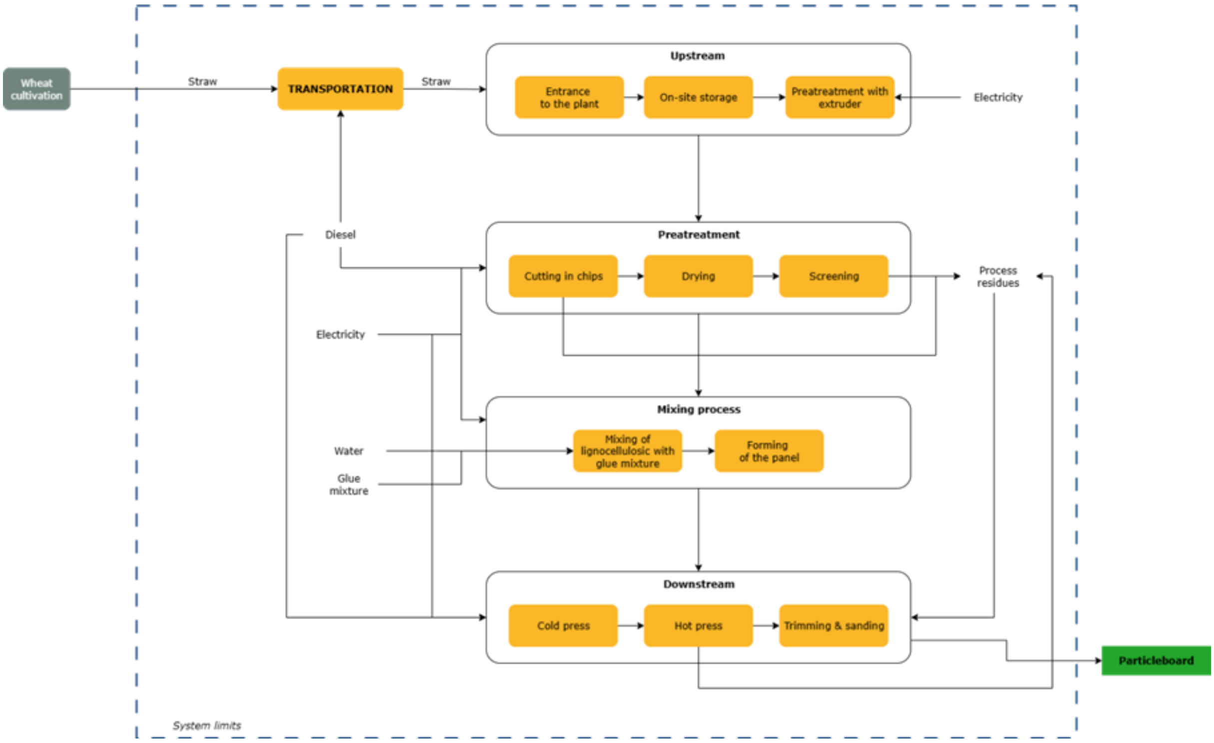


Figure 89. System limits for the particleboard's BioReCer scenario.

Inventory data for the baseline system were obtained from literature and industrial sources on conventional particleboard production, while data for the BioReCer configuration were derived from pilot-scale experiments carried out within the project. Primary data covered the preparation and drying of residues, adhesive formulation, pressing, and finishing operations, as well as electricity and heat consumption. Secondary data were sourced from Ecoinvent v3.10 for background processes. Transport distances were estimated based on realistic regional supply chains in Northern Greece.

The results presented in Annex B and illustrated in Figure 90 and Figure 91 show that the key advantages of the BioReCer scenario is the notable reduction in particulate matter emissions primarily due to the avoidance of open burning of straw and other agricultural residues. However, the comparative analysis reveals several drawbacks and trade-offs. In particular, the BioReCer scenario exhibits higher impact in terms of climate change and fossil resource use, mainly attributed to energy-intensive processing and material treatment. In contrast to the baseline scenario, which is primarily affected by direct emissions, fossil-based product use and waste generation, the BioReCer scenario's dominant impact driver is energy consumption. Nevertheless, it offers a significant benefit in terms of land-use: since straw is an agricultural by-product, its use does not contribute to deforestation, thereby mitigating land-use change impacts. Despite this, the BioReCer scenario shows increased impacts in freshwater and marine eutrophication categories. These are likely linked to upstream agricultural activities, such as fertilizer runoff, and transportation-related emissions, which can raise environmental concerns.

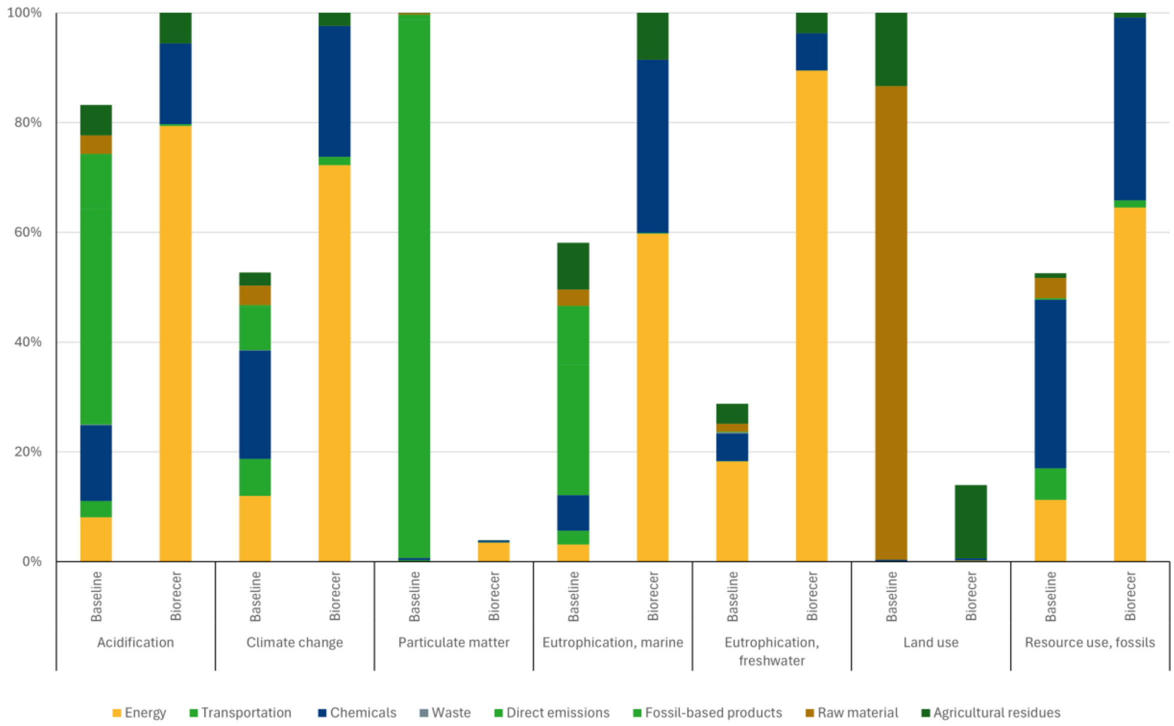


Figure 90. Midpoint impact categories relative comparison for the particle boards case

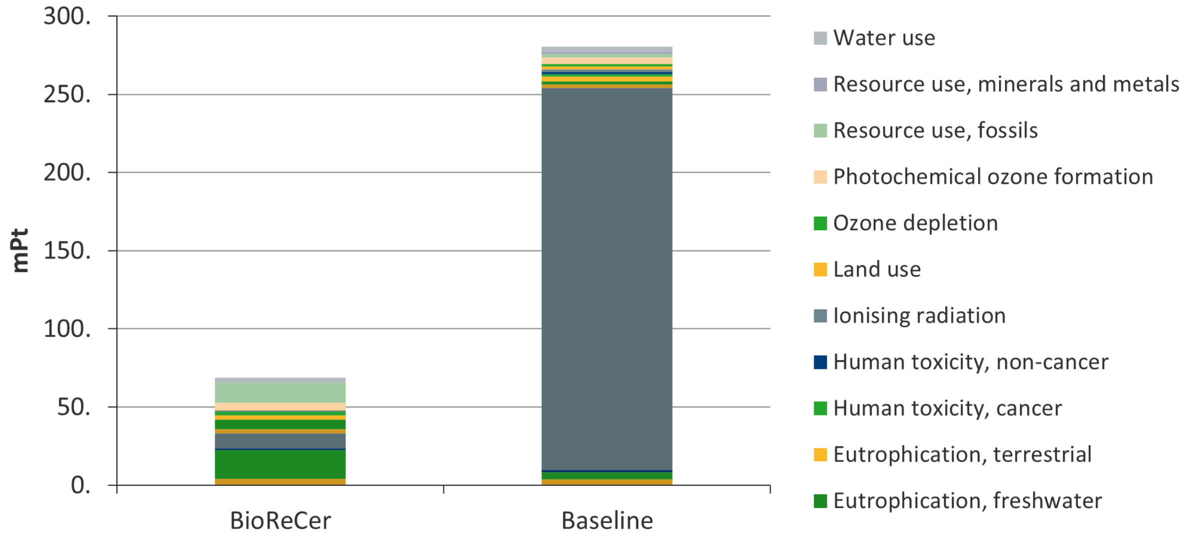


Figure 91. Single score results for both particleboard related scenarios

Despite these trade-offs, the overall environmental profile remains favourable for the BioReCer configuration. The single-score comparison (**¡Error! No se encuentra el origen de la referencia.**) confirms that the BioReCer scenario achieves an overall environmental footprint approximately 30–40% lower than the conventional process.

Overall, this analysis demonstrates that incorporating agricultural residues into the particleboard manufacturing process can significantly reduce environmental impacts, while diversifying feedstock sources and promoting local resource circularity. The findings reinforce the potential of the BioReCer framework to support sustainable material production in Mediterranean regions where agricultural residues are abundant.

3.1.3.2 Biofertiliser value chain

The second assessment in Central Macedonia addressed the environmental performance of agricultural residues and by-products such as straw, prunings, and peach pomace valorisation for the production of organic biofertilisers. The analysis compared a baseline scenario representing the current management of peach pomace (landfilling, straw and prunings (open-field burning) with a BioReCer scenario that integrates anaerobic digestion and composting to obtain high-quality biofertilisers, substituting conventional mineral fertilisers.

The functional unit used was 1 kg of produced biofertiliser. The system boundaries include waste collection, pre-treatment, digestion, composting, and final fertiliser preparation, as well as the upstream production of chemicals, energy, and transport. In the baseline scenario, agricultural residues are typically managed through open-field burning, land application, or disposal, leading to emissions of methane and nutrients to air and water. In the BioReCer scenario, the residue is stabilised and converted into organic fertiliser through composting, producing a material rich in nutrients that can partially replace synthetic fertilisers. The system limits and main process flows are shown in Figure 92 and Figure 93.

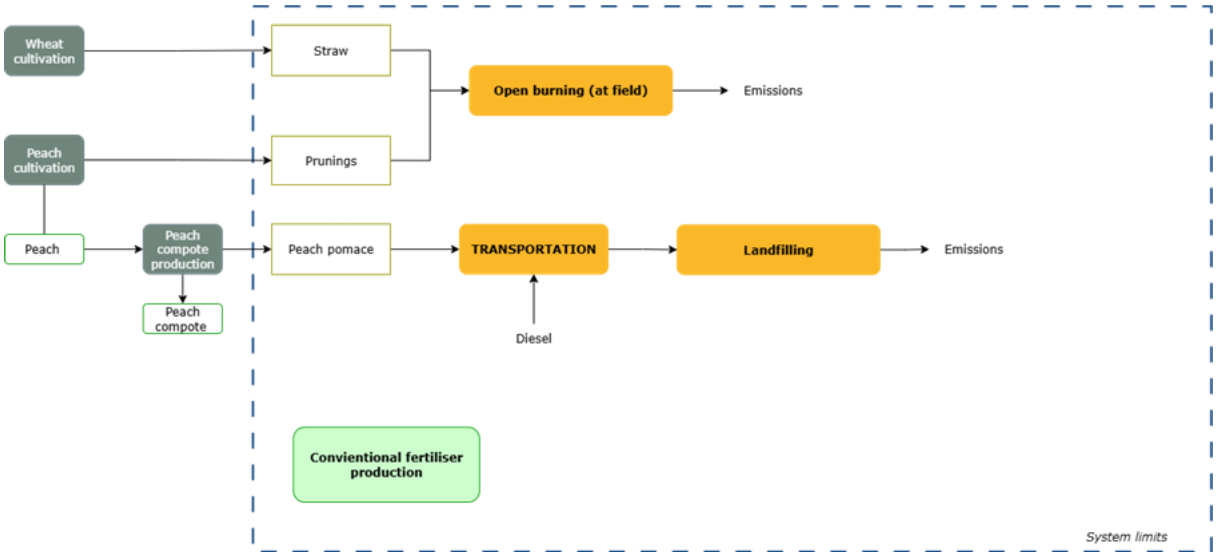


Figure 92. System limits for the fertiliser baseline scenario.

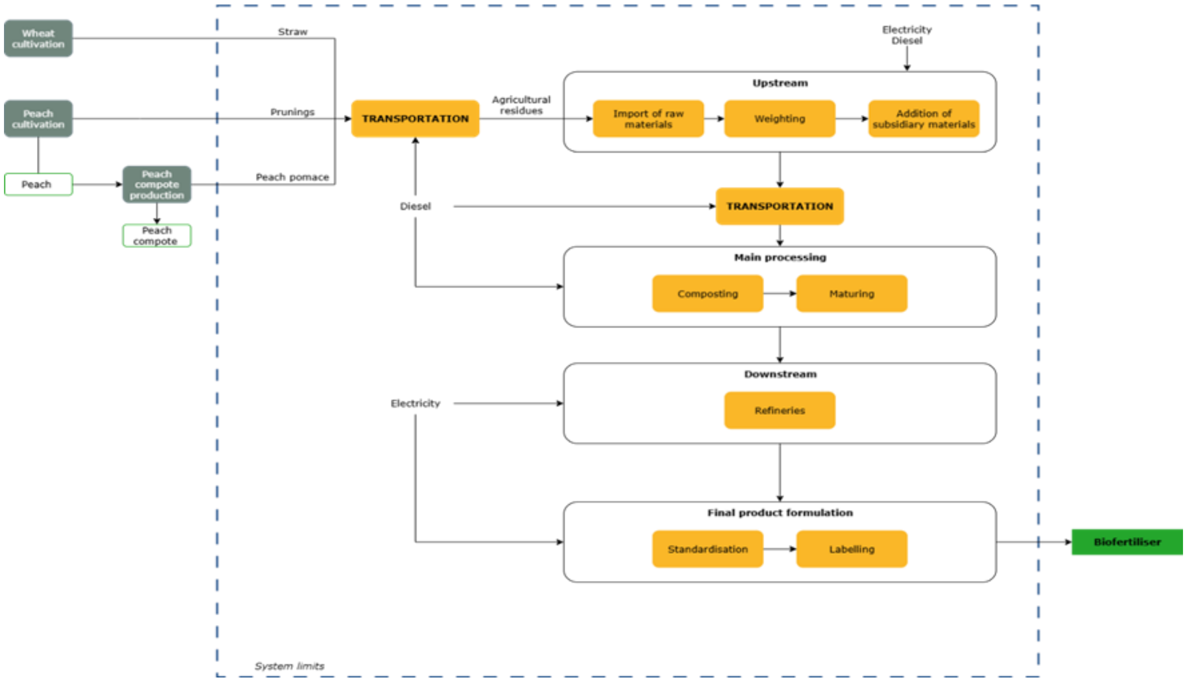


Figure 93. System limits for the biofertiliser BioReCer scenario.

Inventory data were derived from pilot-scale operations and complemented with literature and database sources, including Ecoinvent v3.10 for background processes. Emission factors for composting and digestion were estimated according to IPCC (2006) guidelines. Energy consumption for mixing, aeration, and drying was measured at pilot scale, while transport distances were based on local conditions in Central Macedonia.

The results, shown in Figure 94, indicate that the BioReCer scenario substantially reduces impacts across most categories compared with the baseline. The most significant improvements are observed in climate change, acidification, and eutrophication, resulting from the avoided emissions associated with uncontrolled waste degradation and the substitution of mineral fertilisers. The process also contributes to circular nutrient flows by recycling organic matter back to agricultural soils. The detailed characterisation and normalisation results are presented in Annex B.

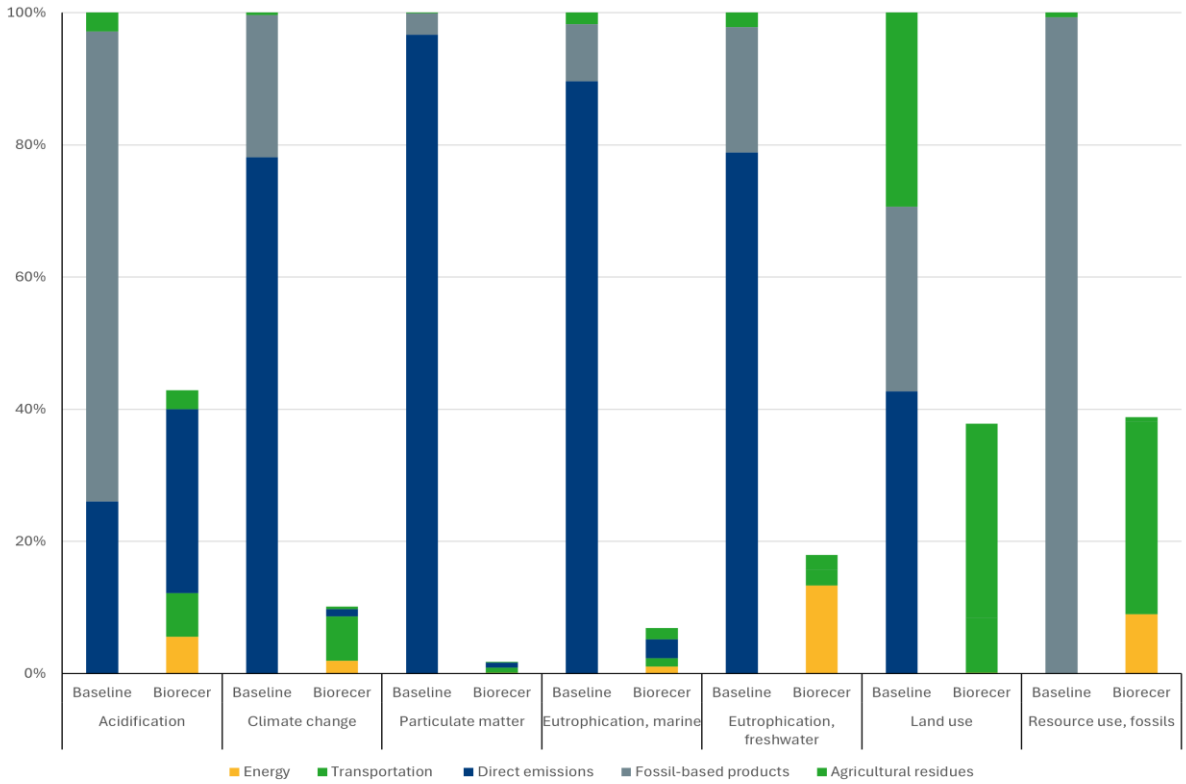


Figure 94. Midpoint impact categories relative comparison for the biofertiliser case.

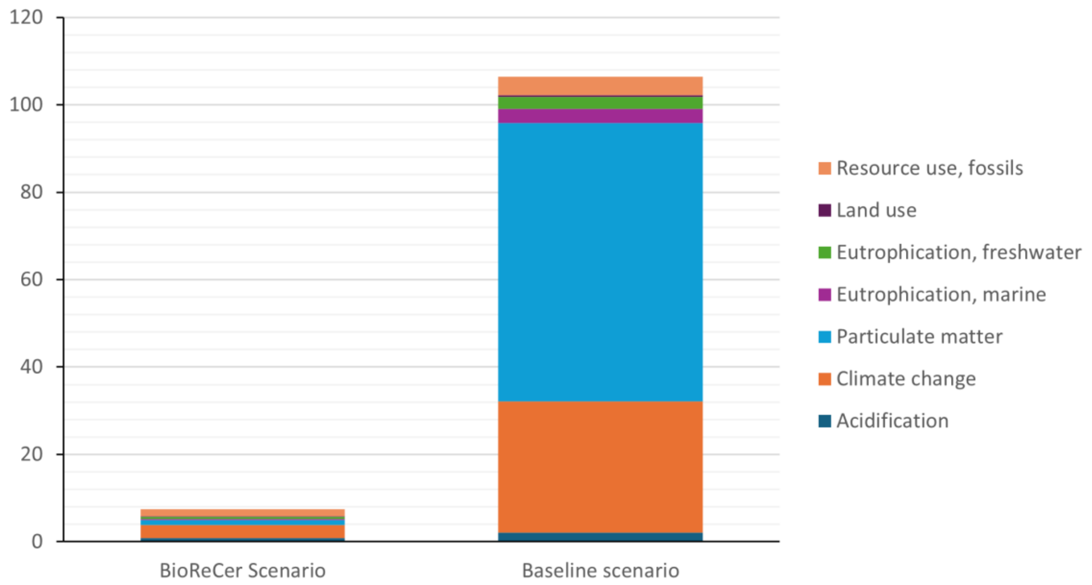


Figure 95. Single score results for both biofertiliser related scenarios

The analysis in Figure 95, further reveals that, in the BioReCer scenario, agricultural residues (such as straw and the associated background processes like cultivation and harvesting), along with transport, and energy use contributes only a relatively small share to the total environmental impact compared to the baseline scenario. Importantly, even in impact categories where trade-offs are commonly observed in bio-based systems, such as land use and fossil resource use, the BioReCer scenario still shows a clear environmental advantage.

3.1.4 Case study 4: Västernorrland, Sweden

3.1.4.1 Forestry residues

Sweden provides about 10% of the sawnwood, and pulp and paper that is traded on the market. This case study evaluates the environmental performance of forestry residue valorisation in the Västernorrland region, comparing a baseline scenario representing current residue management and fossil-based monomer production with a BioReCer scenario integrating hydrothermal liquefaction (HTL) of forestry residues to produce bio-based olefins.

The residues considered include tops and branches (GROT) generated from logging operations, bark from debarking, sawdust from wood sawing, and fibre rejects in the fibre sludge from pulp production. The assessment is based on two industrial facilities, a sawmill with a capacity of 100,000 m^3 of wood input and a pulp mill processing 3,648,000 m^3 of wood (Kangas et al., 2014).

In the BioReCer scenario, forestry residues are processed via HTL to obtain bio-based monomers—mainly n-olefins—used as bioplastic precursors. The baseline scenario assumes conventional production of sawnwood and pulp, where residues such as bark, sawdust, and fibre sludge are used for energy generation, tops and branches (GROT) remain in the forest, and fossil fuel–derived n-olefins are produced. Both scenarios maintain the same land-use conditions. The system boundaries for each configuration are shown in Figure 96 and Figure 97.

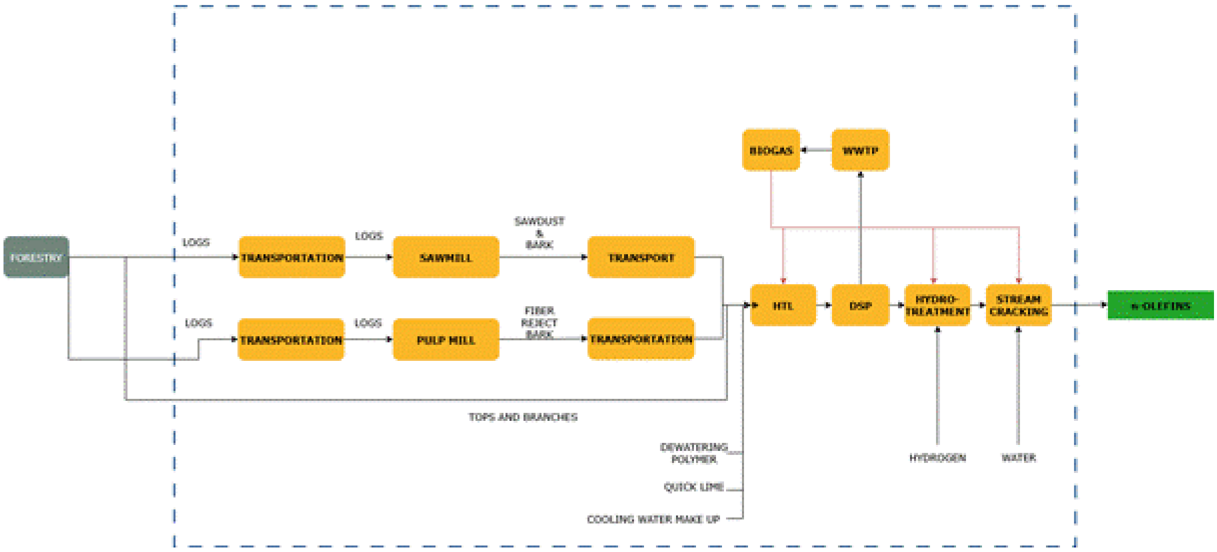


Figure 96. System limits for the BioReCer scenario. HTL stands for Hydrothermal Liquefaction, DSP stands for Downstream Processing

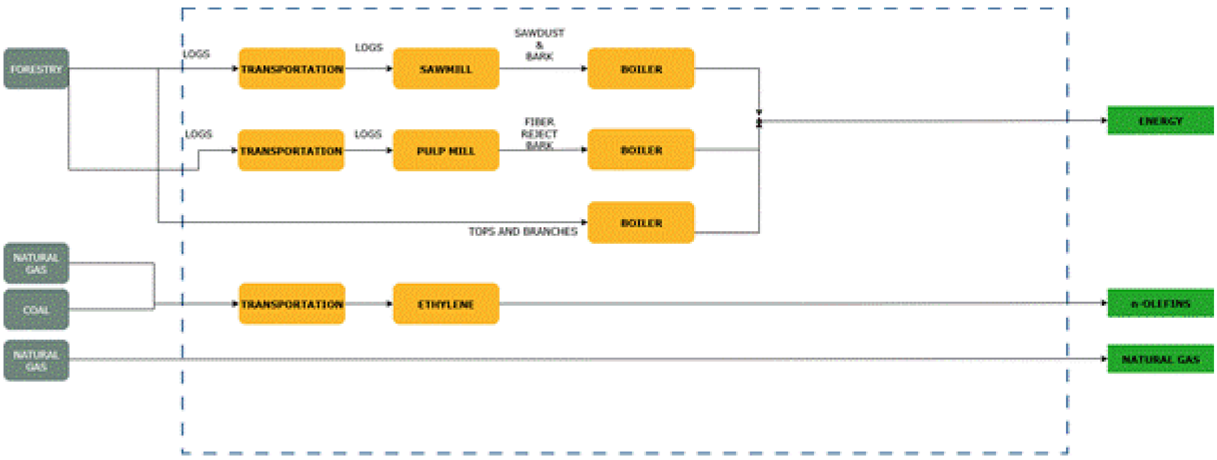


Figure 97. System limits for the baseline scenario. The fossil-based monomers.

The environmental impact assessment followed the same modelling approach and assumptions applied to the other case studies. It considered the entire supply chain from residue collection to product output, including energy and chemical inputs, transport, and emissions from processing stages. Transport distances were kept short, as all facilities are located within approximately 100 km of each other in the Västernorrland region. For the baseline configuration, it was assumed that ethylene and olefin production occur within the same industrial site, using fossil resources imported from within and outside the European Union. The sawmill and pulp mill operations were modelled using representative industrial data for European conditions.

The HTL process uses water and various chemical inputs, and its mass and energy balances are based on the same source. Additional upgrading steps include hydrotreatment to further deoxygenate the HTL biocrude (Jensen et al., 2017) and steam cracking of the hydrocarbons to olefins as reported by Gholami et al. (2021) and Pyl et al. (2011).

The results of the analysis, shown in Figure 98, indicate that the BioReCer scenario outperforms the baseline across most impact categories. For acidification, the baseline scenario shows higher impacts due to emissions from refineries and chemical plants, as well as the use of fossil-based feedstocks, while the BioReCer configuration reduces these impacts thanks to its lower reliance on such inputs. Climate change impacts are also lower for the BioReCer scenario, as its greenhouse gas emissions are largely biogenic and less harmful than those from the combustion or conversion of fossil fuels.

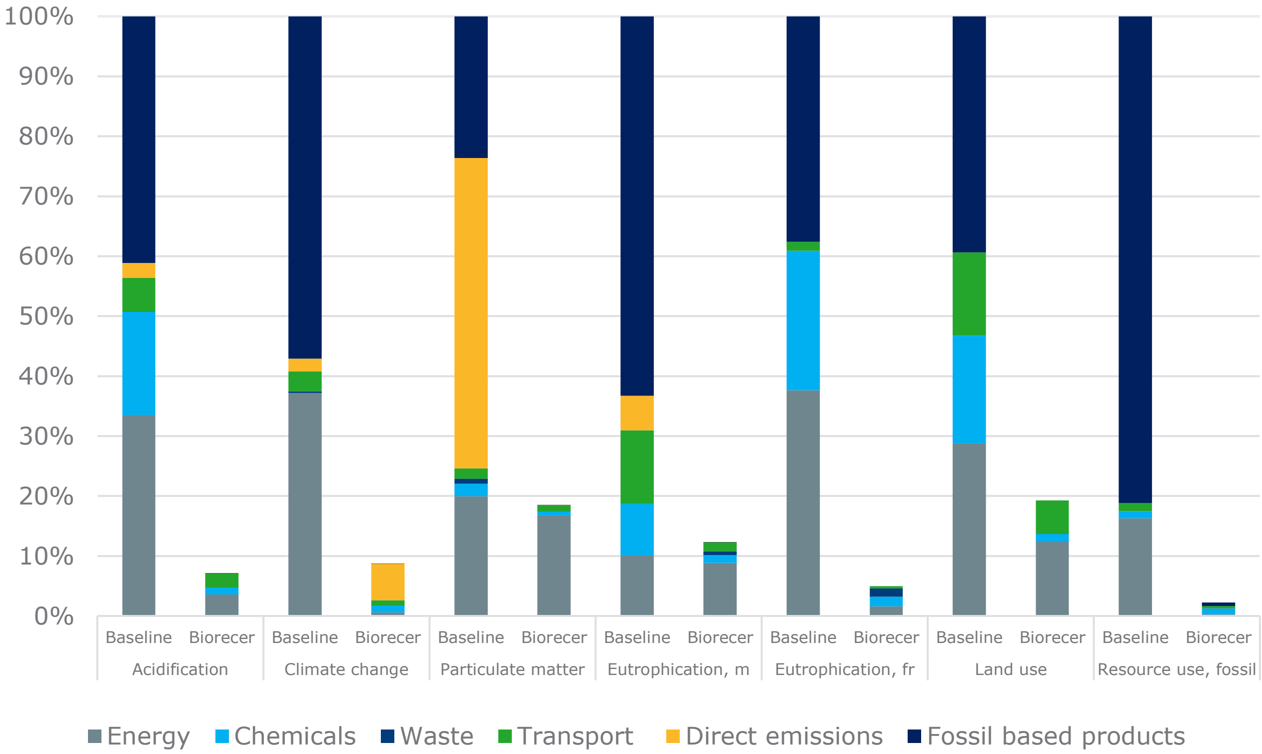


Figure 98. Midpoint impact categories relative comparison for the hydrothermal liquefaction case

For particulate matter, the baseline scenario again shows higher impacts, mainly due to direct emissions of non-methane organic carbon (NMOC) from fossil refining activities. In terms of eutrophication, the production of fossil olefins in the baseline drives marine eutrophication through nitrogen emissions, while freshwater eutrophication stems from phosphorus-containing compounds released during energy and chemical production. The use of forestry residues with lower phosphorus content in the BioReCer system leads to smaller contributions to both eutrophication categories.

Land use impacts are higher in the baseline scenario, as land is required for fossil resource extraction and energy production. In contrast, the residues used in the BioReCer scenario are considered waste materials that require no additional land, thus representing a circular carbon source independent of timber production. Regarding the use of fossil resources, the BioReCer scenario achieves the lowest impact due to its reliance on biogenic carbon and heat integration measures, consistent with the cascading principle of the European Waste Framework Directive.

The aggregated single-score results, presented in Figure 99, confirm the superior performance of the BioReCer scenario. The overall environmental footprint is substantially reduced compared with the baseline, demonstrating the benefits of replacing fossil-based olefin production with bio-based pathways derived from forestry residues. Overall, this case study highlights the environmental advantages of integrating circular carbon flows into existing forestry and pulp value chains, promoting a more sustainable and resource-efficient bio-based industry in Sweden.

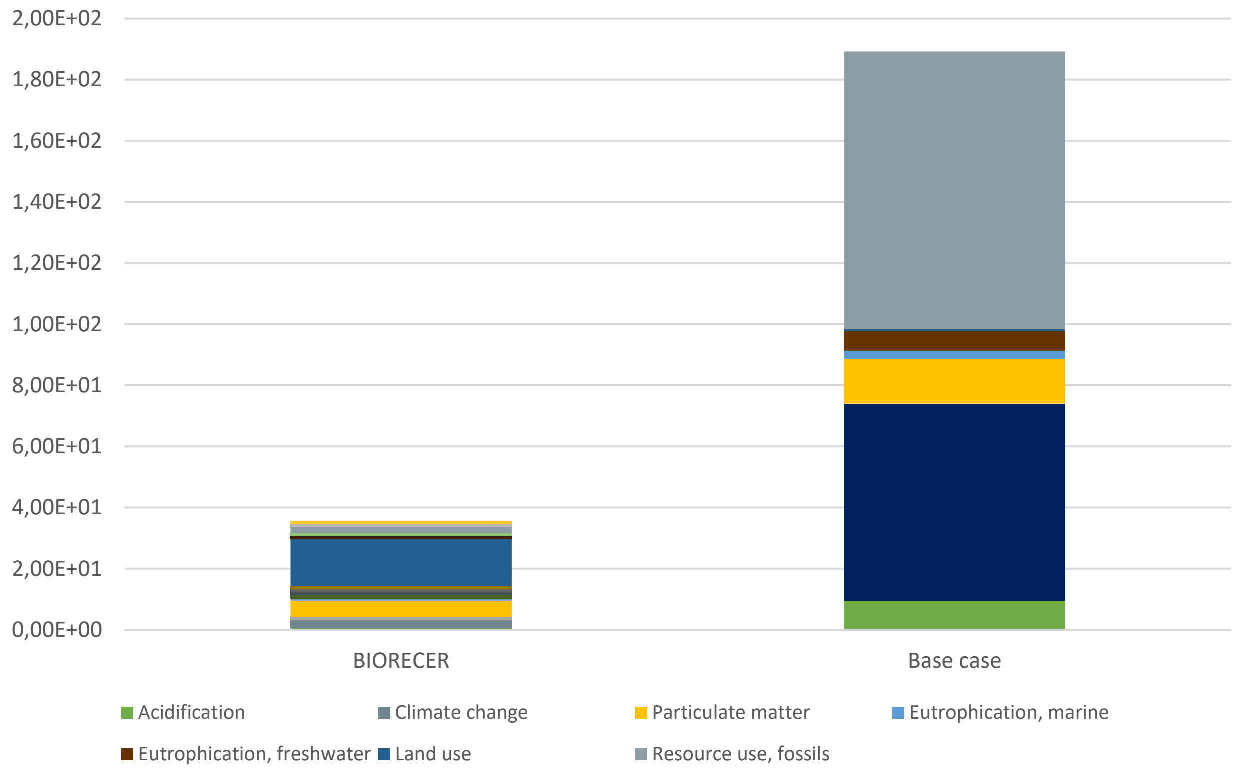


Figure 99. Single score results for both scenarios.

3.2 Conclusions of the environmental outcomes of the BioReCer project

The LCA results obtained for the four BioReCer case studies demonstrate the overall environmental benefits of implementing circular and bio-based strategies compared to conventional linear systems. Across all cases, the BioReCer scenarios show clear improvements in key environmental impact categories, particularly in climate change, acidification, resource use (fossil), and water consumption, highlighting the potential of circular valorisation routes to reduce the overall environmental footprint of industrial and agro-industrial processes.

In Case Study 1 (Galicia), both value chains analysed (polysaccharides from algae and sewage sludge valorisation into VFAs) exhibit significant reductions in environmental burdens under the BioReCer scenario. For the algal polysaccharides, impacts were reduced by 40–60% in most categories due to simpler processing and lower energy and reagent demands. Similarly, in the sewage sludge chain, improvements were mainly associated with reduced chemical consumption and centralised treatment, despite higher energy use during purification.

In Case Study 2 (Italy), the integration of PHA and struvite recovery from wastewater leads to a markedly better performance compared to conventional waste management. Reductions in climate change, freshwater eutrophication, and acidification were achieved due to lower energy consumption, reduced direct emissions, and improved resource recovery. The only trade-off identified was an increase in particulate matter emissions, attributed to magnesium chloride use during struvite precipitation—an aspect that could be mitigated by sourcing alternative reagents or optimising process efficiency.

In Case Study 3 (Greece), both value chains, biofertiliser production from agro-residues and particle boards, confirmed the environmental advantage of circular practices. The biofertiliser route achieved substantial improvements in all categories due to avoided emissions from burning and landfilling agricultural residues. For particleboards, while energy-intensive processing resulted in higher impacts in some categories, the BioReCer system still outperformed the baseline overall, particularly in particulate matter and land use, confirming the potential of agricultural by-products to substitute virgin materials and reduce deforestation.

Finally, Case Study 4 (Sweden) confirmed the environmental benefits of converting forestry residues into bio-oil and olefins through hydrothermal liquefaction. The BioReCer scenario consistently outperformed the baseline in all impact categories, most notably in fossil resource use, land use, and climate change, due to the use of waste-derived biomass and the cascading reuse of carbon and energy flows.

Overall, the LCA validation across all case studies reinforces the environmental relevance of the BioReCer framework and its capacity to support the transition toward a sustainable, resource-efficient, and low-carbon bioeconomy. Although certain trade-offs were identified — mainly linked to chemical consumption or energy use in specific processes— the general trend demonstrates that the circular valorisation strategies proposed within BioReCer can substantially reduce environmental pressures while promoting resource circularity and innovation in key European sectors.

4 Relation of Case Studies with BIT Platform

The BioReCer ICT Tool (BIT) has been validated through the integration of value chains from the four case studies representing different biomass sources and industrial contexts. For each case, the complete chain —from the generation of raw materials or wastes to the production of bio-based products— was uploaded into the platform, following the established methodology to calculate sustainability and circularity indicators.

For the Galician fishery case study (Case Study 1 – Spain), coordinated by ANFACO-CEC, the value chain associated with the tuna cooking process was introduced into the BIT platform as part of the validation activities. The data covered all stages, from waste generation in canning industries to biomass valorisation into high-value ingredients. Information on input and output flows was uploaded for each actor, including tuna canning facilities (primary producers), valorisation processes of cooking waters and residues (intermediate producers), and the transformation of recovered materials into protein extracts or flavour enhancers (final producers). These datasets included operational parameters such as raw material processed, water and energy consumption, by-product composition, and recovery ratios, enabling the calculation of sustainability and circularity indicators and validating the applicability of the BIT tool to the fishery sector.

The sewage sludge case study (Case Study 1 – CETAQUA) also corresponding to the Galician region, focused on the valorisation of urban and industrial wastewater sludge into volatile fatty acids (VFAs). The uploaded data represented all stages of the process, from sludge generation at wastewater treatment plants (waste producers) to VFA concentration and purification (intermediate and final producers). Key inputs and outputs such as treated water volume, COD removed, sludge generated, biogas, and soil improvers were incorporated, allowing dry-matter mass allocation and calculation of relevant circularity metrics.

In the Italian case study (Case Study 2 – Italy), the complete value chain at the biorefinery of Sesto San Giovanni was integrated, covering multiple waste streams including wastewater, sewage sludge, organic fraction of municipal solid waste (OFMSW) and agro-industrial residues. The valorisation of these inputs led to the production of biofertilisers (struvite) and PHA-rich sludge, with all associated flows and by-products such as biogas, and residual sludge included in the tool.

For the Greek case study (Case Study 3 – Greece), two agrifood-based value chains were implemented in the BIT: the production of biofertiliser derived from fruit pomace, straw, and prunings, and the manufacture of straw-based particle boards. Data for all relevant actors — from primary producers to industrial processors— were entered, including inputs, outputs, by-products, energy and material balances, and geographic information, ensuring complete validation of the tool's functionality and indicator calculations.

Finally, the Swedish forestry case study (Case Study 4 – Sweden) introduced data representing the conversion of forest biomass residues into intermediate bio-based products. The value chain began with forest owners producing sawlogs and pulpwood and extended to sawmills and pulp mills, where residual streams were used to produce biooil. These datasets validated the BIT's capacity to manage complex forestry chains involving multiple intermediates and product types.

Further details on the data introduction process and the results obtained from the BIT validation for this case study will be presented in Deliverable D5.3, which will provide an in-depth analysis of the methodology and outcomes.

5 Conclusions

The work conducted within this deliverable has demonstrated the applicability, consistency, and environmental relevance of the BioReCer framework through its validation across four representative case studies covering key European bioeconomy sectors: fishery, wastewater treatment, agro-industrial residues, and forestry.

From the validation of the BioReCer framework, it can be concluded that the circularity indicators developed are conceptually logical, measurable, and aligned with circular economy principles. However, their full implementation and comparability across value chains are still conditioned by the availability, quality, and harmonisation of industrial data. Challenges were particularly evident in pilot or emerging systems (e.g., algae and agro-industrial residues), where incomplete datasets and inconsistent monitoring practices required the use of assumptions and literature-based estimations. Conversely, in mature sectors such as wastewater treatment and forestry, data completeness enabled a more robust assessment. Overall, the framework proved to be a solid basis for measuring circularity performance, but the analysis highlighted the need for standardised reporting and residue characterisation protocols to enhance the reliability of future assessments.

The integration of the case studies into the BIT platform enabled the digital validation of the framework and its operationalisation across diverse industrial contexts. Each value chain — from waste generation to the production of bio-based products— was successfully uploaded and processed, allowing the automatic calculation of sustainability and circularity indicators. This exercise confirmed the flexibility and scalability of the BIT platform, capable of handling complex datasets involving multiple actors, waste streams, and transformation stages. The tool effectively facilitated data organisation, flow allocation, and indicator computation, thus proving its potential as a decision-support system for circular value chain monitoring. Further details on the data introduction process and the results obtained from the BIT validation for each case study will be presented in Deliverable D5.3, which will provide an in-depth analysis of the methodology and outcomes.

Finally, the LCA validation across all four case studies confirmed the positive environmental implications of adopting BioReCer circular strategies. The BioReCer scenarios consistently achieved notable reductions in key impact categories—particularly in climate change, acidification, fossil resource use, and water consumption—when compared to conventional baseline systems. These improvements were mainly driven by reduced energy and chemical requirements, enhanced resource recovery, and the valorisation of waste and by-products. Some trade-offs were identified, such as increased particulate matter formation in specific processes linked to chemical inputs or higher energy use in purification stages. Nonetheless, the overall results clearly demonstrate that circular valorisation pathways substantially lower environmental burdens while contributing to resource efficiency and carbon mitigation.

In summary, this deliverable consolidates the technical, environmental, and digital validation of the BioReCer framework. Together, the results highlight the feasibility of integrating circularity monitoring and environmental performance assessment within real industrial systems, paving the way toward more sustainable bio-based value chains in Europe.

6 List of abbreviations

BIT	BioReCer ICT Tool
BRIE-LL	BioResources Innovation Ecosystem Living Lab
CS	Case Studies
Dx.x	Deliverable x.x
DM	dry mass
EI	Energy indicator
EU	European Union
GROT	Grenar och toppar (Tops and branches in Swedish)
ICT	Information and Communication Technology
ISCC	International Sustainability and Carbon Certification
MFA	Material Flow Analysis
OFMSW	Organic Fraction of Municipal Solid Waste
T&T framework	Track and Traceability framework
VFA	Volatile Fatty Acid
WP	Work Package
WWTP	Waste Water Treatment Plant

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Annex A: The BioReCer Sustainability and Circularity Assessment Framework

Table 42. Answers to the framework questionnaire.

Requirement	Type	CS1 – Sewage sludge	CS1 – polysaccharides	CS2 – Urban and industrial waste	CS3 – Particle boards	CS3 – Biofertilizer	CS4 - Biooil
The company has data available about the type of sources of water use for the production process, including water reclamation	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company has a plan to manage resources and water efficiently	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company identifies the water sources affected by runoffs and discharges	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company identifies and characterizes emissions to air, soil and water in order to comply with legal threshold and proposes strategies to prevent negative impacts	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company shall provide the most updated Environmental Impact assessment (EIA) of the area before starting its operations	Basic	Non applicable	Yes	Non applicable	Yes	Yes	Yes
The company shall indicate whether it adopts ecosystem regeneration and rehabilitation measures	Basic	Yes	Non applicable	Yes	Yes	Yes	Non applicable
The company uses and has appropriate maintenance for machinery, processing, disposal containers, and facilities for handling products, materials, and wastes (excluding legal and safety matters)	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company measures its greenhouse gases (GHG) and has established a reduction plan	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company shall have evaluations about the state of the biodiversity within the area and a plan to maintain and improve biodiversity	Basic	Yes	Non applicable	Non applicable	Yes	Yes	Non applicable

The company shall identify whether its operation is happening in a protected area	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company has some kind of treatment technology to prevent emissions to the environment	Basic	Non applicable	Yes	Non applicable	Yes	Yes	Yes
The company measures the noise and odour to ensure that they are under the legal threshold	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company has an appropriate identification and quantification of the use of chemicals and hazardous substances	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company promotes the use of materials with bio-based origin as well as non-virgin materials on its final products	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company applies the waste hierarchy to reduce and valorise its waste	Basic	Yes	Yes	Non applicable	Yes	Yes	Yes
The company characterizes the introduced genetically modified species	Basic	Non applicable	Non applicable	Non applicable	Non applicable	Non applicable	Non applicable
The company quantifies non-indigenous/invasive species and pathogens introduced into the ecosystem	Basic	Non applicable	Non applicable	Non applicable	Non applicable	Non applicable	Non applicable
The company considers the resilience of the ecosystem to ensure sustainability	Basic	Non applicable	Yes	Non applicable	Yes	Non applicable	Yes
The company establishes and monitors key performance indicators to ensure a responsible use of resources and avoid the degradation of ecosystems	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company has an energy efficiency plan in place	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company identifies whether action has been addressed to ensure food security in biomass production systems	Basic	Non applicable	Yes	Non applicable	Non applicable	Non applicable	Non applicable
The company has established measures to track the disposal of by-products and waste	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company has established measures to improve product traceability	Basic	Yes	Yes	Yes	Yes	Yes	Yes

The company allocates resources to research and development and employee training regarding sustainability and circular economy strategies	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has good management of the unsold finished goods, prevention of generation of waste	Basic	Non applicable	Yes	Yes	Yes	Yes	Yes
The company has in place measures to ensure the optimization of costs (operational, infrastructure, waste treatment)	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company achieves goals of reduction or substitution of resources	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company must ensure that subcontractors also comply with the requirements of the certification schemes	Advance	No	Yes	No	Yes	Yes	Yes
The company has fully documented property rights	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company is a legally defined entity with a clear and documented legal record	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company takes into consideration green procurement criteria in the selection of its suppliers	Advance	No	Yes	Yes	Yes	No	Yes
The company complies with certification schemes and standards verified by a third-party	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has in place specific measures to promote a healthy work-life balance that goes beyond what it is established in national regulation, ILO standards, WHO guidelines, etc	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has a Health and Safety Plan in place	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company provides accident insurance coverage and adequate compensation for all workers	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has effective complaints and grievance mechanisms and take measures to resolve the reported complaints and grievances	Advance	Yes	Yes	Yes	Yes	Yes	Yes

The company ensures equality and no-discrimination in all aspects, regardless of gender, race, ethnicity, religion, age, disability, or any other diversity dimension	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company keeps records on work-related accidents or incidents	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company promotes the participation of its employees on certified training activities and competencies	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has created new jobs positions in line with the needs of the circular economy strategies implemented	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company contributes to enhance the employment rate in the sector	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company ensures the payment of wages that meet or exceed industry minimum standards	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has collaborations with other companies aiming at the good use of resources	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company is able to demonstrate that the implementation of plans, initiatives and practices on circular economy has resulted in economic benefits	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has contracts with suppliers selling products/materials certified as circular	Advance	No	Yes	Yes	Yes	Yes	Yes
The company is willing to share information publicly about its activities related to the circular economy	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has identified the environmental benefits resulting from the implementation of circular economy strategies (reduction, recycling, recovering…)	Basic	Yes	Yes	Yes	Yes	Yes	Yes
The company can demonstrate that its products have the same characteristics and quality as its conventional counterparts	Advance	No	Yes	No	Yes	Yes	Yes
The company has plans, initiatives or practices to ensure the increase of resource productivity	Advance	Yes	Yes	No	Yes	Yes	Yes

The company has defined strategies to promote a system thinking of processes and the analysis of material loops	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has participated in awareness campaigns to promote the benefits of the circular economy	Advance	Yes	Yes	Yes	Yes	Yes	Yes
The company has programmed training activities for workers to tackle with the specificities of circular technologies and/or strategies	Advance	Yes	Yes	Yes	Yes	Yes	Yes

Annex B: Environmental assessment results

Case study 1: Galicia, Spain. Fishery

Table 43. Characterisation result for both scenarios. CS1- fishery

		Climate change (kg CO_2 eq)	Particulate matter (disease inc.)	Acidification (mol H^+ eq)	Eutrophication, freshwater (kg P eq)	Land use (Pt)	Water use (m^3 depriv.)	Resource use, fossils (MJ)
BioReCer scenario	Transport	4.20E+00	4.40E-07	1.05E-02	3.00E-04	6.00E+01	2.90E-01	6.00E+01
	Energy	3.20E+01	5.00E-07	1.10E-01	8.50E-03	9.00E+01	1.70E+01	5.80E+02
	Chemicals	1.20E+01	1.30E-06	7.50E-02	4.50E-03	4.80E+01	4.90E+00	1.70E+02
	Direct emissions	3.50E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste management	9.50E+00	4.00E-07	6.80E-02	2.30E-02	1.30E+01	8.00E-01	4.10E+01
	Total	9.64E+01	3.22E-06	3.13E-01	4.04E-02	2.58E+02	2.39E+01	7.58E+02
Baseline scenario	Transport	5.30E+00	5.10E-07	1.27E-02	3.70E-04	7.10E+01	3.30E-01	7.20E+01
	Energy	7.80E+01	1.10E-06	2.20E-01	1.40E-02	1.40E+02	3.10E+01	1.10E+03
	Chemicals	3.10E+01	2.60E-06	1.39E-01	9.00E-03	6.30E+01	7.20E+00	3.60E+02
	Direct emissions	8.50E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste management	1.20E+01	6.00E-07	8.40E-02	2.80E-02	1.60E+01	1.10E+00	5.10E+01
	Total	**2.03E+02**	**4.43E-06**	**4.85E-01**	**5.66E-02**	**3.87E+02**	**4.22E+01**	**1.60E+03**

Table 44. Single score results for both scenarios. CS1- fishery

	Unit	BioReCer	Baseline
Climate change	Pt	3.20E-03	6.75E-03
Particulate matter	Pt	3.90E-04	6.10E-04
Acidification	Pt	2.95E-04	4.65E-04
Eutrophication, freshwater	Pt	6.80E-04	9.40E-04
Land use	Pt	2.40E-05	3.40E-05
Water use	Pt	1.55E-04	2.70E-04
Resource use, fossils	Pt	1.05E-03	2.10E-03
Total (single score)	Pt	6.33E-03	1.21E-02

Selected impact categories from EF v3.1

Case study 1: Galicia, Spain. Sewage sludge

Table 45. Characterisation result for both scenarios. CS1 – sewage sluge

		Acidification	Climate change	Particulate matter	Eutrophication, marine	Eutrophication, freshwater	Land use	Resource use, fossils
		mol H+ eq	kg CO2 eq	disease inc.	kg N eq	kg P eq	Pt	MJ
BioReCer scenario	Energy	3.94E-01	1.30E+02	1.28E-06	8.99E-02	1.59E-02	2.55E+02	2.85E+03
	Chemicals	4.14E-01	8.72E+01	3.53E-06	1.35E-01	4.76E-02	2.94E+02	1.52E+03
	Waste	4.63E-02	8.90E+00	4.07E-07	4.83E-01	3.47E-02	4.48E+01	1.02E+02
	Transport	8.95E-02	3.80E+01	2.38E-06	2.00E-02	4.11E-03	2.64E+02	5.18E+02
	Direct emissions	3.86E-02	1.97E+02	9.78E-08	1.84E-02	0.00E+00	0.00E+00	0.00E+00
	Total impacts	**9.83E-01**	**4.61E+02**	**7.71E-06**	**7.47E-01**	**1.02E-01**	**8.59E+02**	**4.99E+03**
Baseline scenario	Energy	9.51E-02	2.86E+01	3.04E-07	2.12E-02	3.89E-03	6.29E+01	6.48E+02
	Chemicals	6.76E-01	1.31E+02	6.21E-06	3.70E-01	2.56E-02	2.81E+02	2.46E+03
	Waste	5.22E-01	7.40E+01	3.63E-06	1.92E-01	9.29E-02	7.46E+01	4.20E+01
	Fossil based products	6.41E-01	2.11E+02	9.71E-06	1.24E-01	3.65E-02	4.00E+02	3.96E+03
	Transport	1.97E-01	8.38E+01	5.25E-06	4.40E-02	9.06E-03	5.82E+02	1.14E+03
	Direct emissions	6.72E-03	4.95E+02	1.62E-08	3.31E-03	0.00E+00	0.00E+00	0.00E+00
	Total impacts	**2.14E+00**	**1.02E+03**	**2.51E-05**	**7.54E-01**	**1.68E-01**	**1.40E+03**	**8.25E+03**

Selected impact categories from EF v3.1

Table 46. Single score results for both scenarios. CS1 – sewage sludge

	Unit	Biorecer	Baseline
Acidification	Pt	2.39E-03	1.10E-03
Climate change	Pt	2.85E-02	1.29E-02
Ecotoxicity, freshwater	Pt	1.74E-03	8.16E-04
Particulate matter	Pt	3.78E-03	1.16E-03
Eutrophication, marine	Pt	1.14E-03	1.13E-03
Eutrophication, freshwater	Pt	2.93E-03	1.78E-03
Eutrophication, terrestrial	Pt	1.33E-03	5.09E-04
Human toxicity, cancer	Pt	1.69E-04	5.20E-04
Human toxicity, non-cancer	Pt	2.88E-03	5.20E-04
Ionising radiation	Pt	3.00E-04	9.14E-04
Land use	Pt	1.36E-04	8.32E-05
Ozone depletion	Pt	1.00E-05	8.68E-06
Photochemical ozone formation	Pt	2.08E-03	1.05E-03
Resource use, fossils	Pt	1.06E-02	6.39E-03
Resource use, minerals and metals	Pt	2.49E-03	1.42E-03
Water use	Pt	7.82E-04	2.42E-03
Total	**Pt**	**6.12E-02**	**3.27E-02**

Case study 2: Lombardia, Italy. Urban and industrial waste

Table 47. Characterisation result for both scenarios. CS2

		Climate change	Particulate matter	Acidification	Eutrophication, freshwater	Land use	Water use	Resource use, fossils
		kg CO2 eq	disease inc.	mol H+ eq	kg P eq	Pt	m3 depriv.	MJ
BioReCer scenario	Transport	4.73E+00	4.65E-07	1.14E-02	3.45E-04	7.11E+01	3.24E-01	7.16E+01
	Energy	4.28E+01	6.15E-07	1.46E-01	1.00E-02	1.12E+02	2.06E+01	7.07E+02
	Chemicals	1.99E+01	1.69E-06	9.70E-02	6.54E-03	5.42E+01	6.14E+00	2.60E+02
	Direct emissions	6.11E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Fossil-based products	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Waste management	1.09E+01	5.06E-07	8.12E-02	2.65E-02	1.54E+01	1.03E+00	4.72E+01
	Total impacts	**1.39E+02**	**3.28E-06**	**3.35E-01**	**4.34E-02**	**2.53E+02**	**2.81E+01**	**1.09E+03**
Baseline scenario	Transport	5.28E+00	5.22E-07	1.28E-02	3.86E-04	8.02E+01	3.63E-01	8.01E+01
	Energy	6.15E+01	7.93E-07	1.96E-01	1.36E-02	1.47E+02	2.82E+01	1.03E+03
	Chemicals	2.98E+00	1.43E-07	1.55E-02	5.78E-04	6.69E+00	1.14E+00	5.55E+01
	Direct emissions	9.32E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Fossil-based products	3.08E+00	2.19E-07	5.86E-02	1.08E-03	3.10E+01	1.77E+00	4.77E+01
	Waste management	1.17E+01	5.46E-07	8.76E-02	2.86E-02	1.66E+01	1.11E+00	5.10E+01
	Total impacts	**1.78E+02**	**2.22E-06**	**3.70E-01**	**4.42E-02**	**2.82E+02**	**3.26E+01**	**1.26E+03**

Table 48. Single score results for both scenarios. CS2

	Unit	BioReCer	Baseline
Climate change	Pt	3.89E-03	4.96E-03
Particulate matter	Pt	4.94E-04	3.35E-04
Acidification	Pt	3.74E-04	4.13E-04
Eutrophication, freshwater	Pt	7.57E-04	7.71E-04
Land use	Pt	2.45E-05	2.73E-05
Water use	Pt	2.08E-04	2.42E-04
Resource use, fossils	Pt	1.39E-03	1.61E-03
Total	**Pt**	**7.14E-03**	**8.36E-03**

Selected impact categories from EF v3.1

Case study 3: Region of Central Macedonia, Greece. Biofertiliser case study

Table 49. Characterisation results for both scenarios. CS3 - Biofertiliser

		Acidification	Climate change	Particulate matter	Eutrophication, marine	Eutrophication, freshwater	Land use	Resource use, fossils
		mol H+ eq	kg CO2 eq	disease inc.	kg N eq	kg P eq	Pt	MJ
BioReCer scenario	Energy	0.0001	0.0210	0.0000	0.0000	0.0000	0.0038	0.3004
	Transportation	0.0001	0.0719	0.0000	0.0000	0.0000	0.2739	0.9752
	Direct emissions	0.0005	0.0122	0.0000	0.0001	0.0000	0.0000	0.0000
	Fossil-based products	0.0000	0.0000	0.0000	0.0000	0.0000	0.0001	0.0004
	Agricultural residues	0.0001	0.0040	0.0000	0.0000	0.0000	0.9659	0.0228
	Total impacts	**0.0008**	**0.1090**	**0.0000**	**0.0001**	**0.0000**	**1.2436**	**1.2988**
Baseline scenario	Energy	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Transportation	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Direct emissions	0.0005	0.8409	0.0000	0.0019	0.0001	1.4045	0.0000
	Fossil-based products	0.0013	0.2316	0.0000	0.0002	0.0000	0.9199	3.3235
	Agricultural residues	0.0001	0.0040	0.0000	0.0000	0.0000	0.9659	0.0228
	Total impacts	**0.0019**	**1.0764**	**0.0000**	**0.0021**	**0.0002**	**3.2903**	**3.3463**

Table 50. Single score results for both scenarios. CS3 - biofertiliser

	Unit	Biorecer	Baseline
Acidification	Pt	8.95E-01	2.09E+00
Climate change	Pt	3.01E+00	3.00E+01
Particulate matter	Pt	1.12E+00	6.37E+01
Eutrophication, marine	Pt	2.24E-01	3.25E+00
Eutrophication, freshwater	Pt	4.81E-01	2.71E+00
Land use	Pt	1.19E-01	3.19E-01
Resource use, fossils	Pt	1.65E+00	4.28E+00
Total	**Pt**	**7.50E+00**	**1.06E+02**

Selected impact categories from EF v3.1

Case study 3: Region of Central Macedonia, Greece. Particle Boards

Table 51. Characterisation results for both scenarios. CS3 – Particle boards

		Acidification	Climate change	Particulate matter	Eutrophication, marine	Eutrophication, freshwater	Land use	Resource use, fossils
		mol H+ eq	kg CO2 eq	disease inc.	kg N eq	kg P eq	Pt	MJ
BioReCer scenario	Energy	3.0241	471.9844	0.0001	1.0220	0.3238	71.4390	6572.5541
	Transportation	0.0121	10.1337	0.0000	0.0026	0.0001	0.1698	133.5488
	Chemicals	0.5631	155.9033	0.0000	0.5402	0.0247	108.2029	3390.1471
	Waste	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Direct emission	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Fossil-based products	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Raw materials	0.0000	0.0024	0.0000	0.0000	0.0000	0.0000	0.0528
	Agricultural residues	0.2109	15.5379	0.0000	0.1460	0.0133	3796.9277	89.6298
	Total impacts	**3.8103**	**653.5617**	**0.0001**	**1.7108**	**0.3618**	**3976.7394**	**10185.9327**
Baseline scenario	Energy	0.3086	78.2830	0.0000	0.0535	0.0661	12.4905	1148.3989
	Transportation	0.1138	44.0889	0.0000	0.0434	0.0002	0.7446	585.8004
	Chemicals	0.5261	129.2127	0.0000	0.1100	0.0182	92.6828	3126.1624
	Waste	0.0045	0.4530	0.0000	0.0005	0.0006	0.6939	2.2469
	Direct emission	1.4972	51.1925	0.0016	0.4068	0.0000	0.0000	0.0000
	Fossil-based products	0.3802	2.4659	0.0000	0.1836	0.0005	1.5720	26.1712
	Raw materials	0.1286	23.2155	0.0000	0.0502	0.0053	24594.4303	375.9420

	Agricultural residues	0.2109	15.5379	0.0000	0.1460	0.0133	3796.9277	89.6298
	Total impacts	**3.1699**	**344.4495**	**0.0016**	**0.9940**	**0.1041**	**28499.5419**	**5354.3516**

Table 52. Single score results for both scenarios. CS3 – Particle boards

	Unit	BioReCer	Baseline
Acidification	Pt	4.2446	3.5367
Climate change	Pt	18.1888	4.5939
Particulate matter	Pt	9.6827	244.2348
Eutrophication, marine	Pt	2.5889	2.4069
Eutrophication, freshwater	Pt	6.2816	1.7395
Land use	Pt	0.3838	1.8719
Resource use, fossils	Pt	13.015	2.3685
Total	**Pt**	**54.3855**	**260.7522**

Selected impact categories from EF v3.1

Case study 4: Västernorrland, Sweden. Forestry

Table 53. Characterisation results for both scenarios. CS4

		Acidification	Climate change	Particulate matter	Eutrophication, marine	Eutrophication, freshwater	Land use	Resource use, fossils
		mol H+ eq	kg CO2 eq	disease inc.	kg N eq	kg P eq	Pt	MJ
BioReCer scenario	Energy	3.060E-04	1.330E-02	3.090E-08	1.262E-04	5.712E-06	6.090E-01	1.740E-01
	Transportation	2.000E-04	1.889E-02	1.909E-09	2.121E-05	1.333E-06	2.778E-01	2.758E-01
	Chemicals	1.010E-04	2.770E-02	1.270E-09	1.870E-05	5.540E-06	6.548E-02	6.784E-01
	Waste	8.290E-07	1.560E-04	8.300E-12	9.000E-06	5.020E-06	4.620E-04	1.420E-03
	Direct emission	7.400E-07	1.414E-01	1.600E-12	3.800E-07	0.000E+00	0.000E+00	0.000E+00
	Fossil-based products	9.760E-07	1.090E-04	2.790E-11	4.540E-07	0.000E+00	0.000E+00	3.900E-01
	Total impacts	**6.088E-04**	**2.015E-01**	**3.409E-08**	**2.946E-04**	**1.761E-05**	**9.527E-01**	**1.130E+00**
Baseline scenario	Energy	2.869E-03	8.610E-01	3.681E-08	1.439E-04	1.326E-04	1.422E+00	1.106E+01
	Transportation	4.820E-04	7.670E-02	3.210E-09	1.753E-04	5.280E-06	6.850E-01	9.240E-01
	Chemicals	1.472E-03	3.040E-06	3.890E-09	1.226E-04	8.220E-05	8.910E-01	8.100E-01
	Waste	3.860E-06	5.786E-03	1.530E-09	0.000E+00	0.000E+00	0.000E+00	0.000E+00
	Direct emission	2.132E-04	4.860E-02	9.548E-08	8.183E-05	0.000E+00	0.000E+00	0.000E+00
	Fossil-based products	3.522E-03	1.321E+00	4.363E-08	9.030E-04	1.325E-04	1.946E+00	5.510E+01
	Total impacts	**8.562E-03**	**2.313E+00**	**1.845E-07**	**1.427E-03**	**3.526E-04**	**4.944E+00**	**6.789E+01**

Table 54. Single score results for both scenarios. CS4

	Unit	BioReCer	Baseline
Acidification	Pt	6.78E-01	9.57E+00
Climate change	Pt	2.50E+00	6.45E+01
Particulate matter	Pt	5.40E+00	1.45E+01
Eutrophication, marine	Pt	3.53E-01	2.74E+00
Eutrophication, freshwater	Pt	3.58E-01	6.39E+00
Land use	Pt	1.54E+01	6.01E-01
Resource use, fossils	Pt	1.95E+00	9.09E+01
Total	**Pt**	**2.66E+01**	**1.89E+02**

Selected impact categories from EF v3.1