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Biological Resources Certifications Schemes

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Main biological feedstock flows updated

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Authors

Name	Organisation	Email
Stamatia Skoutida	CERTH	st.skoutida@certh.gr
Anthoula Karanasiou	CERTH	akaranasiou@certh.gr
Maria Batsioula	CERTH	m.batsioula@certh.gr
Sotiris I. Patsios	CERTH	patsios@certh.gr
Georgios F. Banias	CERTH	g.banias@certh.gr

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☐	**DEM**	Demonstrator, pilot, prototype
☐	**DEC**	Websites, patent fillings, videos, etc.
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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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Lead beneficiary

Centre for Research and Technology-Hellas – CERTH (Stamatia Skoutida, Anthoula Karanasiou, Maria Batsioula, Sotiris I. Patsios, George F. Banias)

Contributing beneficiaries

CETAQUA (Lucía González Monjardin, Pedro Villanueva Rey, Carla Carreira Garcia, Jessica Perez Garcia), ANFACO (David Alonso Baptista de Sousa), UNIVPM (Elisa Blumenthal), PROCESSUM (Pietro Bartocci, Anneli Sundman, Isabel Burdallo)

Internal reviewer(s)

Name	Organization	Email
Lucía Jimena Gonzalez Monjardin	CETAQUA	lucia-jimena.gonzalez@cetaqua.com
Nadja Wulff	NOVA	nadja.wulff@nova-institut.de
Elisa Blumenthal	UNIVPM	e.blumenthal@pm.univpm.it
Isabel Burdallo	RISE PROCESSUM	isabel.burdallo@ri.se
Anneli Hellström	RISE PROCESSUM	anneli.hellstrom@ri.se
Pietro Bartocci	RISE PROCESSUM	pietro.bartocci@ri.se
Monica Pandey	MCS	pandey@meo-carbon.com
Sofía Estévez Rivadulla	USC	sofia.estevez.rivadulla@usc.es
Nadja Wulff	NOVA	nadja.wulff@nova-institut.de

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Publishable executive summary

The aim of Deliverable 2.4 is to examine the flows of materials based on the Material Flow Analysis approach. The analysis is conducted on specific regional value chains that also constitute the case studies that are assessed within the BioReCer project, covering the most important pillars of the bioeconomy sector (fishery biomass, urban and industrial waste, agro-industrial biomass and forestry biomass). In the current document, information describing the flows of materials within the established value chains, materials and energy requirements along with the by-products, waste streams and emissions generated throughout the value chains are presented in a concise and practical way. The results of the analysis are provided for 1 kg of final product, and therefore the quantitative information can be used also as a set of conversion factors for the study of similar processes or value chains. A visualisation in the form of Sankey diagrams is included as well, to provide a more comprehensive overview of the flows of the value chains. The information provided in Deliverable 2.4 constitutes the basis for other Tasks performed within the BioReCer project, and in particular the validation of the BioReCer framework that is performed in Task 6.2 and encompasses the calculation of specific indicators in the context of the case studies assessed. Along with the presentation of the fundamental inventories, the key findings of the current deliverable concern the circulation of flows within the value chains, the detection of the most resource intensive stages, and the hotspots in terms of emissions aiming at the more efficient utilization of the biomass feedstocks.

1 Introduction

1.1 Scope and objectives of the Deliverable

The goal of the current Deliverable is to provide detailed information on the specific value chains defined within the case studies of BioReCer project. The information comprises an overview of the value chains and quantitative data for the mass flows of the biological feedstocks, considering the outflows to other processes, up to the production of the final bio-based product. Complementary data are provided for the material and energy inputs to each stage of the value chain along with the waste and emissions generated, considering reliable conversion coefficients. Finally, the extended databases will be used for the calculation of the BioReCer circularity indicators in the context of WP6 for the four different case studies.

In a general context, the presentation of a complete set of data on material flows, resources contribution and waste streams generation sheds light on the efficiency of utilizing the biological feedstocks under study, highlighting gaps and opportunities for the maximization of their added value and retention in the value chain. In parallel, the information contributes to the detection of hotspots in terms of environmental or circularity performance.

1.2 Methodological approach and structure of the Deliverable

The main components of the methodological approach for the fulfilment of D2.4 "Main biological feedstock flows updated" are strongly related to the collection of robust and credible information, data processing and the performance of material flow analysis (MFA). To this end, emphasis has been given on the acquisition of primary data for the description of the case studies, to ensure the accurate reporting of the flows of materials within the local context. Primary data is derived from communication with Cases Study (CS) leaders of the BioReCer consortium and industry experts of the regions under study. Data gaps were covered from regional statistics, official reports and peer-reviewed literature that is directly relevant to the biomass and region of each case. The data is then processed according to the mass balances principle. In this regard, it should be highlighted that all the information is processed to correspond to one unit of final product, thus creating a set of conversion coefficients for each element of the inventory. Additionally, a preliminary environmental impact assessment is conducted on each value chain based on the application of emission factors coefficients. The deliverable is organized in the following Sections of the document:

Section 1 "Introduction": The main scope and objectives of D2.4 are presented as well as the specific content provided and its interrelation with the BioReCer project.

Section 2 "Methodology": A description of the methodological steps that have been applied is provided, focusing on key aspects of implementation that include (i) the mass balances and emissions, (ii) data collection approaches and (iii) the structure of the extended tables.

Section 3 "Results": A separate analysis is conducted for each CS, providing an overview of the defined value chains, the current status of biomass feedstocks in the areas under study, the processes that take place and the extended tables with the quantitative data on the mass flows, resources, waste and emissions.

Section 4 "Conclusions": The key conclusions drawn are presented based on the obtained results.

1.3 Connection with other tasks and deliverables

The current deliverable constitutes an updated version of D2.1 "Main biological feedstock flows". The main differentiation lies in the emphasis given on a regional level, adopting a more case study-oriented approach. In particular, D2.1 examined the generation and fate of biological feedstock flows at a European and country level, comprising a wide spectrum of applications. To complement this information and provide more detailed data on the BioReCer case studies, in the current document the material flow analysis (MFA) is applied on the value chains defined within the project. D2.4 includes data highly relevant to the regional context of the case studies stemming mainly from primary sources and context-specific references. The results are structured based on a unit of the final bio-based product.

Additionally, D2.4 constitutes a basis for other deliverables of the BioReCer project and especially for D6.2 where the validation of the BioReCer certifications schemes on specific case studies will be performed. This document contains practical information for the case studies under investigation presented in a concise and coherent form. The data collected can be directly used for the calculation of the sustainability and circularity indicators that constitute key elements of the BioReCer framework and a basic component of the validation process.

A schematic representation of the interconnection between D2.4 and the other deliverables of the project is depicted in Figure 1.

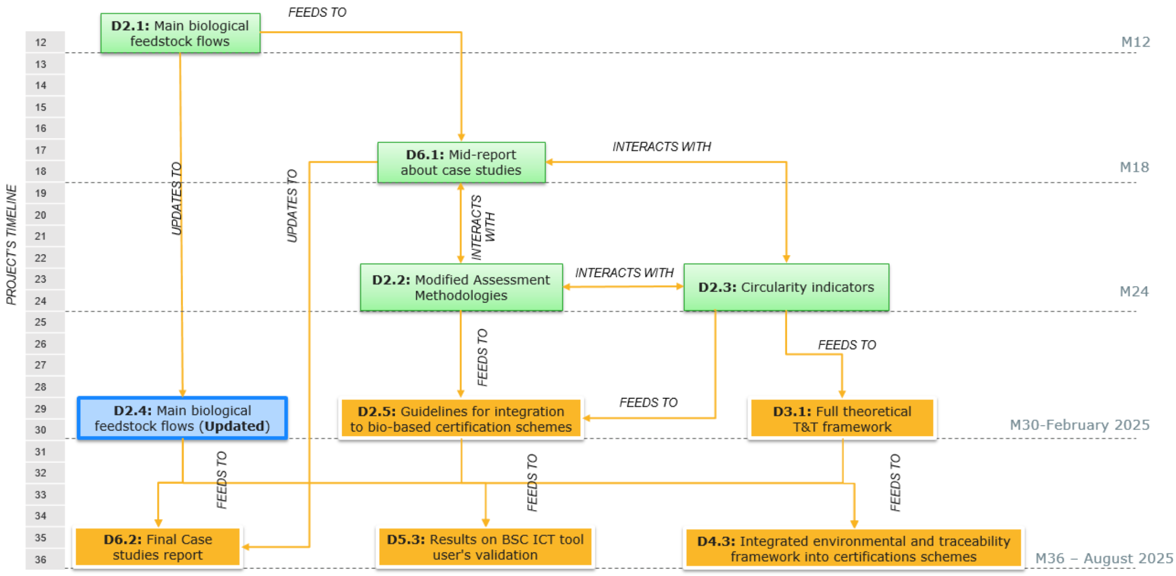

Figure 1: Connection of D2.4 with other deliverables of the BioReCer project.

2 Methodology

2.1 Mass balances and emissions

2.1.1 Material flow analysis

The flows of materials across the BioReCer value chains are calculated based on the principle of mass balance which is a key component of the material flow analysis (MFA). The MFA is a tool that is widely employed to investigate flows and stocks of resources within a defined system (Laner et al., 2016). This method sheds light on the connection among sources, valorization routes and end-uses. It provides quantitative information on material and energy input and output processes, use of resources and stock calculations. To complement, the substance flow analysis (SFA) is applied to specific value chains where it is deemed relevant as a systematic assessment of the flows and stocks of a substance within a system. MFA and SFA map out the flow of materials and substances and offer critical insights into the efficient utilization of resources, product design, waste treatment, environmental management and the estimation of the environmental impacts (Huang et al., 2012; Ning et al., 2025; Raj et al., 2024).

The MFA is based on the law of the conservation of matter (first law of thermodynamics), which states that matter (mass, energy) is neither created nor destroyed by any physicochemical process. It means that what inserts into the system is either accumulated in the system or is leaving the system again as an output and can be expressed as:

$$\text{Total inputs} = \text{Total outputs} + \text{Net accumulation} \quad (1)$$

Therefore, the performance of mass balances entails the quantitative estimation of inputs and outputs of each stage by applying the principle of mass conservation. This is usually performed by employing stoichiometric or technical coefficients and may be assisted by computer simulation. The balancing contributes to the verification of accuracy of empirical data, improved consistency, and estimation of unknown quantities. The MFA provides a comprehensive overview of the material flows and a valuable basis for the management of resources and their circulation in the value chain. This information is critical for the effective utilization of resources, the recovery of materials, energy or components and their retention in the value chain in alignment with the principles of circular bioeconomy.

The MFA can be conducted at a national, regional, industrial, enterprise, and business site levels utilizing the mass-balancing concept (Choi et al., 2024). In the current analysis, the MFA is applied on specific value chains studied in specific regions leading to the production of bio-based products deriving from residual biomass streams. To complement the material flows, quantitative information on the raw material and energy inputs along with the generated by-products, emissions and waste streams are also provided, leading to the creation of complete inventories.

2.1.2 Emission factors

According to the Intergovernmental Panel on Climate Change (IPCC), the emission factor (EF) is defined as a coefficient that quantifies the emissions or removals of a gas per unit activity. Emission factors are often based on a sample of measurement data, averaged to develop a representative rate of emission for a given activity level under a given set of operating conditions. The estimation of emissions is performed based on Eq. 2:

$$\text{Emissions} = \text{AD} \cdot \text{EF} \quad (2)$$

Where AD is the activity data that refers to human activity relating to the emission source (can be area, animal numbers or mass unit, depending on the source type), and EF are the emission factors that quantify the emissions or removals per unit activity (IPCC, 2019). To maximize accuracy, it is important to select emission factors that are appropriate for the relevant context. The elaborate selection of emission factors is presented in further detail in Sections 2.2, 3.1.3-3.4.3.

The estimation of emissions generated across the value chains under analysis is performed, with relevant information being provided through the Global Warming Potential (GWP) indicator. The Global Warming Potential (GWP) is a characterization factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to that of carbon dioxide over a given period of time (Dodd N., 2021). It is a metric that examines each greenhouse gas's ability to trap heat in the atmosphere compared to carbon dioxide. Gases which contribute to global warming include carbon dioxide (GWP of 1 – reference), methane (GWP of 28) and nitrogen dioxide (GWP of 298). GWP is expressed in kg CO_2-equivalents. It is highlighted that this indicator is the one of the most studied in scientific literature for the evaluation of climate impacts within environmental assessments (McAuliffe et al., 2023). The quantity of the pollutant can be estimated by employing the appropriate emission factors for the context of the assessment. The estimation of emissions provides valuable insight on the climate-related impacts of an activity and helps in the identification of hotspots and the elucidation of the vulnerabilities.

2.1.3 Outline of the methodological steps

The steps that are followed for the performance of the current analysis are described below:

1. Definition of the system boundaries and development of the value chain stages.
2. Estimation of the quantities of available biological feedstocks generated in the areas under analysis.
3. Extraction of data for the main biological feedstock flows, material and energy consumption through the value chains.
4. Performance of the mass balances and substance flow analysis, where relevant.
5. Estimation of emissions based on the emission factors coefficients.
6. Processing of data and creation of the extended data tables.
7. Visualization of the results and interpretation.

2.2 Data collection

Data collection is a critical point for the credibility of the analysis. The objective of the study is to collect data that are representative of the studied regions of each CS of the BioReCer project. To achieve this, the collected data and resulting analyses have been developed in close collaboration with the case study leaders.

For the preparation of D2.4, data were retrieved from the following sources:

- Regional and national statistics
- Primary data from companies
- Communication with CS leaders, local experts
- Credible databases (e.g. ecoinvent)
- Peer reviewed literature

Statistical data were drawn from databases managed by local statistical authorities. Specifically, for **CS1 (Spain)**, data were retrieved from Instituto Galego Estatistica (IGE) (https://www.ige.gal/web/index.jsp). IGE is the official statistical office of Galicia, a region in northwest Spain. It is responsible for collecting, analyzing, and disseminating statistical data related to various aspects of Galician society and economy. IGE's main functions include:

- Conducting surveys and censuses on population, health, education, labor, and other sectors
- Providing statistical information on economic activities, such as agriculture, industry, and services
- Publishing reports and data on social conditions, including culture, leisure, and living standards

For **CS2 (Italy)** data were provided by a company responsible for managing integrated water services (water supply, sewage, and wastewater treatment) in the Metropolitan City of Milan. In particular, information relating to the capacity, process flow diagrams and operating parameters of seven Wastewater Treatment Plants (WWTP) of the region of Lombardy, was supplied. Specific information on waste characterization based on laboratory analyses is also provided by the company.

For **CS3 (Greece)** data were collected from the Hellenic Statistical Authority (ELSTAT) (https://www.statistics.gr). ELSTAT is the Greek national statistical service. It operates as an independent authority, having operational, administrative, and financial autonomy. ELSTAT is responsible for collecting, producing, and disseminating official statistics in Greece. ELSTAT's main functions include:

- Conducting statistical surveys and censuses
- Coordinating the activities of other agencies within the Hellenic Statistical System (ELSS)
- Providing statistical data to national and international organizations, including Eurostat

The Official statistics of Sweden (SCB) (https://www.scb.se) was used for **CS4 (Sweden)**. SCB provides reliable and objective information for public use, research, and policy-making. These statistics cover a wide range of areas, including population, labour market, economy, environment, and more. SCB is the main agency responsible for coordinating and producing these statistics. The data is regulated by the Official Statistics Act and the Official Statistics Ordinance, ensuring that it is objective, relevant, and accessible to the public.

For established value chains, such as fishing (CS1), wastewater treatment (CS1 and CS2), fruit cultivation (CS3), forestry (CS4) data were also collected from peer reviewed literature, which were verified and enriched by the experts' opinion of each field. Furthermore, for value chains of existing-operating industries (e.g. CS3 bio-fertilizers and particle boards industries), valuable primary information was retrieved by communication of the CS leaders with the engaged stakeholders of the project. For non-existing value chains, i.e. volatile fatty acids production (CS1), reliable data were used from operating pilot plants. These data were adjusted for an industrial scale unit. Detailed information on the sources of the data for each CS is given in the following chapters.

Concerning the energy consumption conversion coefficients for transportation, data were collected from the "Ecological Transport Information Tool for Worldwide Transports (ETW)" (Knörr et al., 2014) published by the EcoTransIT World Initiative (EWI) (https://www.ecotransit.org). EWI is an independent industry driven platform for carriers, logistics service providers and shippers dedicated to maintain and develop a globally recognized tool and methodology for carbon footprints and environmental impact assessments of the freight transport sector. EWI aims at continuously developing and harmonising the emission calculation methodology for the global transport sector. The methodology follows the guidelines of the standard EN 16258 "Methodology for calculation and declaration of energy consumption and greenhouse gas emissions of transport services" and integrates the latest research available for air pollutants. The data presented in ETW were taken from "The Handbook of Emission Factors for Road Transport 3.2". The energy consumption data that were used for selected trucks with different load factors in Europe are given in Table 1.

Table 1: Energy consumption conversion coefficients (in MJ/km) of selected trucks with different load factors in Europe (Knörr et al., 2014).

Vehicle Type	Full (100%)	Average (50%)	Empty (0%)
> 3.5-7.5 t	5.1	4.9	4.7
> 7,5-12 t	7.1	6.6	6.1
> 12-20 t	8.5	7.8	7.0
> 20-26 t	10.6	7.8	7.8
> 26-40 t	13.3	9.1	8.2
> 40-60 t	19.0	10.9	9.9

In order to determine the consumption of diesel, the net calorific value (NCV) for each CS country was used. The data were retrieved from Eurostat for 2020 (Eurostat, 2025). In Table 2 the diesel consumption conversion coefficients for selected loads (100%) are depicted. These values are comparable to the respective diesel consumption values presented in the EU Reference Scenario 2020 (European Commission, 2020). The EU Reference Scenario is one of the European Commission's key analysis tools in the areas of energy, transport and climate action. It allows policy-makers to analyse the long-term economic, energy, climate and transport outlook based on the policy framework in place in 2020. This scenario can provide policy-makers with a comprehensive analytical basis against which they can assess new policy proposals. National experts from all EU countries contributed to the Reference Scenario 2020 through a consultation process, and stakeholders have also contributed on technology assumptions.

Table 2: Diesel-oil consumption conversion coefficients of loaded trucks (100%) in L/100km. Comparison with the EU Reference Scenario 2020.

Vehicle Type	**Diesel-oil Consumption (L/100km)**			
	Spain	*Greece/Italy*	*Sweden*	*EU Reference Scenario 2020*
>3.5-7.5t, full	13.95	14.08	14.20	13.1 (3.5-7.5 t)
>7.5-12t, full	19.43	19.61	19.77	18.9 (7.5-16 t)
>12-20t, full	23.26	23.47	23.67	26.5 (16-32 t)
>20-26t, full	29.00	29.27	29.52	-
>26-40t, full	36.39	36.73	37.04	36.5 (>32 t)
>40-60t, full	51.98	52.47	52.91	-

The *emission* conversion coefficients for transportation and other activities attributed to the stationary and mobile combustion of diesel-oil were calculated in kg CO_2-eq, where the emissions of CO_2, CH_4 and N_2O were taken into account. The factors presented in the updated "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (Gómez et al., 2006a, 2006b) were used and were converted into kg CO_2-eq/kg diesel oil, taking into account the NCV for diesel-oil of each country. The results are depicted in Table 3.

Table 3: GHG emission conversion coefficients for the combustion of diesel-oil in kg CO_2-eq/ kg of diesel oil

	Spain	**Greece/Italy**	**Sweden**
Emissions for stationary combustion of diesel-oil (in energy, manufacturing and construction industries)	3.197	3.167	3.141
Emissions for mobile combustion of diesel-oil	3.240	3.210	3.183

(road transport)			
Emissions for mobile combustion of diesel-oil (water born navigation)	3.189	3.219	3.162

For the collection of electricity related GHG emission factors (EFs), a database provided by the Joint Research Centre (JRC) was used, which was created in the context of EU and Global Covenant of Mayors (CoM) for Climate and Energy. The dataset is also referred to as National and European Emission Factors for Electricity (NEEFE). In the current deliverable EFs used were the ones calculated with the activity-based approach. The activity-based approach builds on IPCC emission data for stationary combustion of the most commonly used energy sources and carriers. Furthermore, it was selected to express the emissions in CO_2-eq, were three GHGs are included, namely CO_2, CH_4 and N_2O. For the GHG EFs, GWPs for a 100-year time horizon are combined with each of the single-gas EFs (Bastos et al., 2024a, Bastos et al., 2024b). In Table 4 the GHG emission factors for national electricity of the CSs (in t of CO_2-eq/MWh) are depicted.

Table 4: Covenant of Mayors (CoM) emission factors for national electricity of the CSs: Activity-based (IPCC) approach, GHG emissions in t CO_2-eq/MWh

	Spain	Italy	Greece	Sweden
Year	2021	2021	2021	2021
Emission factor (t CO_2-eq/MWh)	0.175	0.285	0.412	0.015

2.3 Description of extended data tables

The objective of the extended tables is to summarize in a compact and uniform way the quantitative information that describes each defined value chain. More specifically, all the inflows (including the main feedstocks, additional raw materials, resources and utilities) and outflows (referring to the material streams, waste, losses and emissions) are provided. This information will serve as a practical basis for the complete documentation of the mass flows and the calculation of the indicators developed within the BioReCer project.

A thorough description of the structure and components of the extended tables is provided below. This guideline refers to the generic version of the table, which has been further modified to adapt to the specific conditions of each case study. For each case study, a flow diagram is created, depicting the stages and flows of the value chain, based on which the extended tables are built. A schematic representation of a module of the flow diagram value chains is illustrated on Figure 2. This module includes all the input and output flows of a process.

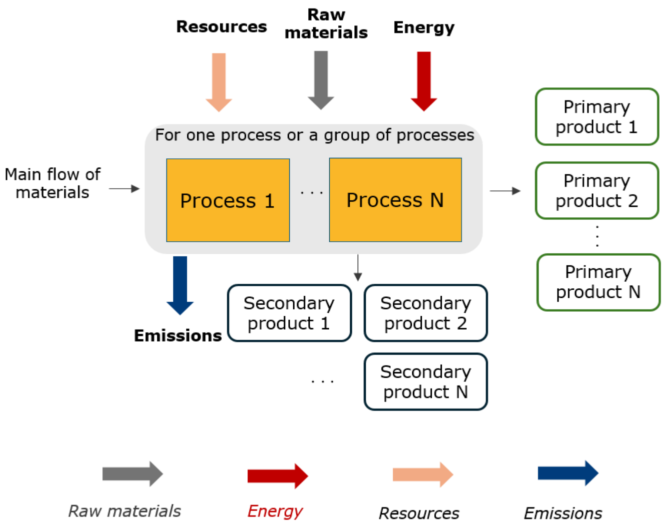

Figure 2: Schematic representation of the modules of the value chains that correspond to the extended tables

2.3.1 Structure of the Extended Table

- **Process stages**

Each value chain is divided into "process stages". The "process stage" constitutes an aggregation of stages of the value chain that serve the same purpose (e.g., pretreatment of the material, transportation, etc). Appropriate coding along with a short description of the scope of each "process stage" is provided on the diagrams, which are represented in Figure 2.

- **Input section**

Each "Process stage" is associated with specific resources that are required for its proper function. A flow number is assigned to each input stream. Two levels of categorization have been assigned for the complete definition of the input streams. According to the **first level of categorization**, namely "Flow categorization", the input streams can be divided into four large categories (Table 5):

Table 5: Description of first level of categorization for input components of the Extended Tables

Name	Description
Main flow (total or component)	It refers to the main biological feedstock of interest that is evaluated within the BioReCer project. This input category is a basic component for the system under analysis and the basis on which the material flow analysis is performed. Therefore, an additional level of detail is provided with specifications about the moisture content and the dry mass of these kinds of flows while in some cases the substance analysis is provided.
Resources	This category includes assets or materials that are utilized in the production stage but are not consumed as part of the final product. For instance, the land and water used within production are registered as resources.
Raw material	It includes all other input materials that are added directly to the system.
Energy	It refers to the power sources required and includes fuels and electricity provided to the system.

On the **second level of specification**, the precise input category is specified. Moreover, for each input flow the quantitative information is provided expressed in specific measuring units. An additional level of detail is provided for the substance flow of the main materials in cases where this information is relevant.

Output section

A similar approach is followed for the construction of the output flows, which also comprise a unique flow number and two levels of categorization. The **first level of categorization** defines the output categories as (Table 6):

Table 6: Description of first level of categorization for output components of the extended tables

Name	Description
Main flow (total or component)	The main flow constitutes the obtained intermediate product of each stage. The processing of the main flow leads to the final product and thus it is the main internal flow. Given the importance of this output category, an additional level of specifications is provided regarding the moisture content, the dry mass and the elemental components where necessary. Also, any losses or alternative uses associated with this flow are quantified in the corresponding columns.
Primary product	This category refers to the main commodities that are produced on the stages (e.g., primary production, processing units) of the value chain.
Co-product	A product that is produced along with the main product
Other by-products	This section refers to the by-products that are generated through the processing stage and are not related to the main flow.
Waste	This category includes the waste streams generated on the stages (e.g., primary production, processing units) of the value chain.
Emissions (direct)	Direct emissions derive from sources that are controlled within the processing stage. It includes the emissions that are directly created by, for instance, the use of diesel and corresponds to the Scope 1 emissions according to the GHG Protocol.
Emissions (indirect)	This kind of emissions is not generated on-site. It occurs in the facility that produces the energy consumed, such as electricity or steam and refers to the Scope 2 emissions according to the GHG Protocol. It is highlighted that the indirect emissions are related only to the supply of energy and do not include the emissions derived from the infrastructure or raw materials utilized.

Similarly to the input section, the quantitative information of each flow is presented, expressed in specific measuring units. Part of the data referring to the main flows is presented in wet mass (WM) or dry mass (DM), while information regarding the moisture content (MC) is also provided in the cases that this data is relevant to the analysis.

Throughout the whole table, the quantitative information (both of input and output streams) corresponds *to 1 kg of final product as is*. Therefore, the data of the extended tables can be utilized as conversion coefficients for the estimation of (i) material conversion yields throughout the main stages of the value chain as well as important sub-processes, (ii) all the necessary inputs in terms of materials and energy that are required for the appropriate operation of each stage, (iii) flows of the main materials assessed covering the losses and alternative uses (where applicable), (iv) the creation of co-products, by-products, waste streams and emissions for each stage.

The structure of the input-output tables is indicatively presented in Figure 3. In some cases (e.g. the sewage sludge value chain) the tables may differ depending on the specificities of the value chain. Furthermore, some repeated inputs and outputs are omitted

Inputs						
Process Stage	Description	Flow Number	Level 1: Flow Characterization	Level 2: Material Specification	Measuring Unit	Quantity
BFR-101	Upstream	101	Energy	Electricity	kW	0.0001
		101	Energy	Diesel	L	0.0010
		102	Raw material	Straw	kg DM	0.2450
		103	Raw material	Prunings	kg DM	0.1497
		104	Raw material	Pulp	kg DM	0.7623

Outputs												
Flow Number	Level 1: Flow Characterization	Level 2: Material Specification	Measuring Unit	Total Quantity			Loss			Available Quantity		
				FM	MC	DM	Total	DM	Water	FM	MC	DM
102	Main flow - Total	Mixture	kg			1.16	0.14	0.06	0.08	2.59	1.49	
102	Main flow - Component	N	kg			0.0107		0.0005				
102	Main flow - Component	P	kg			0.0022		0.0001				
102	Main flow - Component	K	kg			0.0135		0.0007				
102	Main flow - Component	C	kg			0.5667		0.0283				
103	Emissions - diesel	CO2eq	kg	0.0005								
104	Emissions - Electricty	CO2eq	kg	2E-05								

Figure 3: Outline of the extended tables

3 Results

The description and results for each CS are presented in the following subsections.

3.1 Case study 1: Galicia, Spain

3.1.1 System boundaries

Galicia is one of the 17 autonomous regions that make up the political map of Spain. It is located in the northwest Iberian Peninsula, and it covers 29,574.4 km^2 (Instituto Galego Estatistica, 2025; Piñeiro-Antelo et al., 2019). It is divided into four provinces, A Coruña (7,949.90 km^2), Lugo (9,858.03 km^2), Ourense (7,273.96 km^2) and Pontevedra (4,494.85 km^2). In 2024 its population reached 2,705,833 inhabitants with Pontevedra being the most populous (population density 210.9). Specifically, A Coruña's population was 1,128,449, Lugo's 325,048, Ourense's 304,467 and Pontevedra's 947,869. In total, Galicia consists of 313 municipalities (Instituto Galego Estatistica, n.d.). A map of the region is depicted in Figure 4. The main activities of Galicia include fishing and aquaculture, agriculture and livestock, textile industry, shipbuilding, automotive industry, forest and wood, renewable energies, tourism and food industry.

Figure 4: The Region of Galicia (Encyclopædia Britannica)

The biomasses which are studied for CS1 in the context of BioReCer are the *fishery products* and the sewage sludge coming from the local *Wastewater Treatment Plants (WWTP)*.

Biomass from fishery products

According to the EU legislation the fishery products are aquatic organisms resulting from any fishing activity or products derived therefrom.
In the context of external trade statistics, fishery products consist of:

1. Edible fishery products, including fresh, chilled, frozen, salted, smoked and dried fish, fish preserves and conserves, fresh, chilled, frozen, dried and smoked crustaceans and molluscs and preparations and conserves of crustaceans and molluscs
2. Inedible products, including meals and soluble, oils and fats, sponges, corals, etc.
3. Aquatic plants.

The fisheries sector plays an important role in the EU economy, being the fifth largest producer in the world in terms of capture and aquaculture. In 2019, Spain was the first among the EU-28 countries in fishery capture, representing around 17.5% of EU production in terms of volume in tons live weight. Furthermore, around 22.4% of the EU-28 aquaculture production comes from Spain, making it the third largest among the Member States (2019 data). Additionally, it is the main contributor to the EU turnover of the fish processing industry, representing 23% of it (2018 data). This is why Spain accounts for a quarter of total EU's employment in the fisheries sector, i.e. capture, aquaculture and processing (Cortés et al., 2020; European Commission & Publications Office of the European Union, 2022).
Galicia is one of the main contributors in the development of Spain's fisheries sector and it plays an important role to the region's economy. Galicia has a coastline of approx. 1,498 km. Its highly varied morphology consists of Rías and inlets, cliff areas with beaches or marshes, and areas exposed to storms with shaded areas. The continental Galician shelf (coastal zone up to 200 meters deep), is rather narrow, with a width of 20 to 35 km and the total area from Ribadeo to the mouth of the Miño River covers approximately 10,000 km^2. The Galician coastal and shelf areas are rich in organic content and nutrients, a fact which is attributed to the wind-driven upwelling pulses. This coastal morphology and conditions favor growth of various marine organisms and consequently the development of the fisheries sector. Furthermore, the features of the Galician coastal waters favor the growth of marine macroalgae or seaweeds, leading to their exploitation for food, cosmetics, pharmaceuticals, agriculture etc. The development of the fisheries sector is making Galicia one of the most important European regions, concerning the fishery capture, aquaculture

and fisheries processing sectors (Fraga-Corral et al., 2022; Surís-Regueiro & Santiago, 2014; Villasante et al., 2021).

Fishery capture: In 2020, 252,184 live weight of fish was caught in ports owned by Galicia and other Spanish regions. In fact, 50% of the Spanish fishing ships operate in the Galician region, which is responsible for approximately 60% of the national fish-canning production (Instituto Galego Estatistica, 2025a). The fishing fleet is divided to the small-scale fleet, the coastal fleet, the distant water fleet and the long-distance fleet. This distinction is attributed to the size of the fishing vessels, the type of fisheries captured as well as the fishing areas (Surís-Regueiro and Santiago, 2014). Small-scale fisheries use low-capacity vessels with a length under 12 m (average 6 m), low-power engines and one or two crew members. These vessels operate in the Rías and are able to catch high value fisheries (mainly crustaceans, mollusks and ground fish), which may vary depending to the period of year and the ecosystem characteristics. The fish catches are usually channeled to the local market. Small-scale fisheries are usually family artisan businesses, and the owners are involved directly in the fishing activity (Surís-Regueiro & Santiago, 2014, Villasante et al., 2021). The coastal fleet comprises vessels with an average length of 20 m, gross tonnage capacity of 84tn and is active in the Galician-Portuguese coastline outside the Rías. Depending on the kind of fishing equipment (hooks, trawl nets, purse seine gear, or gill nets), the crew size may vary, but on average, it is comprised of eight people. Their fresh products, which include hake, sardine, horse mackerel, mackerel, Norway lobster, blue whiting, and more, are sold to the many first-sale facilities around the Galician coastline. They are usually larger companies than the artisanal ones. The distant water fleet includes vessels with an average length of 33 m and a capacity of around 700 gross tonnage each. Based on the type of fishing, this category can be divided into two groups: long-liners, which typically have twelve people in their crews, and trawlers, which typically have ten. They usually operate in the waters of the EU Celtic Sea. They often land their catches in Galician port facilities or in other ports (i.e. France, Ireland, and the UK) from which they transfer their goods to Galicia's seafood markets. These kinds of fleets are run by industrial companies. Finally, the long-distance fleet is comprised of long-line vessels 35m long and 465 gross tonnage, freezer trawlers 60m long and 1,250 gross tonnage, and freezer seiners 90m long and 2,700 gross tonnages, depending on the kind of fishing activity. Long-liners typically have nine crew members, while freezer trawlers and seiners typically have sixteen. Their size allows them to fish at long distances, in international and non-EU country waters. Most of the catches are frozen and processed on board before arriving in various locations worldwide. The connection between the fishing companies and their place of origin is confirmed by the fact that these products are frequently transported in refrigerated containers by merchant vessels to Galician ports, namely in the port of Vigo. The long-distance fleets are run by the largest and most industrialized fishing companies (Surís-Regueiro & Santiago, 2014).

The *marine aquaculture* production of Galicia in 2023 was 190,407 t live weight from which a great portion is consisted of Bivalves (179,896 t) and smaller algae (19 t) and fish (10,492 t) (Instituto Galego Estatistica, 2025a). Aquaculture is divided into rafts, aquaculture farms and fish farms. Mussels are produced with rafts, which are floating structures in the middle of the inland waters of Rías. Their organizational structure lies in the middle of an industrialized firm and a family business. Bivalve mollusks farming (mainly clams) is carried out at aquaculture farms, which are public land concessions at inter-tidal, shallow areas in the Rías. They are run artisanally by family businesses. Finally, the fish farms are businesses with a high level of industrial development with onshore facilities engaged mainly in the breeding and fattening of turbot and sole (Surís-Regueiro & Santiago, 2014).

At the end of the 20th century (1990s), the exploitation of macroalgae or seaweed for human consumption was encouraged in Galicia, in some cases by food companies seeking to diversify their activity with new products or by new business initiatives dedicated exclusively to the marketing of macroalgae. The interest in these aquatic plants for use in human food has grown since they are considered tasty, nutritious and healthy. The qualitative demands required by this sector led to the exploitation of marine macroalgae and the specialization of the activity. In the West, practically all the biomass used for these purposes comes from natural populations. The quantity of algae declared in 2013 in Galicia by producer organizations and processing companies was 713 t distributed among 19 species or groups of species. Of the total amount collected, 461 t (64.7%) were used for the production of phycocolloids (carrageenans) and 252 t (35.3%) for human consumption, mainly in food. There is also demand for small quantities of algae for other uses (pharmaceutical, dietary, personal care, etc.). The forms of commercialization are the following: fresh, dehydrated, preserved, incorporated into other products, crushed to be used as condiments, etc. (García Tasende & Peteiro, 2015).

Concerning fisheries processing, Spain is the first fish-canning producer in the EU with canned seafood production reaching 330,429 t in 2021 (Fernández Otero, 2021). Galicia is the leading region at national level, accounting for more than 80-85% of Spanish production (Cortés et al., 2021; Fernández Otero, 2021). In Galicia the number of industrial facilities with activities on producing derivatives from fishing (CNAE 10.2) are 163 (2022 data) (Instituto Galego Estatistica, 2025a) from which 7 are of the 10 largest companies on the Spanish canning sector, including the Top-5. The rest of them are small and medium-sized enterprises (SMEs). Small companies (<50 employees) represent 66% of the total, while very small companies with less than 10 employees represent 22% of the total (Cortés et al., 2021).

These activities are linked with the production of rather challenging *waste/by-product streams* with economic and environmental disadvantages. Fish waste production ranges from 300 t/y for those companies producing frozen fish up to 4,000 t/y for big fish-canning industries. Furthermore, 4,000 t/y of algae is seasonally produced in Rias Baixas. Taking into account the importance of fisheries and algae to the local ecosystem, the sustainable management and co-treatment of the fishery products and by-products is considered important for the preservation of natural resources and development of Galicia's economy.

Sewage sludge (SS)

As mentioned in the previous section Galicia consists of 313 municipalities which are divided into the provinces depicted in Table 7 (Instituto Galego Estatistica, 2025b).

Table 7: Administrative structure of Galicia (2023)

	Galicia	A Coruña	Lugo	Ourense	Pontevedra
Municipalities	313	93	67	92	61
Collective entities (parishes)	3,772	927	1,264	915	666
Disseminated	20,812	6,582	8,663	1,249	4,318

The wastewater of the area is mainly treated in local Wastewater treatment plant (WWTPs). In Galicia, 299 waste management facilities operate in total, which include wastewater collection and treatment; collection, treatment and disposal of waste; recovery, and decontamination activities, and other waste management services. In 2022, 1,498,152 m^3/d of wastewater was treated by the WWTPs (Instituto Galego Estatistica, 2025b). In the wastewater treatment facilities, except from treated water, sewage sludge (SS) is also produced. Based on results of D2.1, it emerged that a significant amount of sewage sludge is produced in EU-28 (~10 mt^{db}/y) suitable for utilization into products of biological origin. A significant fraction of the available SS (~37% w/w) is used in agriculture, due to its high nutrient content, while ~10% w/w is used in the production of biofertilizer (compost) and in other applications. Incineration is another important management option (~25% w/w), while landfilling (~8% w/w) is declining as a management practice. Finally, the amount of SS that is used for the production of bio-based products remains very low (0.3% w/w), but with many prospects for development, as many valorization technologies are maturing towards commercial exploitation. According to the results of D2.1, the average production of SS in Spain for the years 2018-2020 was 1,192.3 kt^{db}. Specifically in Galicia, in 2022, 68,136 t of SS (dry mass) were produced, from which 84.4 % was headed for agricultural purposes, while 15.6% was landfilled (Instituto Nacional de Estadística, 2024). The SS is mainly used as soil amendment after disinfection and composting. However, the possibility of the occurrence of heavy metals and Emerging Pollutants (EPs) in the sludge raises concerns about its application in the agricultural sector (Castro-Fernandez et al., 2025). Taking into account these concerns, the valorization of SS for the production of value-added products in bio-refineries is proposed.

3.1.2 Definition of the value chain

Fisheries biomass – Value chain

As presented in D2.1 fisheries biomass and by-products are rich in bioactive molecules, such as proteins, polysaccharides, lipids etc. which could be valorized for the production of pharmaceuticals, cosmeceuticals etc. Despite the importance of the aforementioned uses, limited applications have reached commercialization. The valorization value chains, which are studied in BioReCer are the following:

- The production of fish oil
- The production of collagen
- The production of polysaccharides

Fish oil and collagen: The value chain starts from the capture of fisheries. The fish catches are landed at the ports of Galicia and are temporarily stored until they are transported to the processing industries. The transportation is carried out into refrigerated trucks (15m long) and the average transportation distance is approx. 100 km. The main destination of processed fish is for human consumption. During fish processing, a considerable quantity of by-products is generated which is co-processed in the fish processing industries in order to produce value added products, such as fish-oil and collagen. The current uses of crude fish oil are animal nutrition, while collagen is mainly used in human nutrition and in additives. In the context of BioReCer the valorization of fish oil and collagen in the bio-chemical, biofertilizer, cosmeceutical and pharmaceutical industry is proposed.

For fish oil, the fish by-products (crude fish oil) undergo two stages of chemical treatment. The first one consists of degumming, neutralization and washing and the second, drying, bleaching, winterization and deodorizing. Refined fish-oil can be used in the biofertilizer, pharmaceutical or in the cosmeceutical industry.

For the production of collagen, the fish by-product first undergoes a chemical treatment, which includes deproteinization, demineralization and degrease. Afterwards collagen is recovered through hydrolysis, and finally is purified through centrifugation, precipitation and dialysis. Collagen can be used in the cosmeceutical and bio-chemical industry.

Concerning the algae sector, the algae after collection and separation, is transported to the processing industry in refrigerated trucks for the production of polysaccharides. The quantity of the produced algae which is headed to the polysaccharides industry constitutes the 30% of the totally produced biomass. The remaining quantity is mainly used in agriculture. The distance of transportation is approx. 50 km. Firstly, algae undergo a series of mechanical processing steps, such as cleaning, washing, milling, filtration and concentration. Afterwards, it undergoes chemical precipitation with alcohol and salts. At the end of the value chain, polysaccharides come to their final form through drying, milling and blending. Polysaccharides can be used for cosmetics, human nutrition and pharma. The value chains are described in detail in D6.1 and are depicted in Figure 5 (fish oil), Figure 6 (collagen) and Figure 7 (polysaccharides).

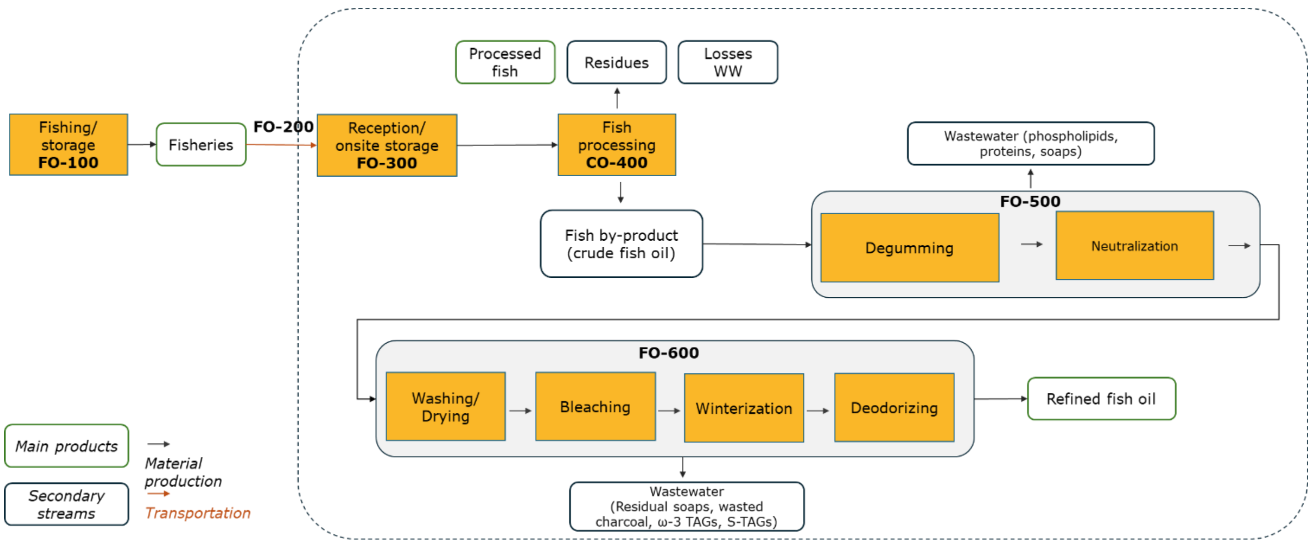

Figure 5: Simplified flow diagram of CS1 value chain (Fish oil production)

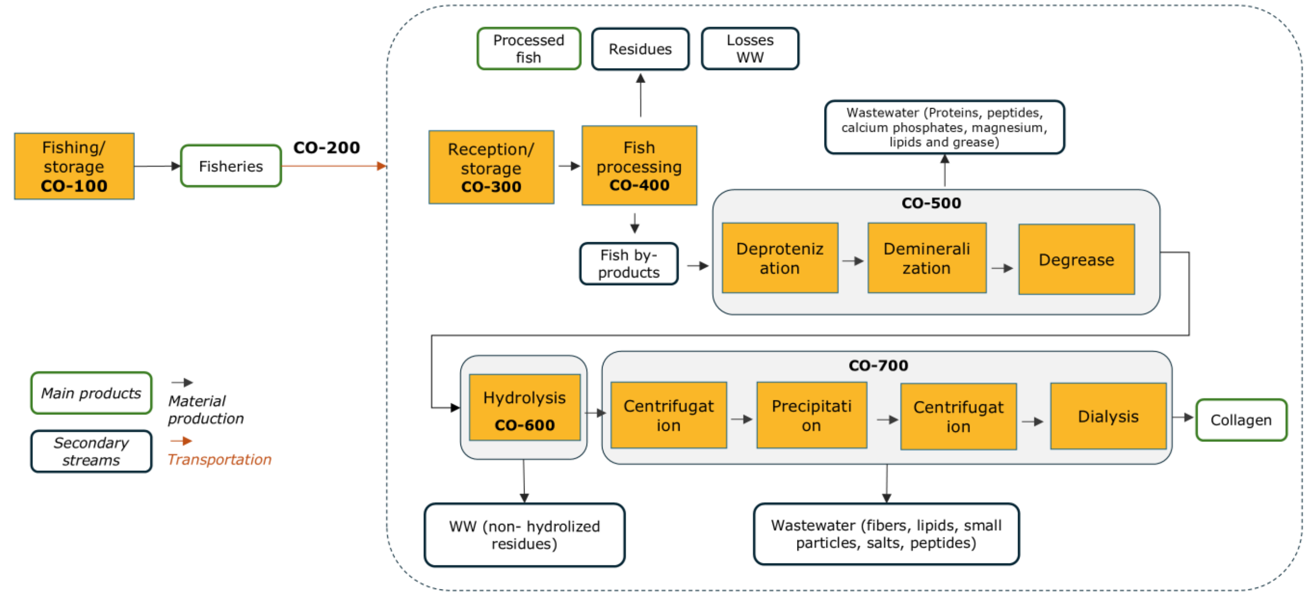

Figure 6: Simplified flow diagram of CS1 value chain (Collagen production)

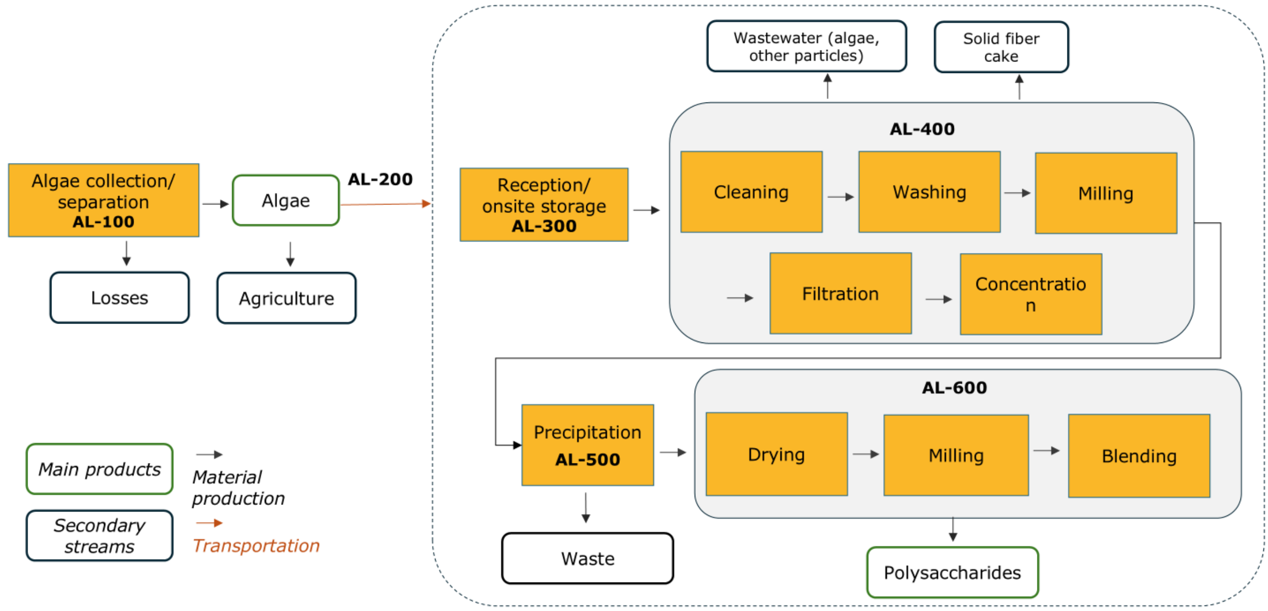

Figure 7: Simplified flow diagram of CS1 value chain (Polysaccharides production)

Sewage sludge (SS) – Value chain

SS sludge is characterized by its high organic content and as analyzed in D2.1, it is considered a valuable resource, which can be used as feedstock in biorefineries. In the current deliverable, the value chain for the production of volatile fatty acids (VFA) is studied, as depicted in Figure 8.

The value chain starts with the entrance of the wastewater (urban and industrial) in the WWTP, where it is processed resulting in the production of treated water and unstabilized SS. A fraction of the SS exits the value chain to composting and landfilling, while the remaining is dehydrated in order to be transported to the biorefinery. Heavy duty trucks are used for transportation while the distance is approx. 150 km. The dehydrated SS enters the biorefinery, where it is hydrated in order to enter the fermentation stage. The fermentation effluent undergoes a downstream processing (Solid - liquid separation, concentration and purification) in order to recover the liquid fraction and to purify it to the VFA mixture. The recovered water is either re-used at the hydration stage or is led to the WWTP. The solid fraction of the fermentation stage enters an anaerobic digestion (AD) reactor for the production of biogas, which is used at a Combined Heat and Power (CHP) facility in order to cover the biorefinery's energy needs. The anaerobic digestate undergoes a downstream processing, which includes solid-liquid separation. The liquid fraction enters the WWTP while the solid fraction, which is stabilized sludge, is used in agriculture.

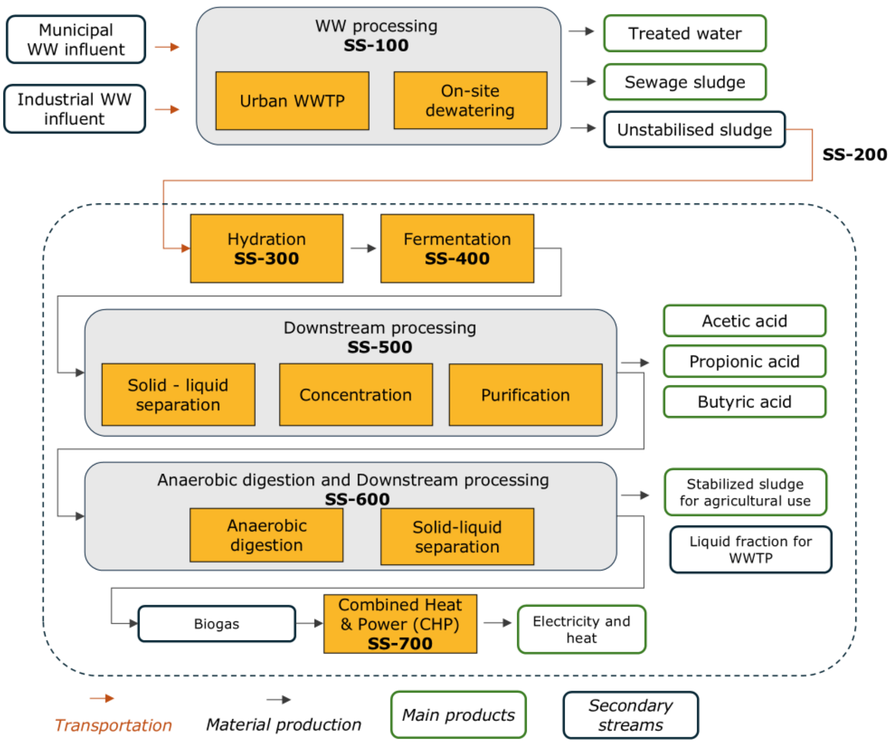

Figure 8: Simplified flow diagram of CS1 value chain (Sewage Sludge feedstock)

3.1.3 Data collection

The initial Input-Output tables for the *fisheries/algae value chains* have been constructed in the context of D6.1. The data constituting these tables is primary information shared by the stakeholders of the project (fisheries and algae processing industries). For the needs of the current deliverable, these data were enriched with further communication with the stakeholders focusing on energy requirements and emission estimations. In cases where data could not be given by the local stakeholders, data from pilot plants and the literature were used. Specifically, reliable data were retrieved concerning:

- Fish capture, storage and transportation (Ahadi et al., 2021; Sala et al., 2022; Vázquez-Rowe et al., 2014).
- Algae collection and separation (Chutia et al., 2022).
- Fish-oil production value chain (EUMOFA MONTHLY HIGHLIGHTS & European Market Observatory for Fisheries and Aquaculture Products, 2019; Hilmarsdóttir et al., 2022; Monsiváis-Alonso et al., 2020).
- Collagen production value chain (Wojdalski et al., 2020).
- Algae processing value chain (Saadia, 2017).

Where no data were not available, fair assumptions were made, based on the field experts' opinion, which are the following:

- All the produced fish are headed to the processing industry.
- For 7.5 kg (wet mass) of fisheries, 1 kg (wet mass) of fish by-products are produced.
- Refined fish-oil and collagen are co-processed with fish destined for human consumption in the same installation.
- In the cases where it was hard to identify the losses of the biomass throughout the stages of the value chain, the losses were considered to be zero.

Currently, SS is mainly used for composting and landfilled in Galicia. The construction of the value chain and the Input-Output tables is based on real information given by stakeholders and operating WWTPs, a viability study and pilot testing which was held by the CS leaders (CET). In cases where data could not be given by the local stakeholders, literature data were used. The assumptions made were the following:

- The WW, which enters the WWTP, comes mainly from municipal WW. The volume of industrial wastewater is quite low.

- The trustees of BioReCer cover a 20% (approximately) of the defined region (Galicia). The data given by them, was extrapolated for the entire region.
- ~34% of the produced unstabilized sludge is used in the BioReCer value chain
- ~56% of the produced unstabilized sludge is used for composting
- ~ 10 % of the produced unstabilized sludge is landfilled
- The electricity needed for the operation of the WWTP (without dewatering) is considered equal to 1 kWh/m^3 influent which is typical for such facilities.
- The sludge with total solids content ≤30% is considered dilute enough to have a density of 1000 kg/m^3
- Losses of biomass are not considered throughout the value chain

The (thermal and electrical) energy produced in the combined heat and power (CHP) facility, which is located in the bio-refinery, is used within the facility. If any excess energy is produced, it exits the value chain. If extra energy is needed, it is obtained from external sources. For the calculation of direct emissions from the combustion of biogas, the emission factors from the updated "2006 IPCC Guidelines for National Greenhouse Gas Inventories" (Gómez et al., 2006a) were used.

3.1.4 Results and interpretation

The inventory for the fish oil value chain depicted in Figure 5 is presented in Table 8. The table includes quantitative data of the material flows, the input of raw materials and energy along with the emissions generated in each aggregated stage. During fisheries processing crude oil is produced which is mainly used in husbandry. If crude fish oil undergoes the proposed processing, refined fish oil can be produced, which is a value-added product. Refined fish oil can be used in biofertilizer, pharmaceutical or in the cosmeceutical industry. For the production of 1 kg refined fish oil, 17.5 kg fisheries are needed, while for the production of 1kg of refined fish oil, 1.28 kg of crude fish oil is needed. The most energy (electricity) intensive stage is F-600 (Washing/Drying, Bleaching, Winterization, Deodorizing), which requires 80% of the total energy needed for processing crude fish oil. The total direct emissions for the production of 1 kg refined fish oil, attributed to fish capture and fisheries transportation to the processing industry, are 7.341 kgCO_2-eq. The total indirect emissions for the production of 1 kg refined fish oil, attributed to onsite storage and processing of fisheries and the stages of crude fish oil processing, are ~0.6 kgCO_2-eq.

Table 8: Extended table for fish oil production

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Measuring unit	Total quantity		
								Main flow	
							WM	MC	DM
FO-100	Fishing and storage	Input	101	Energy	Diesel	kg	1.72		
		Output	102	Main product	Fisheries	kg	17.5	75%	4.38
		Output	103	Emissions (direct)	GHG	$kgCO_2$-eq	5.54		
FO-200	Transportation	Input	201	Energy	Diesel	kg	0.557		
		Output	202	Main flow	Fisheries	kg	17.5	75%	4.38
		Output	203	Emissions (direct)	GHG	$kgCO_2$-eq	1.81		
FO-300	Reception Onsite storage	Input	301	Energy	Electricity	kWh	0.350		
		Output	302	Main flow	Fisheries	kg	17.5	75%	4.38
		Output	303	Emissions (indirect)	GHG	$kgCO_2$-eq	0.0613		
FO-400	Fisheries processing	Input	401	Main flow	Fisheries	kg	17.5	75%	4.38
		Input	402	Resource	Water	kg	87.5		
		Input	403	Energy	Electricity	kWh	1.75		
		Output	404	Product	Processed fishes (for food)	kg	9.9	75%	2.48
		Output	405	By-product	Crude fish oil	kg	1.28	8%	1.18
		Output	406	By-product	Residues	kg	6.30	89%	0.72
		Output	408	Waste	Wastewater	kg	87.5		
		Output	409	Emissions (indirect)	GHG	Kg CO_2-eq	0.31		
FO-500	Degumming Neutralization	Input	501	Main flow	Crude fish oil	kg	1.28	7.99%	1.18
		Input	502	Raw material	NaOH	kg	0.0128		
		Input	503	Resources	Water	kg	0.192		
		Input	504	Energy	Electricity	kg	0.256		
		Output	505	Main flow	Mixture	kg	1.13	1.69%	1.12
		Output	506	Waste	Wastewater (WW)	kg	0.353		
		Output	506	Component	phospholipids, proteins, soaps in WW	kg	0.0641		
		Output	507	Emissions	GHG	$kgCO_2$-eq	0.0449		

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Measuring unit	Total quantity		
								Main flow	
							WM	**MC**	**DM**
				(indirect)					
FO-600	Washing/Drying Bleaching Winterization Deodorizing	Input	601	Energy	Electricity	kWh	1.03		
		Output	602	Main product	Fish oil	kg	1.0	0%	1.0
		Output	603	Waste	WW	kg	0.28		
		Output	604	Component	Residual soaps, wasted charcoal, ω-3 TAGs, S-TAGs	kg	0.147		
		Output	605	Emissions (indirect)	GHG	kgCO_2-eq	0.179		

The extended table for the collagen value chain (Figure 6) is depicted in Table 9. The main product of the value chain is collagen gel with 94% moisture content. For the production of 1 kg collagen (DM) 306 kg (WM) of fish residues are needed, which come from the processing of 2,297 kg of fisheries (WM). The most energy intensive stage of fish residue processing to collagen, in terms of electricity, is CO-700 (centrifugation, precipitation, centrifugation, and dialysis), which consumes 80% of the total energy required. The total indirect emissions of fisheries storage and processing and fish residue processing per kg of produced collagen (DM) are ~66.5 kg CO_2-eq, while the direct emissions for fishing, storage and transportation of fisheries are 964 kg CO_2-eq. As it can be concluded the fishing activities have a direct impact on the greenhouse emissions. Collagen is currently used in human nutrition and additives, while BioReCer proposes its use in cosmetics and pharma.

Table 9: Extended table for collagen production

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity		
								Main flow	
							WM	**MC**	**DM**
CO-100	Fishing and storage	Input	101	Energy	Diesel	kg	226		
		Output	102	Main product	Fisheries	kg	2297	75%	574
		Output	103	Emissions (direct)	GHG	Kg	727		

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity		
									Main flow
							WM	**MC**	**DM**
						CO_2-eq			
CO-200	Transportation	Input	201	Energy	Diesel	kg	73.1		
		Output	202	Main flow	Fisheries	kg	2297	75%	574
		Output	203	Emissions (direct)	GHG	Kg CO_2-eq	237		
CO-300	Reception/ Onsite storage	Input	301	Energy	Electricity	kWh	45.9		
		Output	302	Main flow	Fisheries	kg	2297	75%	574
		Output	303	Emissions (indirect)	GHG	Kg CO_2-eq	8.04		
CO-400	Fisheries processing	Input	401	Main flow	Fisheries	kg	2297	75%	574
		Input	402	Resource	Water	kg	11845		
		Input	403	Energy	Electricity	kWh	230		
		Output	404	Product	Processed fishes (for food)	kg	3905	90%	402
		Output	405	By-product	Residues	kg	613	75%	153
		Output	406	Losses	Residues	kg	76.6	75%	19.1
		Output	407	Waste	Wastewater	kg	9188		
		Output	408	Emissions (indirect)	GHG	Kg CO_2-eq	40.2		
CO-500	Deproteiniza-tion, Demineralization, Degrease	Input	501	Main flow	Residues	kg	306	75%	76.6
		Input	501	Component	Protein in residues	kg	37.5		
		Input	501	Component	Fats in residues	kg	8.50		
		Input	501	Component	Ash in residues	kg	19.9		
		Input	502	Raw material	HCl (25%)	kg	2.24		
		Input	503	Raw material	NaOH	kg	0.746		
		Input	504	Resource	Water	kg	149		
		Input	505	Energy	Electricity	kWh	5.2		
		Output	506	Main flow	Mixture	kg	306	88%	36.3
		Output	507	Losses	Mixture	kg	7.76	75%	1.94
		Output	508	Waste	WW	kg	152		
		Output	508	Component	Proteins, peptides, calcium phosphates, magnesium, lipids and grease in WW	kg	50.3		

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity		
								Main flow	
							WM	MC	DM
		Output	509	Emissions (indirect)	GHG	Kg CO_2-eq	0.9		
CO-600	Hydrolysis	Input	601	Main flow	Residue-water mixture	kg	298.5	89%	34.3
		Input	602	Resources	Water & chemicals	kg	149.3		
		Input	603	Energy	Electricity	kWh	15.67		
		Output	604	Main flow	Hydrolysate	kg	180.6	92%	14.4
		Output	605	Waste	Wastewater (WW)	kg	267.2		
		Output	606	Component	non- hydrolized residues in WW	kg (DM)	19.90		
		Output	607	Emissions (indirect)	GHG	Kg CO_2-eq	2.7		
CO-700	Centrifugation Precipitation Centrifugation Dialysis	Input	701	Raw material	NaOH	kg	0.149		
		Input	702	Energy	Electricity	kWh	83.6		
		Output	703	Main product	Collagen gel	kg	17.9	94%	1.0
		Output	704	Component	Protein	kg	0.800		
		Output	705	Waste	Wastewater (WW)	kg	163		
		Output	706	Component	fibers, lipids, small particles, salts, peptides	kg (DM)	13.4		
		Output	707	Emissions	GHG	kg CO_2-eq	14.6		

The results for the fish oil and the collagen value chains are illustrated in the Sankey diagrams of Figure 9 and Figure 10 , respectively.

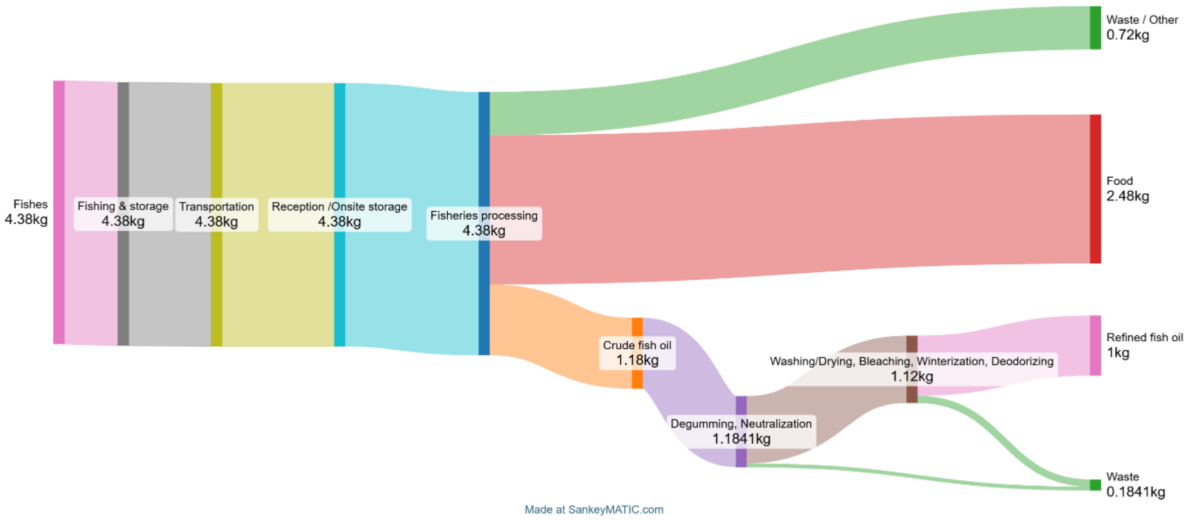

Figure 9: Sankey diagram for CS1 (production of 1 kg of refined fish oil); quantities in DM

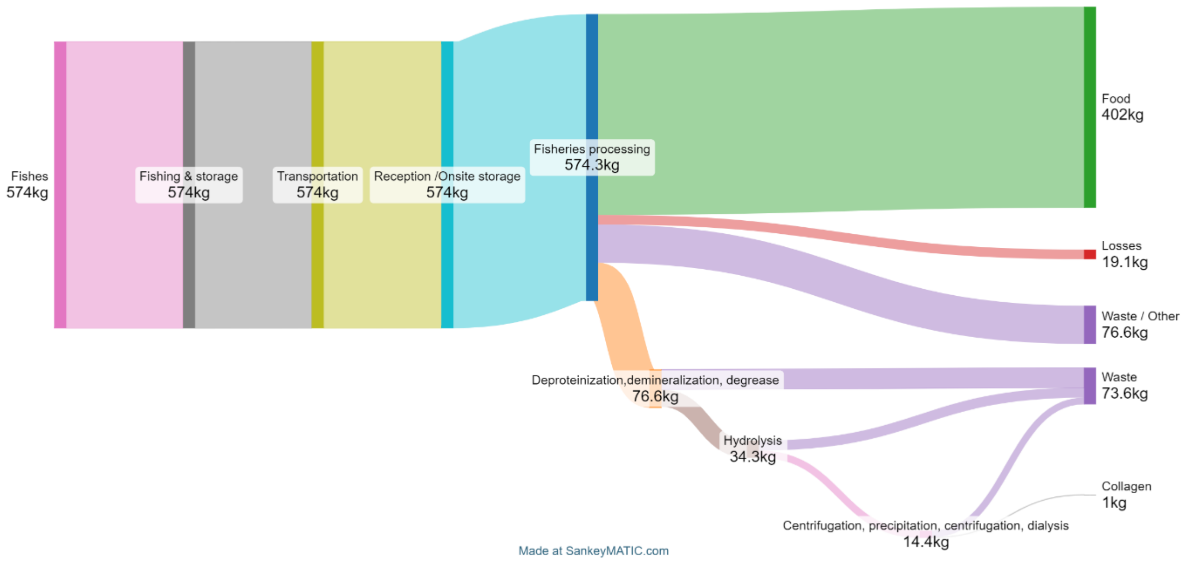

Figure 10: Sankey diagram for CS1 (production of 1 kg of collagen); quantities in DM

The extended table for the polysaccharide value chain (Figure 7) is depicted in Table 10. The valorisation of algae for the production of polysaccharides (PS) is of great interest for the BioReCer stakeholders. Currently 70% of algae are used in agriculture, but the produced PS can be used in added-value-products, such as pharmaceuticals and cosmeceuticals. For the production of 1 kg (DM) of PS 12.7 kg (WM) of algae is processed. The most energy (electricity) intensive stage of PS processing is AL-600 (drying, milling, and blending) which consumes 80% of the totally required electricity. The indirect greenhouse emissions coming from electricity consumption are 11.55 kg CO_2-eq, while the direct emissions coming from algae collection and transportation are 7.06 kg CO_2-eq. Generally, the studied value chains are water intensive, and they produce a considerable amount of wastewater.

Table 10: Extended table for polysaccharides production

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity		
									Main flow
							WM	MC	DM
ALGAE									
AL-100	Algae collection/ separation	Input	101	Energy	Diesel	kg	1.12		
		Output	102	Main product	Algae	kg	13.4	80%	2.69
		Output	103	Losses	Algae	kg	0.746	80%	0.149
		Output	104	Emissions (direct)	GHG	kg CO_2-eq	3.62		
AL-200	Transportation	Input	201	Main flow	Algae	kg	12.7	80%	2.54
		Input	202	Energy	Diesel	kg	1.06		
		Output	203	Main flow	Algae	kg	12.7	80%	2.54
		Output	204	Emissions (direct)	GHG	kg CO_2-eq	3.44		
AL-300	Reception Onsite storage	Input	301	Energy	Electricity	kWh	2.54		
		Output	302	Main flow	Algae	kg	12.7	80%	2.54
		Output	303	Emissions	GHG	kgCO_2-eq	0.444		
AL-400	Cleaning Washing Milling Filtration Concentration	Input	401	Resource	Water	kg	76.1		
		Input	402	Energy	Electricity	kWh	29.8		
		Output	403	Main flow	biomass mixture	kg	2.54	80%	1.02
		Output	404	Waste	Wastewater	kg	83.8		0.25
		Output	405	Waste	solid fibre cake	kg	2.54	50%	1.27
		Output	406	Emissions	GHG	kg CO_2-eq	5.22		
AL-500	Precipitation	Input	501	Main flow	Biomass mixture	kg	2.54	60%	1.02
		Input	502	Raw material	alcohol	kg	0.761		

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity		
								Main flow	
							WM	**MC**	**DM**
		Input	503	Raw material	salts	kg	0.127		
		Input	504	Energy	Electricity	kWh	1.90		
		Output	505	Main flow	Polysaccharides mixture	kg	1.25	20%	1.00
		Output	506	Waste	Waste	kg	2.18		0.14
		Output	507	Emissions (indirect)	GHG	kg CO_2-eq	0.333		
AL-600	Drying Milling Blending	Input	601	Raw material	Vegetable proteins	kg	0.100		
		Input	602	Energy	Electricity	kWh	31.7		
		Output	603	Main product	Polysaccharides	kg	1.02	1.5%	1.00
		Output	604	Emissions	GHG	kg CO_2-eq	5.55		

The results of the polysaccharides value chain are depicted in Figure 11.

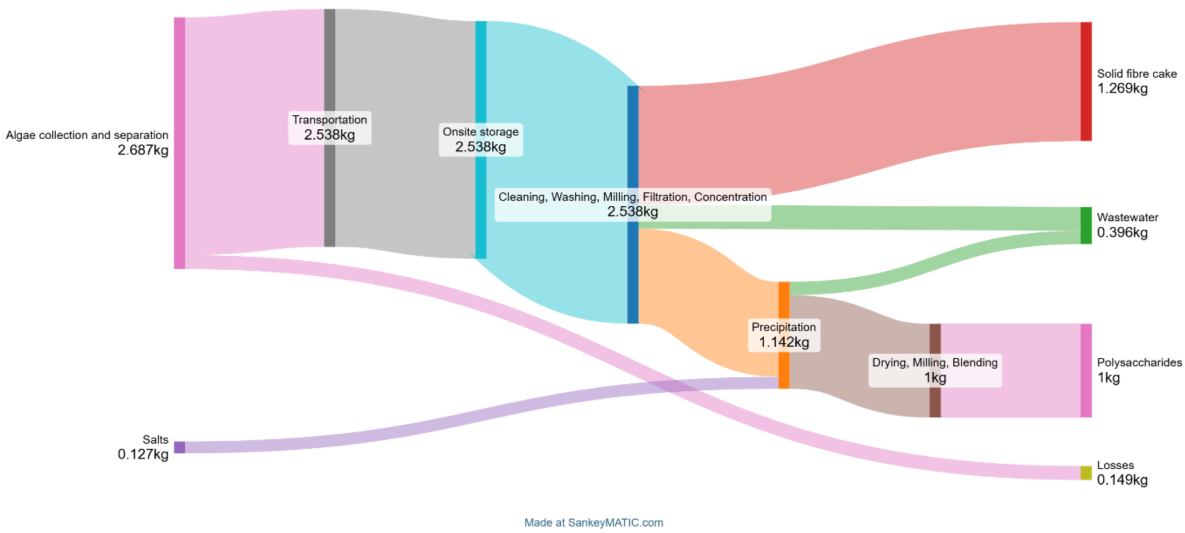

Figure 11: Sankey diagram for CS1 (production of 1 kg of polysaccharides); quantities in DM

The inventory for the VFA value chain depicted in Figure 8 is presented in Table 11**¡Error! No se encuentra el origen de la referencia.**. Currently, the produced sewage sludge heads mainly to agriculture. The proposed value chain (production of VFAs), in the concept of BioReCer, emerged through pilot testing and viability studies. For the production of 1 kg of VFAs, 16.1 kg (DM) are needed, while the remaining quantities from WWTPs are headed to agriculture (26.7 kg DM) and landfill (4.9 kg DM). The total produced SS (47.7 kg DM) comes from the treatment of 3.83 m^3 WW. The total electrical energy consumed for the production of 1 kg of VFAs is 14.10 kWh, while the thermal energy is 14.76 kWh. The most energy intensive processes are the fermentation (electricity: 5.65 kWh and thermal: 5.80 kWh) and the downstream processing of the VFAs (electricity: 6.57 kWh and thermal: 7.26 kWh). The CHP facility located in the biorefinery produces 2.62 kWh electricity and 18.0 kWh thermal energy from the combustion of the produced biogas.

Table 11: Extended table for VFAs production from sewage sludge

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Meas. unit	Total quantity			WWTP	Agriculture	Land fill
							WM	TS	DM	WM	DM	DM
SS-100	WWTP	Inputs	101	Main flow	Municipal WW	m^3	268					
		Inputs	102	Main flow	Industrial WW	m^3	115					
		Inputs	102	Component	BOD	kg	113					
		Inputs	102	Component	TN	kg	19.4					
		Inputs	103	Energy	Electricity	kWh	383					
		Outputs	104	Product	Treated water	m3	383					
		Outputs	105	By-product	SS (30%)	kg	53.7	30%	16.1			
		Outputs	105	Component	tCOD	kg	17.0					
		Outputs	105	Component	t VS	kg	12.1					
		Outputs	106	By-product	SS (3%)	kg	1054	3%	31.6		26.7	4.9
		Outputs	107	By-product	Water from dewatering	kg	483			483		
		Outputs	108	Emissions (WWT & discharge)	CH4	Kg	1.79					
		Outputs	109	Emissions (WWT & discharge)	N2O	kg	0.0489					
		Outputs	110	Emissions (indirect)	Electricity consumption	Kg CO_2-eq	67.0					
SS-200	Transportation	Inputs	201	Energy	Diesel	kg	0.08					
		Outputs	202	Main flow	Sewage Sludge	kg	53.7	30%	16.1			

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Meas. unit	Total quantity			WWTP	Agriculture	Land fill
							WM	TS	DM	WM	DM	DM
		Outputs	202	Component	tCOD	kg	17.0					
		Outputs	202	Component	t VS	kg	12.1					
		Outputs	203	Emissions (direct)	GHG	$kgCO_2$-eq	0.25					
SS-300	Hydration	Inputs	301	Resource	Water	kg	161					
		Outputs	302	Main flow	Sewage Sludge	kg	215	8%	16.1			
		Outputs	302	Component	tCOD	kg	17.0					
		Outputs	302	Component	t VS	kg	12.1					
SS-400	Fermentation	Input	401	Raw material	NaOH	kg	0.69					
		Input	402	Energy	Electricity (grid)	kWh	4.60					
		Input	403	Energy	Electricity (recovered)	kWh	1.05					
		Input	404	Energy	Thermal	kWh	5.80					
		Output	405	Main flow	Mixed liquor	kg	215					
		Output	405	Component	t VFA	kg	2.15					
		Output	405	Component	t VFA-COD	kg	2.54					
		Output	405	Component	t no VFA-COD	kg	14.4					
		Output	405	Component	t TS no VFA	kg	14.0					
		Output	405	Component	t VS	kg	9.94					
		Output	406	Emissions (indirect)	GHG	Kg CO_2-eq	0.80					
SS-500	Downstream	Input	501	Raw material	Flocculant	kg	0.54					

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Meas. unit	Total quantity			WWTP	Agriculture	Land fill
							WM	TS	DM	WM	DM	DM
	processing				(cationic polyelectrolite)							
		Input	502	Raw material	Coagulant (commercial)	kg	0.32					
		Input	503	Raw material	HCl	kg	1.50 E-04					
		Input	504	Raw material	Fresh Solvent	kg	3.13 E-03					
		Input	505	Raw material	NaOH (2%) for CIP	kg	0.624					
		Input	506	Raw material	HCl (2%) for CIP	kg	0.130					
		Input	507	Energy	Electricity (grid)	kWh	5.35					
		Input	508	Energy	Electricity (recovered)	kWh	1.22					
		Input	509	Energy	Thermal	kWh	7.26					
		Output	510	Product	VFAs	kg	1.00					
		Output	510	Component	acetic	kg	0.776					
		Output	510	Component	propionic	kg	0.121					
		Output	510	Component	butiric and others	kg	0.100					
		Output	510	Component	solvent	kg	3.13 E-03					

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Meas. unit	Total quantity			WWTP	Agriculture	Land fill
							WM	TS	DM	WM	DM	DM
		Output	511	By-products	water-solid mixture (centrifuge+UF +NF)	kg	63.0	22%	14.0			
		Output	512	Waste	RO concentrate	kg	102			102		
		Output	513	Waste	L-L extraction + distillation 2 water	kg	46.7			46.7		
		Output	514	Waste	L-L extraction + distillation 1 water	kg	2.46			2.46		
		Output	515	Emissions (indirect)	GHG	Kg CO_2-eq	0.94					
SS-600	Anaerobic Digestion and downstream processing	Input	601	By-products	water-solid mixture (centrifuge+UF +NF)	kg	63.0	22%	14.0			
		Input	601	Component	VS	kg	9.94					
		Input	601	Component	COD	kg	15.0					
		Input	602	Resource	water	m3	76.4					
		Input	603	Raw material	polyelectrolyte	kg	1.4 E-05					
		Input	604	Energy	Electricity	kWh	1.53					

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Meas. unit	Total quantity			WWTP	Agriculture	Land fill
							WM	TS	DM	WM	DM	DM
					(grid)							
		Input	605	Energy	Electricity (recovered)	kWh	0.35					
		Input	606	Energy	Thermal	kWh	1.70					
		Output	607	By-product	Stabilized sludge	kg	31.8	35%	11.1			
		Output	608	Waste	Wastewater	kg	107			107		
		Output	609	Product	Biogas	Nm3	3.45					
		Output	610	Emissions (indirect)	GHG	kg CO_2-eq	0.268					
SS-700	Combined Heat & Power (CHP)	Input	701	Raw material	Biogas	Nm3	3.45					
		Output	702	Energy	Electricity (recovered)	kWh	2.62					
		Output	703	Energy	Thermal (recovered)	kWh	18.0					
		Output	704	Emissions (direct)	GHG	kg CO2-eq	5.48					

The results for the VFAs value chain are depicted in the Sankey diagram of Figure 12.

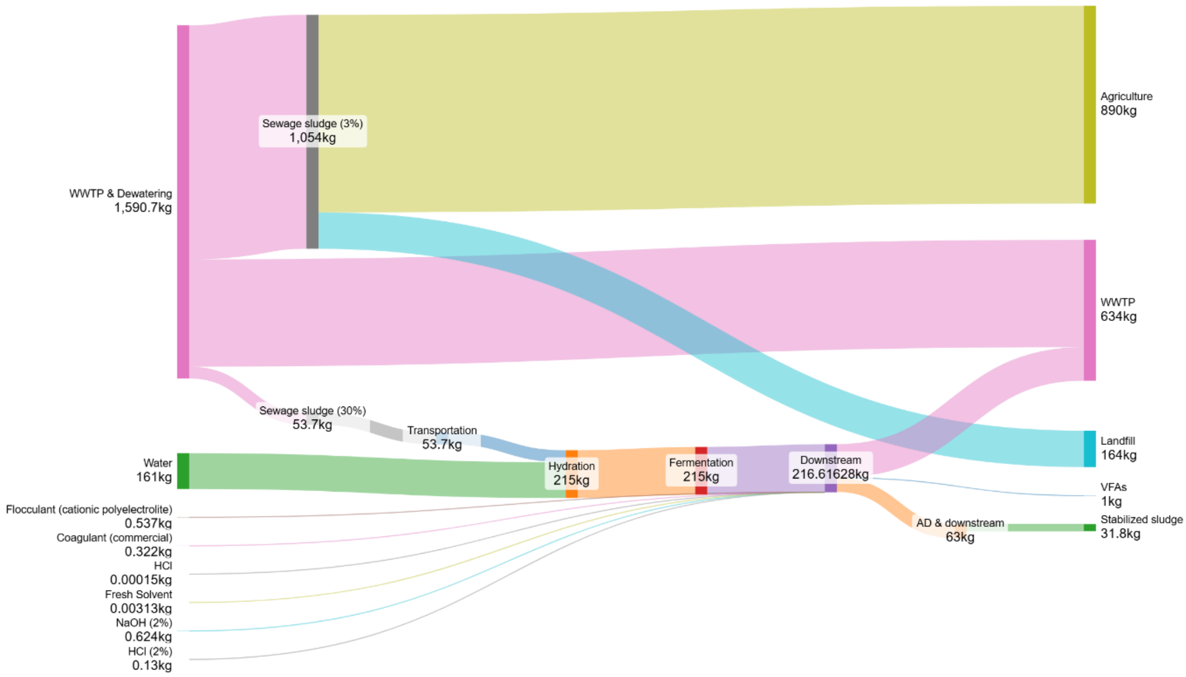

Figure 12: Sankey diagram for CS1 (production of 1 kg VFA from SS)

3.2 Case study 2: Lombardy, Italy

3.2.1 System boundaries

Lombardy is a region located in the North of Italy. The Region is divided in 11 provinces, 1 metropolitan area (Milan) and 1,523 municipalities. The population of the region is almost 10 million inhabitants and accounts for 16.9% of Italy's total population. Noticeably, it is the first most populated region in Italy and the third most populated Region in Europe (Vanguard Initiative, 2024).

Figure 13: Lombardy region (Encyclopædia Britannica)

Lombardy exhibits a very competitive economic performance, with a GDP in 2022 of approximately €439.9 billion, constituting roughly 23% of Italy's total GDP. In the Region, 81.3 companies per 1000 inhabitants are established, surpassing the national average. In total, 6,133 companies were active in the food and beverages industry in Lombardy. Most of these companies refer to the category of bakery and flour products, with 3,798 units (65.4% of the total) mainly related to artisanal bread-making and pastry-making. Other important categories of the food industries include meat processing activities (10.7% of the total), dairy products (6%), grains and starch production (2.3%), fruit and vegetable processing (2.1%) and animal feed products (1.8%). Concerning the beverage industry, most companies are engaged in the production of beer (34.5% of the total) and in winemaking (29.2% of the total), followed by the distillation of alcohol (19.3%) and soft drinks industry (14.6%) (BioReCer, 2024).

The biological feedstocks explored in this case study include:

Sewage sludge which is defined as the solid or semi-solid residues obtained from the treatment of wastewater. In the EU, the annual production of sewage sludge amounts to approximately 10 million tonnes of dry mass, considering only urban wastewater processing. Biological processing of sewage sludge provides substantial benefits as it enables the safe valorization of sewage sludge and the efficient recovery of nutrients and energy. The processes aimed at reducing the volume of the sludge (e.g., thickening, dewatering, composting) enhance treatment efficiency, lower disposal costs, and minimize the environmental impact of waste management. A typical concern associated with sewage sludge is the potential presence of pathogens, organic and inorganic pollutants, heavy metals, microplastics and others (Cucina, 2023). In Lombardy region, 1,206 WWTP are operating (Collivignarelli et al., 2023) with the production of sewage sludge amounting to

468,800 t in 2020. For Italy, in total, it is reported that 44% of the sewage sludge is recovered. In this context, the main recovery route includes the utilization of sewage sludge in agriculture. To this end, Lombardy has implemented regional regulations that introduce standards for the acceptability of sludge entering the sludge treatment plants as well as quality classes for the reused solids, defined characteristics for the agricultural soils and the spreading methods. Additionally, the production of biogas from sewage sludge is an alternative established application. Data referring to the Italian context highlight that 1.5% of the totally produced biogas derives from sewage sludge, while Lombardy contributes to 3.8% of the total biogas production at a national scale (Domini et al., 2022).

The Organic Fraction of Municipal Solid Waste (OFMSW) is defined as the mixture of the wastes derived from parks, gardens, kitchen, and restaurants. This type of waste is characterised by high moisture and biodegradability (Alibardi & Cossu, 2015).

Agro-industrial waste is generated throughout the industrial processing of agricultural or livestock products. This type of waste constitutes a good source of nutrients or energy and an excellent basis for microbial growth (Naik et al., 2023). The list of waste considered in the study according to the European List of Waste is presented in Table 12.

Table 12: List of waste considered in the analysis (BioReCer, 2024)

Type of waste	EER code	Definition	Sub-chapter
Sewage Sludge	19 08 05	sludges from treatment of urban wastewater	19 08: wastes from wastewater treatment plants not otherwise specified
OFMSW	20 01 08	biodegradable kitchen and canteen waste	20 01: separately collected fractions
Agro-industrial waste	02 02 01	sludge from washing and cleaning	02 02: wastes from the preparation and processing of meat, fish and other foods of animal origin
	02 02 04	sludges from on-site effluent treatment	
	02 03 01	sludges from washing, cleaning, peeling, centrifuging and separation	02 03: wastes from fruit, vegetables, cereals, edible oils, cocoa, coffee, tea and tobacco preparation and processing; conserve production; yeast and yeast extract production,
	02 03 04	materials unsuitable for consumption or processing	
	02 03 05	sludges from on-site	

		effluent treatment	molasses preparation and fermentation
	02 05 01	materials unsuitable for consumption or processing	02 05: wastes from the dairy products industry
	02 06 01	materials unsuitable for consumption or processing	02 06: wastes from the baking and confectionery industry
	02 07 01	wastes from washing, cleaning and mechanical reduction of raw materials	02 07: wastes from the production of alcoholic and nonalcoholic beverages (except coffee, tea and cocoa)

3.2.2 Definition of the value chain

The value chain studied in Lombardy region focuses on the valorization of the urban wastewater effluents, OFMSW and agro-industrial by-products for the acquisition of high value products. Starting from the urban wastewater, it enters the municipal WWTPs of the region where the removal of pollutants is achieved. The output of this processing is the sewage sludge with a total solids (TS) content of 4% which is transported to the biorefinery unit with tank trucks. Similarly, the waste streams of the agro-industrial and municipal activities are collected and transported to the biorefinery unit. The biorefinery inflow consists mainly of sewage sludge. In particular, the TS derived from the sewage sludge stream constitutes 98.8% of the total amount of TS entering the facility. The first stage of the biorefinery includes the fermentation of the inflow and the subsequent thickening of the fermented outflow. The liquid fraction (supernatant) is then sent to the crystallizer unit in order to recover phosphorus as struvite ($MgNH_4PO_4 \cdot 6H_2O$). Struvite is considered as an effective slow-release P fertilizer with a P content close to that of phosphate rock (Muys et al., 2021). The solid part of the thickener outflow is sent to the anaerobic digestion unit for the production of biogas. In particular, the biogas is purified and converted into approximately 99% pure biomethane and could be utilized to cover the energy needs of the biorefinery. The digestate that is also produced from the anaerobic digestion is sent to the screw press (dewatering unit) to perform the solid/liquid separation. The solid fraction constitutes a final product and more specifically it is a sludge with 25% TS content, exhibiting potential for utilization in composting applications. The liquid outflow of the separation is mixed with part of the crystallizer output. The mixture, rich in VFA, is fed to

Sequential Batch Reactors (SBR), where nitritation and biomass selection occur. Nitritation is a common and economically attractive side-stream process for the treatment of NH_4^+-rich wastewater in which ammonium is oxidized to nitrite by ammonia oxidizing bacteria (Rodriguez-Caballero et al., 2013), followed by heterotrophic denitrification. During the process of biomass selection, PHA-accumulating microbial culture can be selected and enriched. This culture transforms the VFA into PHA and is then subjected to conditions that maximize PHA accumulation in the dedicated tank. Once the cells reach their peak PHA content, they are ready for extraction and purification processes (Kourmentza et al., 2017; *SMART-Plant Project*, 2025). The PHA-rich sludge is dewatered and sent to bioplastic industries for the extraction and purification steps, which are not considered in this study. Therefore, the final product considered in this value chain is PHA rich sludge containing 1 kg of PHA. The processes described are illustrated in Figure 14, where the appropriate aggregations have been made.

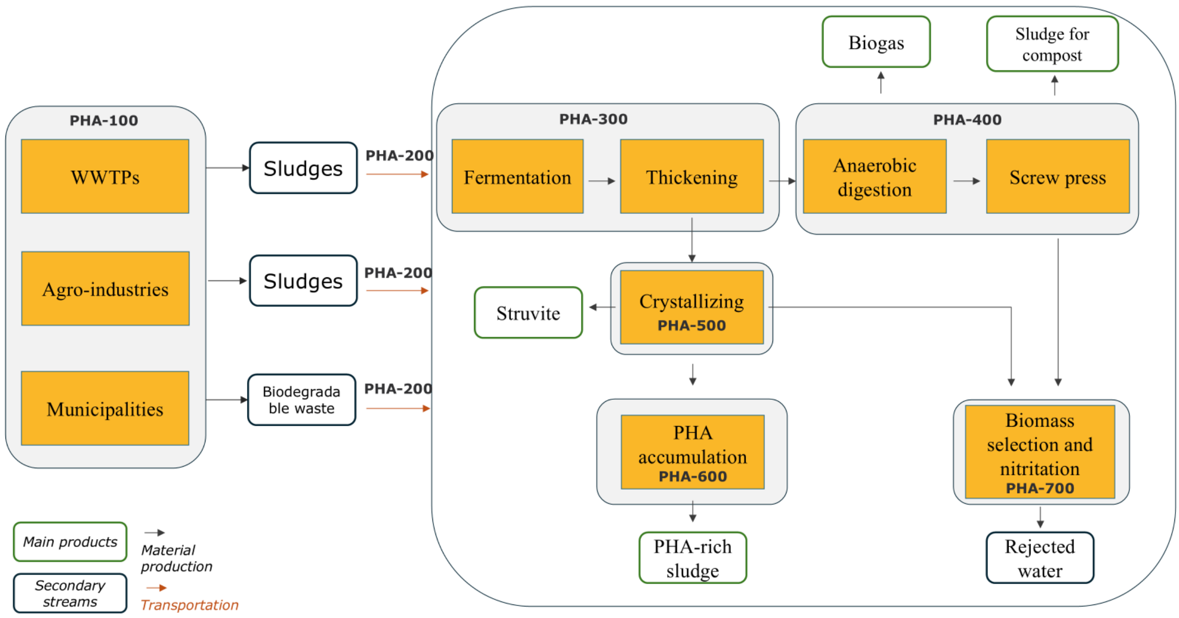

Figure 14: Simplified flow diagram of CS2 value chain

3.2.3 Data collection and assumptions

Primary data derived from actual industries operating in the area are utilized, provided by UNIVPM, which is the CS leader of the Lombardy region value chain. An elaborate network of WWTPs and agro-industries operating in the region is used in this study. In this context, actual data is provided for the distances of the sites and the annual capacities, enabling the precise calculation of the transportation stage impact. Information regarding the operation of the biorefinery unit refers to waste from urban and industrial activities treated in biorefineries managed by 'Metropolitan City of Milan Water System Manager'.

It is highlighted that the emissions for the operation of the agro-industries and municipalities is not taken into account. The emissions are considered only for the wastewater treatment plants that produce the sewage sludge inflow. This is a fair assumption since the sewage sludge inflow constitutes 98.8% of the total solids inflow.

3.2.4 Results and interpretation

The inventory including the quantitative data of the material flows, the input of raw materials and energy along with the waste generated in each aggregated stage of Figure 14, is provided in Table 13 and the corresponding Sankey diagram is illustrated in Figure 15. All data included in the table refer to PHA rich sludge containing 1 kg of PHA.

Table 13: Extended table for PHA production

Process stage	Description		Flow number	Flow characterization (Level 1)	Material specification (Level 2)	Measuring unit	Total quantity	*Relevant only to the main flow*	
							WM	**TS %**	**DM (kg)**
PHA-100	WWTPs	Inputs	101	Main flow	Wastewater influent	m^3	2400		
			102	Energy	Electricity	kWh	909.6		
		Outputs	103	Main flow - total	SS	m^3	5.60	4%	224 kg
				Main flow - Component	N in SS	kg	7.06		
				Main flow - Component	P in SS	kg	3.47		
			104	Emissions (indirect)	GHG	$kgCO_2$-eq	259.24		
PHA-200	Transportation of sludges to biorefinery	Inputs	201	Energy	Diesel	L	1.69		
		Outputs	202	Emissions (direct)	Diesel consumption	$kgCO_2$-eq	4.50		
PHA-300	Fermentation and thickening	Inputs	103	Main flow	SS	m^3	5.60		
			302	Energy	Electricity	kWh	6		
		Outputs	303	Main flow - total	Supernatant	m^3	1.95		
				Main flow - Component	VFA in supernatant	kg	10.74		
				Main flow - Component	N in supernatant	kg	0.96		

				Main flow - Component	P in supernatant	kg	0.29		
			304	Main flow – total	Fermented flow for AD	m^3	3.92		
			304	Main flow - Component	N in fermented flow	kg	7.32		
			304	Main flow - Component	P in fermented flow	kg	3.88		
			305	Emissions (indirect)	GHG	$kgCO_2$-eq	1.71		
PHA-400	Anaerobic digestion and dewatering	Inputs	304	Main flow	Fermented flow for AD	m^3	3.92		
		Inputs	401	Energy	Electricity	kWh	8.30		
		Inputs	402	Raw material	Polyelectroylyte	kg	0.81		
		Outputs	403	Primary product	Biogas	Nm^3	39.57		
		Outputs	404	Main flow - total	Sludge for composting	m^3	0.62	25%	155 kg
		Outputs	404	Main flow - Component	TS in sludge	kg	154		
		Outputs	404	Main flow - Component	N in sludge	kg	7.70		
		Outputs	404	Main flow - Component	P in sludge	kg	3.08		
		Outputs	405	Main flow - total	Supernatant	m^3	3.30		
		Outputs	405	Main flow - Component	N in supernatant	kg	1.11		

				Main flow - Component	P in supernatant	kg	0.30		
			406	Emissions (indirect)	GHG	kgCO_2-eq	2.36		
PHA-500	Crystallizing	Inputs	303	Main flow	Supernatant	m^3	1.95		
			501	Energy	Electricity	kWh	2.07		
			502	Raw material	$MgCl_2$	kg	2.91		
		Outputs	503	Primary product	Struvite	kg	1.72		
				Primary product - Component	P in struvite	kg	0.20		
			504	Main flow	Internal flow stored	m^3	1.95		
				Main flow - Component	VFA in internal flow stored	kg	10.74		
				Main flow - Component	N in internal flow stored	kg	0.96		
				Main flow - Component	P in internal flow stored	kg	0.29		
			505	Emissions (indirect)	GHG	kgCO_2-eq	0.59		
PHA-600	Biomass selection and nitritation	Inputs	601	Raw material	NaOH	kg	0.23		
			602	Main flow	Internal flow	m^3	3.89		
		Outputs	603	Waste	Rejected water	m^3	3.89		
				Waste - component	N in Rejected water	kg	0.13		
				Waste - component	P in Rejected water	Kg	0.07		

PHA-700	PHA accumulation	Inputs	701	Main flow - total	Internal flow	m^3	1.36		
				Main flow - Component	VFA in internal flow stored	kg	7.52		
				Main flow - component	N in Internal flow	Kg	0.67		
				Main flow - component	P in Internal flow	kg	0.20		
		Outputs	702	By-product	Sludge	Kg	3.30		
			703	Primary product	PHA	kg	1		

The main flows of the urban and agro-industrial wastewater value chain, starting from the entrance to the biorefinery facility up to the production of the final product are depicted in the form of a Sankey diagram in Figure 15.

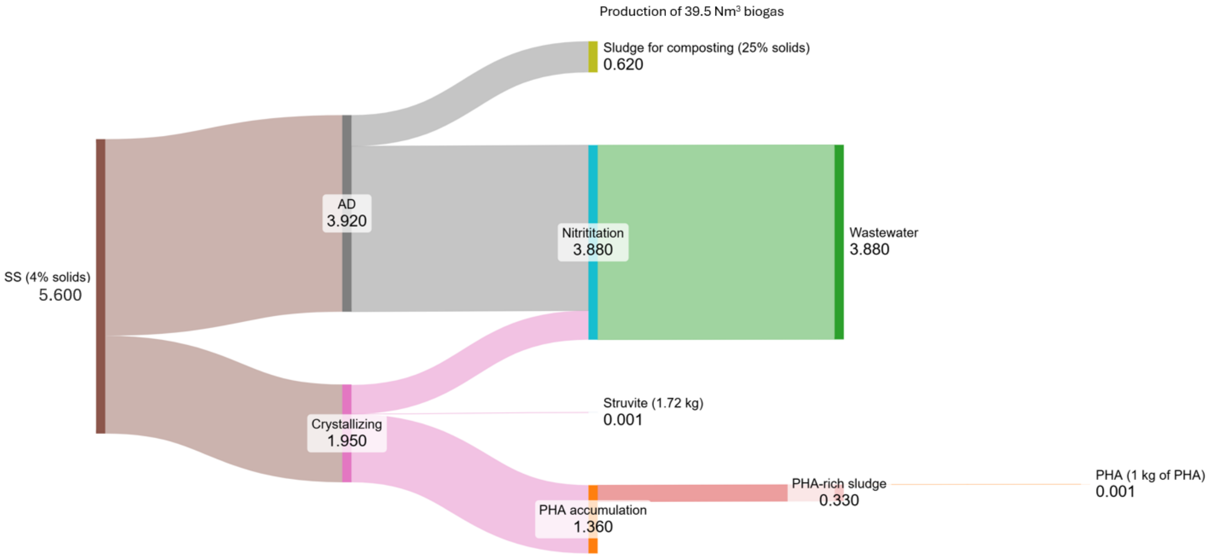

Figure 15: Sankey diagram for CS2 (production of 1 kg PHA); quantities in m^3 or tons

The SS that enters the facility is a resource that contains high quantities of VFAs, N and P. The selected processing attains the recovery of these valuable compounds. The rejected wastewater stream that exits the facility contains 34 mg/L of N and 18 mg/L of P which is significantly lower that the respective concentrations in the inflow (1,411 mg/L of N and 711 mg/L of P).

The operation of the facility, apart from the production of 1 kg of PHA, leads to the generation of 1.72 kg of struvite (containing 0.20 kg P), 39.5 Nm^3 biogas and 0.62 m^3 of sludge with potential for composting applications, achieving a complete valorization of urban waste and efficient resource recovery. The production of 1 kg of PHA results from the processing of 2,400 m^3 of wastewater entering the WWTP that is subsequently converted to 5.60 m^3 SS. This is by far the most energy intensive stage of the value chain producing approximately 95% of the emissions, followed by the transportation stage. The emissions attributed to the operation of the facility amount to 4.7 $kgCO_2$-eq/ kg of PHA which can be further reduced with the utilization of the biogas produced within the facility.

3.3 Case study 3: Central Macedonia, Greece

3.3.1 System boundaries

The agricultural sector constitutes a field with substantial potential for the development of bio-based value chains aiming at the valorization of secondary biomass flows. Two illustrative value chains are explored in the Region of Central Macedonia (RCM) of Greece. The region of Central Macedonia is situated in Northern Greece (Figure 16), has a population of 1.8 million inhabitants. The largest city of RCM is Thessaloniki, while in the region, the largest plain of Greece is situated.

Figure 16: Region of Central Macedonia

RCM occupies a leading role in the country's agricultural production as it contributes 20.2% of the gross value added at a national level. Greece is among the top three EU producers of olives, peaches and citrus fruits and the leading EU peach processor. It is worth mentioning that the production of clingstone peaches that are exclusively used for industrial processing is among the biggest in the world (Ordoudi et al., 2018). Additionally, Greece is a country with a relatively high fraction of the population residing in rural areas (31.3%) compared to the EU average (24%) (European Commission, 2024).

The agricultural production of the Region is officially recorded by the Hellenic Statistical Authority in the "Annual Agricultural Statistics Survey". The latest available report refers to the year 2022. This document provides information on the primary production of the region which amounts to 385,630 t of wheat (32% of the national produce), 87,012 t of barley (28%), 7,682 t of oats (7%), 2,310 t of rye (13%) and 153,917 t of rice (86%). By employing appropriate conversion factors for the calculation of residual agricultural biomass (Skoutida et al., 2025), it can be estimated that 830,000 t of straw are produced in the area with the available quantities to be collected amounting to 354,500 t. Additionally, peach trees constitute the main tree cultivation, which is studied for the valorization of both its pruning and the residual pulp after peach processing. In this case, it is reported that 643,836 t of peach fruits (85.5% of the national produce) are produced in RCM, corresponding to the production of 89,000 t of pruning with the available quantity being 71,000 t.

In RCM operate approx. 14 big fruit processing industries, which process mainly peaches for the production of canned compote and peach puree. According to their environmental permits, these companies produce approx. 16,500 t/year fruit pulp (wet mass) which is usually used for feed, compost, anaerobic digestion or is lead to landfills according to data published (Greek Exporters Association, 2024; Ministry of Environment and Energy Greece, 2024).

3.3.2 Definition of the value chain

For the CS of RCM two value chains are studied for the valorisation of the produced biomass:

- The production of compost using wheat straw, peach tree pruning and peach pulp.
- The production of particle boards using wheat straw or tree pruning.

The value chains start with the cultivation of wheat and peach trees. After wheat cultivation and grain collection, approx. 70% of the wheat straw is pre-treated through windrowing and balling and is temporarily stored on field. The remaining 30% of straw remains on the field. The pre-treated straw is either used for feed or is destined to one of the two BioReCer value chains (compost or particle boards). The straw balls are transported in heavy duty trucks (26 t). The mean distance to the compost installation is 30 km, while to the particle board industry is 500 km. During peach tree cultivation, branches are cut from the trees and a significant amount of pruning is produced. The pruning is shredded and 30% of them remain on field, 20% are burned because they are inappropriate for further uses, while 50% are transported to the compost industry or the particle board manufacturer. The transportation is done in heavy duty trucks (26 t) and the distance is 30 km to the compost installation and 500 km for the particle board industry. The collected peaches are either used for human consumption or they are transported to the fruit processing industry (3.5 t trucks/ distance 20 km). During the processing of peaches, peach pulp is produced which is temporarily stored in the facilities of the industry and then is transported to the compost/biofertilizer industry (heavy duty trucks 26 t/ distance 30 km).

The biofertilizer production consists of four major groups of processing stages:

- The upstream processing, which consists of the entrance of raw materials, weighting and addition of subsidiary materials;
- The main processing, which consists of the composting and the maturing;
- The downstream processing/maturing and
- The final product formulation, which consists of the standardization and the labelling.

In the same manner the particle board value chain was divided into four groups of processing:

- The upstream processing, which consists of the entrance to the plant, on-site storage and pre-treatment with an extruder;
- The pre-treatment, which includes cutting in chips, drying and screening;
- The main processing, which consists of mixing of lignocellulosic with glue mixture and forming of the panel and finally;
- The downstream processing/product finalization, which includes the cold pre-press, the hot press and trimming and sanding of the particle board.

The value chains are schematically presented in Figure 17 and Figure 18 respectively.

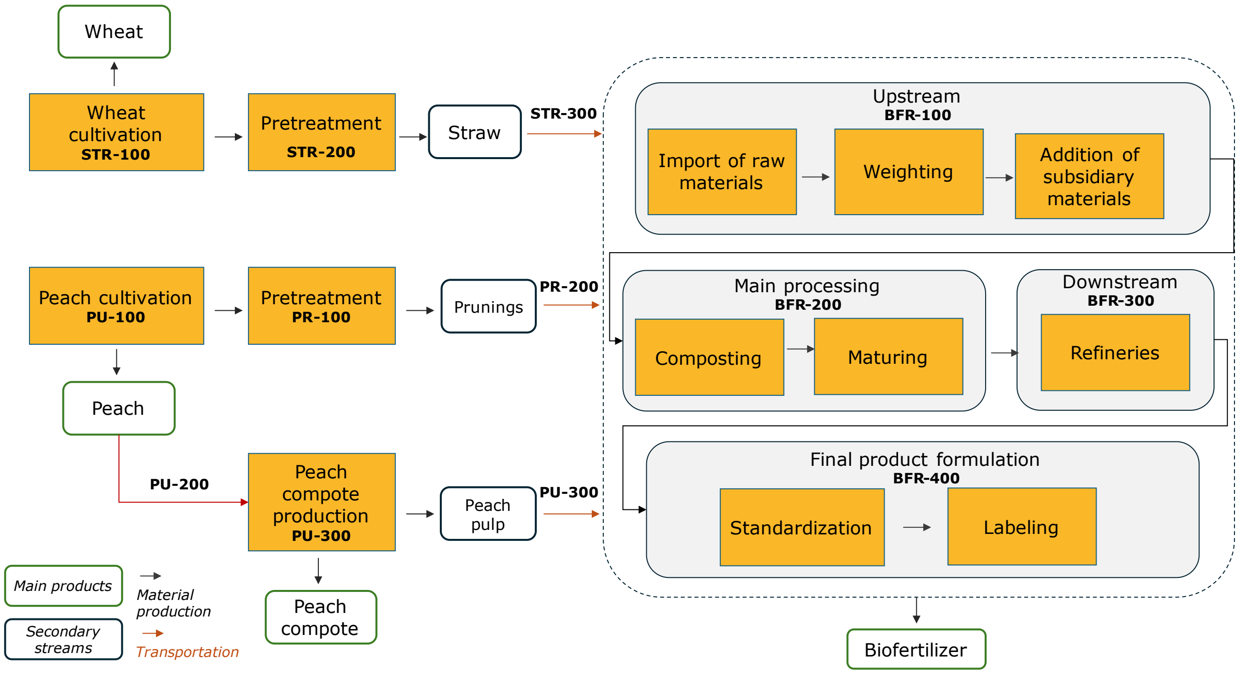

Figure 17: Simplified flow diagram of CS3 value chain (Biofertilizer production)

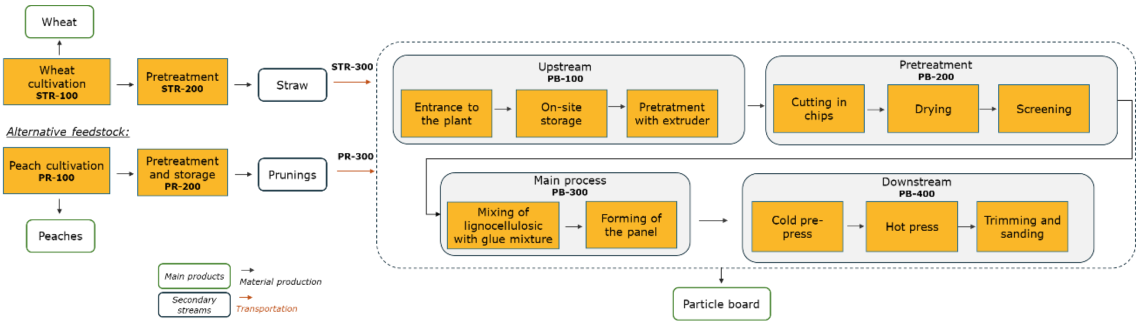

Figure 18: Simplified flow diagram of CS3 value chain (Particle board production)

3.3.3 Data collection and assumptions

To provide a fully representative set of data, information has been derived from the official website of Greek National Statistics concerning the production of the primary commodities in the region under analysis. This data is available at the most recent version of the "Annual Agricultural Statistical Survey" conducted for 2022 (Hellenic Statistical Authority, 2024). Data on the agricultural production stage is derived from scientific literature that specializes in the cultivations considered for the residue production (wheat and peach cultivation) in Mediterranean countries with similar climatic conditions and agricultural practices to Greece. More specifically, data was collected from the following literature sources:

- Wheat production is studied based on the research of Fantin et al., (2017) and Lovarelli et al., (2020) who study cereal cultivation in Italy.
- Data for peach cultivation, pruning and shredding were derived from literature describing peach orchards of the Mediterranean area (Aydın & Aktürk, 2018; Boer et al., 2020; Fotiou & Goula, 2024; Holmatov et al., 2021; Ingrao et al., 2015; Nanaki & Koroneos, 2018; Royan et al., 2012).
- Data describing the operation of the intermediate industry of peach processing is derived from (Nanaki & Koroneos, 2018) and (Paraskevopoulou et al., 2022), that perform an assessment of a Greek peach canning industry for the production of peach compote.

For the two processing units that produce the main bio-based products (compost and chipboard), primary data is collected from representative plants in the region. The distances related to the materials' transportation are provided by the industries reflecting their established supply chains. Finally, to obtain a complete picture of the flows of the target feedstocks, including the current uses that prevail in the RCM along with the typical losses that occur, experienced agronomists in the region were interviewed. It is worth mentioning that the biogenic emissions from the utilization of residual biomass streams for energy generation are excluded from the scope of the current analysis.

3.3.4 Results and interpretation

The results of the implementation of mass balancing and the quantification of the raw materials, energy and waste flows including emissions based on the biofertilizer value chain are presented in Table 14 and Table 15 (Table 14 includes the information for the feedstocks up to their entrance to the facility and Table 15 refers to the processing industry that produced the bio-based product). Information is presented for 1 kg of biofertilizer. This dataset can be used as a reference for conversion factors that may apply to different capacities or similar systems.

For the production 1 kg of biofertilizer (WM) 0.17 kg of straw (DM), 0.103 kg of pruning (DM) and 0.525 kg of pulp (DM) are needed. Straw can be produced from the cultivation of $1.02 \cdot 10^{-3}$ ha of land which produces approx. 2.39 kg (DM) of wheat, as primary product. From the total quantity of straw produced (3.14 kg DM), 0.94 kg (DM) is left on field, 1.61 kg (DM) is used for feed, while the remaining is either lost or burnt, because it is considered inappropriate. The field pre-treatment and transportation of straw is not considered energy intensive (4.28 10^{-03} kg diesel and 5.71 10^{-05} kg diesel, respectively).

The required peach pulp is produced from the cultivation and processing of peaches. A peach orchard of $3.37 \cdot 10^{-3}$ ha, produces 54.4 kg (WM) of peaches as primary product, from which, 39.2 kg (WM) enter the peach processing industry. 20% of harvested peaches are used for food, while a small fraction is lost during cultivation and transportation. Peach processing is a rather water intensive industry, consuming 1.36 m^3 of water for the processing of 39.2 kg (WM) of peaches. The produced peach pulp (0.773 kg DM) enters the biofertilizer industry (0.525 kg DM) or is led to anaerobic digestion facilities (0.232 kg DM), while a small amount is lost during transportation. The same peach orchard produces 8.6 kg (DM) of pruning. From this quantity, 0.103 kg (DM) enters the bio-fertilizer facility, 2.45 kg (DM) are left on field, while the remaining quantity can be valorized in energy or biomaterials production.

The MFA for the production of the biological feedstocks (in DM) which enter the bio-fertilizer industry is illustrated in the Sankey diagram of Figure 19.

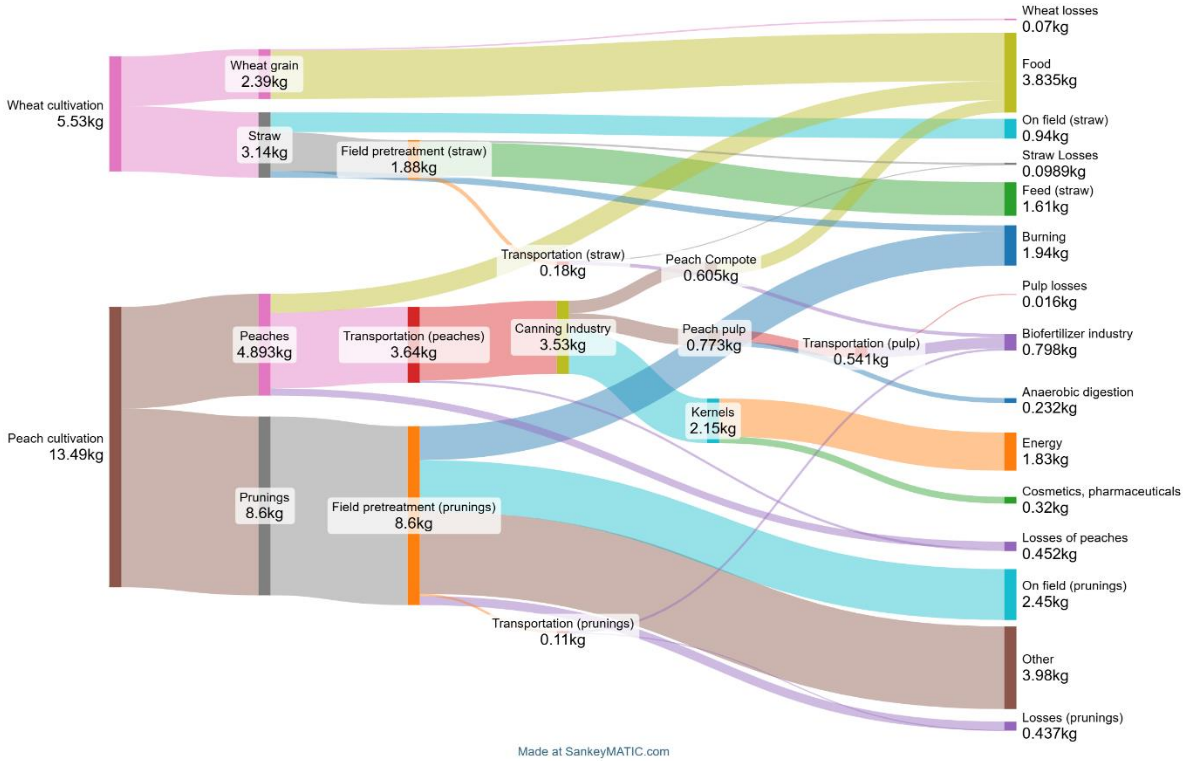

Figure 19: Sankey diagram for CS3 (production of biological feedstocks which enter the bio-fertilizer industry); quantities in DM

The Sankey diagram that indicates the flows of materials within the processing facility for the production of biofertilizer is presented (in DM) in Figure 20. It is worth mentioning that during the main processing (composting and maturing stage), a substantial loss of moisture content occurs. The mixture loses 36% of its mass (equal to 0.63 kg/ kg of biofertilizer produced), with the most important outflow stream being the composting leachate. Additionally, in the downstream processing approximately 10% of the biomass inflow is lost due to the refinement process where impurities are removed along with excessive moisture in order to reach a 30% MC for the final product. Finally, it is highlighted that the composting stage contributes the most to the generation of emissions, which are attributed to the physical process that occurs and not to the consumption of energy.

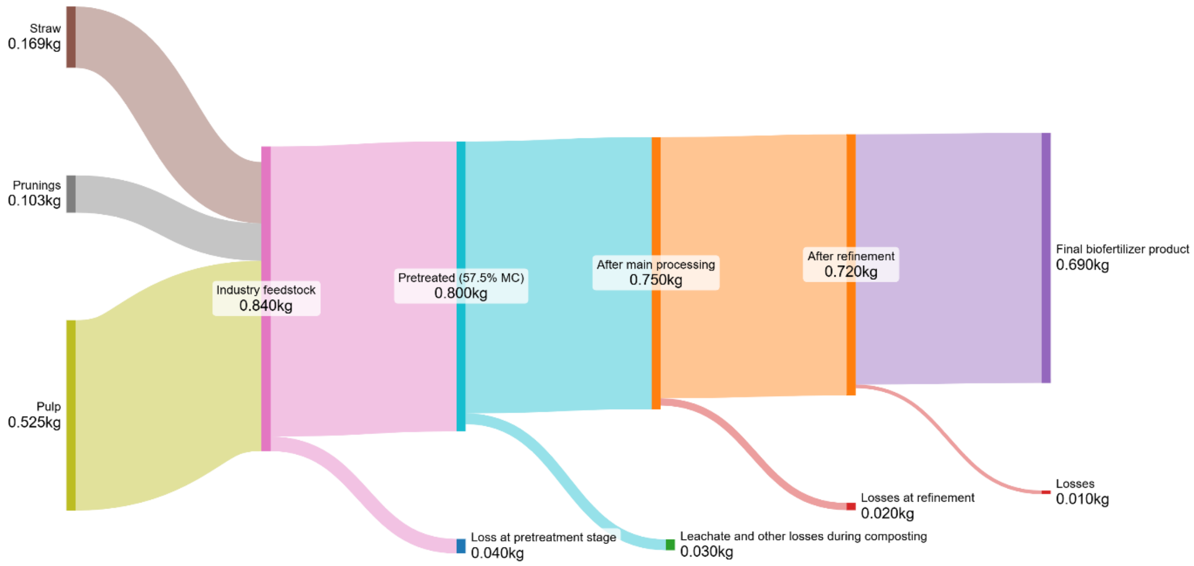

Figure 20: Sankey diagram for CS3 (production of 1 kg biofertilizer at 30% moisture); quantities in kg DM

Table 14: Extended table for biofertilizer production (part A: Feedstocks)

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
STRAW													
STR-100	Cultivation Grain collection	Input	101	Resource	Land	ha	1.02 E-03						
		Input	102	Raw Material	Seeds	kg	0.204						
		Input	103	Raw Material	Fertilizers	kg N	0.173						
		Input	104	Raw Material	Fertilizers	kg P2O5	0.0581						
		Input	105	Resource	Water	m3	9.17 E-04						
		Input	106	Raw Material	Herbicides	kg ai	4.12 E-05						
		Input	107	Raw Material	Fungicides	kg ai	3.85 E-04						
		Input	108	Raw Material	Lubricants	m^3	7.86 E-07						
		Input	109	Energy	Diesel	kg	0.165						
		Output	110	Main product	Wheat grain	kg	2.81	15 %	2.39	0.0843	0.0716	2.32	Food
		Output	111	By-product	Straw	kg	3.49	10 %	3.14			0.94 0.31	On field Burning
		Output	111	Component	N in straw	kg			0.0209				
		Output	111	Component	P in straw	kg			4.24 E-03				
		Output	111	Component	K in straw	kg			9.70				

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
									E-02				
		Output	111	Component	C in straw	kg			1.34				
		Output	112	Emissions (direct)	GHG	kg CO_2-eq	0.529						
		Output	113	Emissions (direct)	NH_3 airborne	kg	3.83 E-03						
		Output	114	Emissions (direct)	N_2O airborne	kg	6.21 E-04						
		Output	115	Emissions (direct)	NO_3^- waterborne	kg	0.0161						
		Output	116	Emissions (direct)	Lubricants	m^3	5.06 E-07						
STR-200	Field pre-treatment Field storage	Input	201	Main flow	Straw	kg	2.09	10 %	1.88	0.105	0.0942		
		Input	201	Component	N in straw	kg			0.0125				
		Input	201	Component	P in straw	kg			2.54 E-03				
		Input	201	Component	K in straw	kg			0.0582				
		Input	201	Component	C in straw	kg			0.802				
		Input	202	Energy	Diesel	kg	4.28 E-03						

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	203	Main flow	Straw	kg	2.09	10 %	1.88	0.105	0.0942	1.61	Feed
		Output	204	Emissions (direct)	GHG	kg CO_2-eq	0.0137						
STR-300	Transportation	Input	301	Main flow	Straw	kg	0.199	10 %	0.179				
		Input	301	Component	N in straw	kg			1.19 E-03				
		Input	301	Component	P in straw	kg			2.42 E-04				
		Input	301	Component	K in straw	kg			5.53 E-03				
		Input	301	Component	C in straw	kg			0.0762				
		Input	302	Energy	Diesel	kg	5.71 E-05						
		Output	303	Main flow	Straw	kg	0.199	10 %	0.179	9.94 E-03	8.95 E-03	0.17	Biofertilizer industry
		Output	303	Component	N in straw	kg			1.19 E-03		5.95 E-05	1.13 E-03	
		Output	303	Component	P in straw	kg			2.42 E-04		1.21 E-05	2.30 E-04	

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	303	Component	K in straw	Kg			5.53 E-03		2.76 E-04	5.25 E-03	
		Output	303	Component	C in straw	kg			0.0762		3.81 E-03	7.24 E-02	
		Output	304	Emissions (direct)	GHG	kgCO_2-eq	1.83 E-04						
PULP													
PU-100	Cultivation Fruit collection	Input	101	Resource	Land	ha	3.37 E-03						
		Input	102	Raw Material	N-fertilizers	kg N	0.379						
		Input	103	Raw Material	P-fertilizers	kg P	0.367						
		Input	104	Raw Material	K-fertilizers	kg K	0.226						
		Input	105	Resource	Water	m^3	4.08						
		Input	106	Raw Material	Pesticides	kg	9.26E-02						
		Input	107	Raw Material	Plastic boxes	pieces	0.169						
		Input	108	Energy	Electricity	kWh	1.29						
		Input	109	Energy	Diesel	kg	0.688						
		Output	110	Main product	Peaches	kg	54.4	91 %	4.89	3.81	0.343	0.910	Food
		Output	110	Component	N in peaches	kg			0.0398		2.79 E-03		

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	110	Component	P in peaches	kg			0.0173		1.21 E-03		
		Output	110	Component	K in peaches	kg			0.0541		3.78 E-03		
		Output	110	Component	Sugars in peaches	kg			3.51		0.246		
		Output	111	By-product	Pruning	kg	15.63	45 %	8.60	0.782	0.430	8.60	Field pretreatment
		Output	111	Component	N in pruning	kg			0.0860				
		Output	111	Component	P in pruning	kg			9.46E-03				
		Output	111	Component	K in pruning	kg			0.0404				
		Output	111	Component	C in pruning	kg			4.23				
		Output	112	Emissions (direct)	GHG	$kgCO_2$-eq	2.21						
		Output	113	Emissions (indirect)	GHG	$kgCO_2$-eq	0.530						
		Output	114	Emissions (direct)	NH3 airborne	kg	9.23 E-03						
		Output	115	Emissions	N2O airborne	kg	4.74 E-03						

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
				(direct)									
		Output	116	Emissions (direct)	NOX	kg	4.74 E-04						
PU-200	Transportation	Input	201	Main flow	Peaches	kg	40.46	91 %	3.64				
		Input	201	Component	N in peaches	kg			0.0296				
		Input	201	Component	P in peaches	kg			0.0129				
		Input	201	Component	K in peaches	kg			0.0402				
		Input	201	Component	Sugars in peaches	kg			2.61				
		Input	202	Energy	Diesel	kg	0.0277						
		Output	203	Main flow	Peaches	kg	40.46	91 %	3.64	1.21	0.109		
		Output	203	Component	N in peaches	kg			0.0296		8.89 E-04		
		Output	203	Component	P in peaches	kg			0.0129		3.87 E-04		
		Output	203	Component	K in peaches	kg			0.0402		1.21 E-03		
		Output	203	Component	Sugars in	kg			2.61		0.0783		

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
					peaches								
		Output	204	Emissions (direct)	GHG	kg CO_2-eq	0.0888						
PU-300	Fruit processing Pulp storage	Input	301	Main flow	Peaches	kg	39.2	91 %	3.53				
		Input	301	Component	N in peaches	kg			0.0287				
		Input	301	Component	P in peaches	kg			0.0125				
		Input	301	Component	K in peaches	kg			0.0390				
		Input	301	Component	Sugars in peaches	kg			2.53				
		Input	302	Raw Material	Sugar	kg	2.90						
		Input	303	Raw Material	Glucose	kg	7.81						
		Input	304	Raw Material	Caustic soda	kg	0.275						
		Input	305	Resource	Water	m^3	1.36						
		Input	306	Raw Material	Tinplate cans	p.	81.9						
		Input	307	Raw Material	Paper Boxes	kg	1.43						
		Input	308	Energy	Diesel	kg	2.90						
		Input	309	Energy	Electricity	kWh	3.24						
		Output	310	By-product	Peach pulp	kg	3.09	75 %	0.773			0.232	Energy[1]

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	310	Component	N in peach pulp	kg			6.88 E-03				
		Output	310	Component	P in peach pulp	kg			9.28 E-04				
		Output	310	Component	K in peach pulp	kg			9.05E-03				
		Output	310	Component	Sugars in peach pulp	kg			0.571				
		Output	311	Main product	Canned compote	kg	81.9	99 %	0.605			0.605	Food
		Output	312	Direct emissions	Wastewater	m3	1.37						
		Output	313	By-product	Peach kernels	kg	2.69	20 %	2.15			1.831 0.323	Energy Other[2]
		Output	313	Component	N in kernels	kg			8.62 E-03				
		Output	313	Component	P in kernels	kg			4.31 E-05				
		Output	313	Component	K in kernels	kg			2.58 E-03				

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	313	Component	C in kernels	kg			1.11				
		Output	314	Emissions (direct)	GHG	kgCO_2-eq	9.20						
		Output	315	Emissions (indirect)	GHG	kgCO_2-eq	1.34						
PU-400	Transportation	Input	401	Energy	Diesel	kg	6.22 E-04						
		Output	402	Main flow	Peach pulp	kg	2.165	75 %	0.541	0.0649	0.0162	0.525	Biofertilizer industry
		Output	402	Component	N in peach pulp	kg			1.93 E-02		1.45 E-04	4.67 E-03	
		Output	402	Component	P in peach pulp	kg			2.60 E-03		1.95 E-05	6.30 E-04	
		Output	402	Component	K in peach pulp	kg			2.53 E-02		1.90 E-04	6.14 E-03	
		Output	402	Component	Sugars in peach pulp	kg			1.60		0.0120	0.388	
		Output	403	Direct emissions	GHG	kgCO_2-eq	2.00 E-03						
PRUNING													
PR-100	Field pre-	Input	101	Main flow	Pruning	kg	15.6	45	8.60				

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
	treatment							%					
	Field storage	Input	102	Energy	Diesel	kg			0.0118				
		Output	103	Main flow	Pruning	kg	15.6	45 %	8.60	0.782	0.43	1.63 2.45 3.98	Burning Left on field Other[3]
		Output	104	Direct emissions	GHG	kgCO_2-eq	0.0374						
PR-200	Transportation	Input	201	Main flow	Pruning	kg	0.197	45 %	0.108				
		Input	201	Component	N in pruning	kg			1.08E-03				
		Input	201	Component	P in pruning	kg			1.19E-04				
		Input	201	Component	K in pruning	kg			5.10E-04				
		Input	201	Component	C in pruning	kg			0.0533				
		Input	202	Energy	Diesel	kg			5.66 E-05				
		Output	203	Main flow	Pruning	kg	0.197	45 %	0.108	9.86 E-03	5.42 E-03	0.103	Biofertilizer industry

Process stage	Description	Input/ Output	Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	204	Direct emissions	GHG	kg CO_2-eq	1.82 E-04						

Table 15: Extended table for biofertilizer production (part B: Processing industry)

Process stage	Description	Input/ Output	Flow number	Flow characterization (Level 1)	Material specification (Level 2)	Measuring unit	Total quantity			Loss	Available Quantity		
							WM	MC %	DM	DM	WM	MC	DM
BFR-100	Upstream (Import of raw materials, Weighting, Addition of subsidiary materials)	Inputs	101	Main flow	Straw	kg	0.1875	10%	0.1688				
			102	Main flow	Pruning	kg	0.1875	45%	0.1031				
			103	Main flow	Pomace	kg	1.5	65%	0.5250				
			104	Energy	Electricity	kWh	3.7E-05						
			105	Energy	Diesel	L	0.0007						
		Outputs	106	Main flow - Total	Internal flow	kg	1.875	29%	0.54	0.04	1.76	57.5%	0.75
			106	Main flow - Component	N in Internal flow	kg			0.0073	0.0004			0.0069
			106	Main flow - Component	P in Internal flow	kg			0.0015	0.0001			0.0014

			106	Main flow - Component	K in Internal flow	kg			0.0092	0.0005			0.0087
			106	Main flow - Component	C in Internal flow	kg			0.3854	0.0193			0.3661
			107	Emissions (direct)	GHG	$kgCO_2$-eq	0.0015						
			108	Emissions (indirect)	GHG	$kgCO_2$-eq	1.5E-05						
BFR-200	Main Process (Composting Maturing)	Inputs	106	Main flow - Total	Total	kg	1.76	57.5%	0.75				
			201	Energy	Diesel	L	0.0005						
		Outputs	202	Main flow - Total	Total	kg	1.76	57.5%	0.75	0.03	1.13	36.5%	0.72
			202	Main flow - Component	N in Total	kg			0.0069	0.0003			0.0065
			202	Main flow - Component	P in Total	kg			0.0014	0.0001			0.0011
			202	Main flow - Component	K in Total	kg			0.0087	0.0004			0.0083
			202	Main flow - Component	C in Total	kg			0.3661	0.0151			0.3226
			203	Emissions (direct)	GHG (from Composting process and diesel consumption)	$kgCO_2$-eq	0.1714						
			204	Waste - Total	Leachate - Total	kg							

										0.1185			
			204	Waste - component	N in Leachate	kg				0.0001			
			204	Waste - component	P in Leachate	kg				0.0002			
			204	Waste - component	K in Leachate	kg				0.0001			
			204	Waste - component	C in Leachate	kg				0.0002			
			205	Waste - Total	Water evaporated	kg				0.4663			
BFR-300	Downstream (Refineries)	Inputs	202	Main flow - Total	Total	kg	1.13	36.5%	0.72				
			301	Energy	Electricity	kWh	0.0071						
		Outputs	302	Main flow - Total	Internal flow	kg	1.13	36.5%	0.72	0.0226	1.02	31.6%	0.69
			302	Main flow - Component	N in Internal flow	kg				0.0002			0.0063
			302	Main flow - Component	P in Internal flow	kg				3.43E-05			0.0011
			302	Main flow - Component	K in Internal flow	kg				0.0002			0.0080
			302	Main flow - Component	C in Internal flow	kg				0.0097			0.3129
			303	Emissions (indirect)	GHG	$kgCO_2$-eq	0.0029						
BFR-400	Product	Inputs	302	Main flow - Total	Total	kg	1.02	31.6%	0.69				

	formulation (Standardization, Labeling)		401	Energy	Electricity	kWh	0.0245						
			402	Raw materials	Polyethylene film	kg	0.0029						
		Outputs	403	Main flow - Total	Biofertilizer	kg	1.02	31.6%	0.69	0.01	1	31%	0.68
				Main flow - Component	N in Biofertilizer	kg					0.0062		
				Main flow - Component	P in Biofertilizer	kg					0.0011		
				Main flow - Component	K in Biofertilizer	kg					0.0078		
				Main flow - Component	C in Biofertilizer	kg					0.3065		
				Emissions (indirect)	GHG	$kgCO_2$-eq	0.0101						

For the production of 1 kg of particleboard (WM), 0.99 kg (DM) of straw are required, which originate from the cultivation of 5.94 10^{-3} ha of land. If pruning are used for the production of 1 kg of particle board (WM), then 1.61 of peach pruning (WM) are needed, which come from the cultivation of 8.39 10^{-04} ha of land. The inventories for the production of the two feedstocks are illustrated in Table 16 (for straw) and Table 18 (for pruning). Similarly, for the particle board processing industry, the inventories are presented in Table 17 and Table 19. For the value chain of the straw and pruning that enter the particleboard producing facility, the uses and losses are analogous to those presented for corresponding stages of the biofertilizer value chain. Within the producing facility, a small percentage of main flow is lost in each stage (0.5-2%). It is important to highlight that the straw residues or sawdust are collected and further utilized in order to cover the energy needs of the facility. The quantities collected as by-products of the processing phase are 120% larger than the biomass that needs to be utilized for energy production and therefore a part of the particle board waste streams (i.e., 0.08 kg of straw residues or sawdust/kg of particleboard produced) can be used as by-product for energy applications.

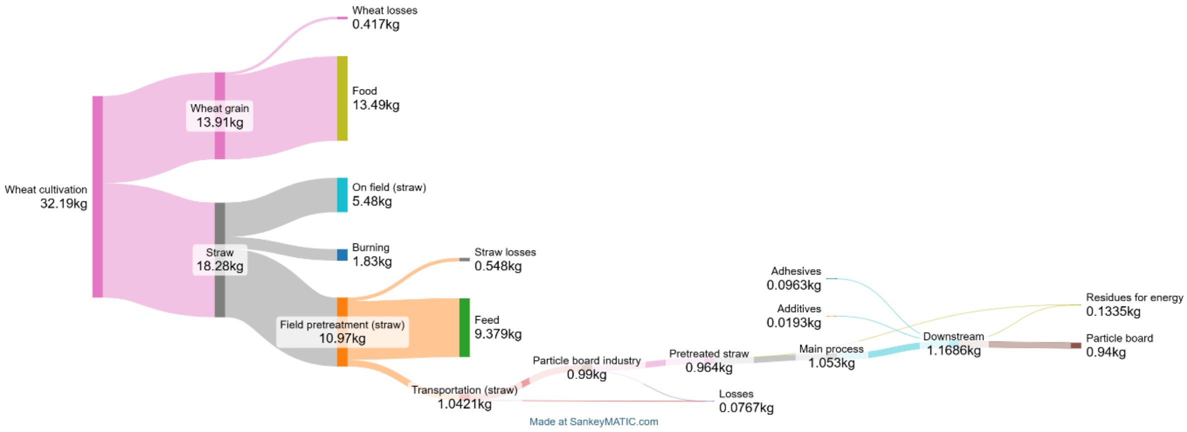

Figure 21: Sankey diagram for CS3 (production 1 kg of particle board from straw, 6% MC); quantities in kg DM

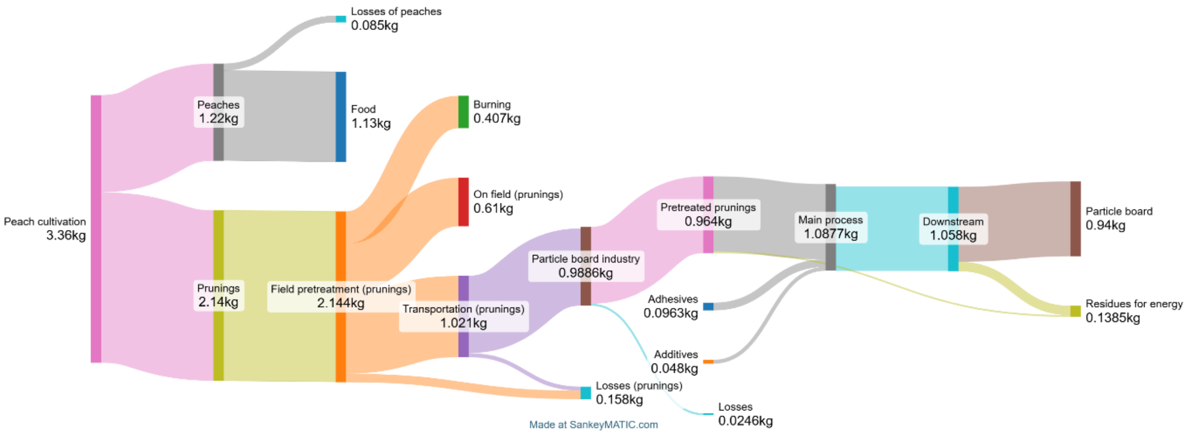

Figure 22: Sankey diagram for CS3 (production 1 kg of particle board from pruning, 6% MC); quantities in kg DM

Table 16: Extended table for particle board production from straw (Part A: Feedstock)

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
STRAW													
STR-100	Cultivation Grain collection	Input	101	Resource	Land	ha	5.94 E-03						
		Input	102	Raw Material	Seeds	kg	1.187						
		Input	103	Raw Material	Fertilizers	kg N	1.009						
		Input	104	Raw Material	Fertilizers	kg P2O5	0.338						
		Input	105	Resource	Water	m3	5.34 E-03						
		Input	106	Raw Material	Herbicides	kg ai	2.40 E-04						
		Input	107	Raw Material	Fungicides	kg ai	2.24 E-03						
		Input	108	Raw Material	Lubricants	m^3	4.58 E-06						
		Input	109	Energy	Diesel	kg	0.960						
		Output	110	Main product	Wheat grain	kg	16.36	15%	13.91	0.491	0.417	13.49	Food
		Output	111	By-product	Straw	kg	20.31	10%	18.28	-	-	5.48 1.83	On field Burning
		Output	111	Component	N in straw	kg			0.122				
		Output	111	Component	P in straw	kg			0.0247				
		Output	111	Component	K in straw	kg			0.565				

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
		Output	111	Component	C in straw	kg			7.79				
		Output	112	Emissions (direct)	GHG	kg CO_2-eq	3.08						
		Output	113	Emissions (direct)	NH_3 airborne	kg	0.0223						
		Output	114	Emissions (direct)	N_2O airborne	kg	3.62 E-03						
		Output	115	Emissions (direct)	NO_3^- waterborne	kg	0.0938						
		Output	116	Emissions (direct)	Lubricants	m^3	2.94 E-06						
STR-200	Field pre-treatment Field storage	Input	201	Main flow	Straw	kg	12.19	10%	10.97				
		Input	201	Component	N in straw	kg			0.073				
		Input	201	Component	P in straw	kg			0.0148				
		Input	201	Component	K in straw	kg			0.339				
		Input	201	Component	C in straw	kg			4.673				
		Input	202	Energy	Diesel	kg			0.0249				
		Output	203	Main flow	Straw	kg	12.19	10%	10.97	0.609	0.548	9.379	Feed
		Output	204	Emissions (direct)	GHG	kg CO_2-eq	0.0800						
STR-300	Transportation	Input	301	Main flow	Straw	kg	1.16	10%	1.04				
		Input	301	Component	N in straw	kg			6.93 E-03				
		Input	301	Component	P in straw	kg			1.41				

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
									E-03				
		Input	301	Component	K in straw	kg			0.0322				
		Input	301	Component	C in straw	kg			0.444				
		Input	302	Energy	Diesel	kg			3.32 E-04				
		Output	303	Main flow	Straw	kg	1.16	10%	1.04	0.0579	0.0521	0.990	Particle board industry
		Output	303	Component	N in straw	kg			6.93 E-03		3.47 E-04	6.58 E-03	
		Output	303	Component	P in straw	kg			1.41 E-03		7.03 E-05	1.34 E-03	
		Output	303	Component	K in straw	kg			0.0322		1.61 E-03	0.0306	
		Output	303	Component	C in straw	kg			0.4439		0.0222	0.422	
		Output	304	Emissions (direct)	GHG	$kgCO_2$-eq	1.07 E-03						

Table 17: Extended table for particle board production from straw (part B: Processing industry)

Process stage	Description	Input/ Output	Flow number	Flow characterization (Level 1)	Material specification (Level 2)	Measuring unit	Available quantity			Loss			Residues for energy
							WM	MC %	DM	WM	Water	DM	DM
PB-100	Upstream (On site storage Extrusion)	Inputs	101	Main flow	Straw	kg	1.10	10%	0.99				
			102	Energy	Electricity	kWh	0.2559						
		Outputs	103	Main flow	Total	kg	1.0710	10%	0. 964	0.0273	0.0027	0.0246	-
			104	Emissions (indirect)	GHG	$kgCO_2$-eq	0.1054						
PB-200	Pretreatment (Cutting, Drying, Screening)	Inputs	103	Main flow	Total	kg	1.0710	10%	0.964				
			201	Energy	Electricity	kWh	0.1147						
			202	Energy	Diesel	m^3	0.0001						
		Outputs	203	Main flow	Total	kg	0.9626	2%	0.9434	0.1084	0.0879	0.0205	0.0205
			204	Emissions (direct)	GHG	$kgCO_2$-eq	0.1611						
			205	Emissions (indirect)	GHG	$kgCO_2$-eq	0.0473						
PB-300	Main process (Mixing with glue, Forming of	Inputs	203	Main flow	Total	kg	0.9626	2%	0.9434				
			301	Energy	Electricity	kWh	0.0324						
			302	Raw material	Adhesives mixture	Kg	0.0963						

	panel)		303	Resources	Water	Kg	0.0193							
			304	Raw material	Additives	kg	0.0193							
			305	Raw material	Straw residues	Kg	0.0516							
		Outputs	306	Main flow	Total	kg	1.1263	6.5%	1.0531	0	0	0	-	
			307	Emissions (indirect)	GHG	kgCO_2-eq	0.0133							
PB-400	Downstream (Cold pre-press, Hot press, Trimming)	Inputs	306	Main flow	Total	kg	1.1263	6.5%	1.0531					
			401	Energy	Electricity	kWh	0.0647							
			402	Energy	Diesel	m^3	1.84E-05							
			403	Raw materials	Straw residues	Kg	0.0155							
		Outputs	404	Main flow	Particle Board	kg	1	6%	0.9400	0.1263	0.013	0.113	0.113	
			405	Emissions (direct)	GHG	kgCO_2-eq	0.0489							
			406	Emissions (indirect)	GHG	kgCO_2-eq	0.0267							

Table 18: Extended table for particle board production from pruning (part A: Feedstock)

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
PRUNING													
PR-100	Cultivation Fruit collection	Input	101	Resource	Land	ha	8.39 E-04						
		Input	102	Raw Material	N-fertilizers	kg N	0.0945						
		Input	103	Raw Material	P-fertilizers	kg P	0.914						
		Input	104	Raw Material	K-fertilizers	kg K	0.562						
		Input	105	Resource	Water	m^3	1.02						
		Input	106	Raw Material	Pesticides	kg	0.0231						
		Input	107	Raw Material	Plastic boxes	pieces	0.0420						
		Input	108	Energy	Electricity	kWh	0.320						
		Input	109	Energy	Diesel	kg	0.171						
		Output	110	Main product	Peaches	kg	13.5	91%	1.22	0.95	0.085	1.13	Food
		Output	110	Component	N in peaches	kg			9.91 E-03		6.94 E-04	9.22 E-03	
		Output	110	Component	P in peaches	kg			4.31 E-03		3.02 E-04	4.01 E-03	
		Output	110	Component	K in peaches	kg			0.0135		9.42 E-04	0.0125	
		Output	111	Component	Sugars in	kg			0.874		0.0612	0.813	

Process stage	Description		Flow No	Flow characterization (Level 1)	Material specification (Level 2)	Unit	Total quantity			Main flow losses		Main flow fate / uses	
							WM	MC	DM	WM	DM	DM	Specification
					peaches								
		Output	112	By-product	Pruning	kg	3.57	40%	2.14			2.14	
		Output	112	Component	N in pruning	kg			0.0214			0.0214	
		Output	112	Component	P in pruning	kg			2.35 E-03			2.35 E-03	
		Output	112	Component	K in pruning	kg			0.0101			0.0101	
		Output	112	Component	C in pruning	kg			1.05			1.05	
		Output	113	Emissions (direct)	GHG	$kgCO_2$-eq	0.550						
		Output	114	Emissions (indirect)	GHG	$kgCO_2$-eq	0.0132						
PR-200	Field pre-treatment Field storage	Input	201	Main flow	Pruning	kg	3.57	40%	2.14				
		Input	202	Energy	Diesel	kg	2.94 E-03						
		Output	203	Main flow	Pruning	kg	3.57	40%	2.14	0.178	0.107	0.407 0.61	Burning Left on field
		Output	204	Direct emissions	GHG	$kgCO_2$-eq	9.31 E-03						
PR-300	Transportation	Input	301	Main flow	Pruning	kg	1.69	40%	1.02				
		Input	301	Component	N in pruning	kg	0.0102						
		Input	301	Component	P in pruning	kg	1.119E						

Process stage	**Description**		**Flow No**	**Flow characterization (Level 1)**	**Material specification (Level 2)**	**Unit**	**Total quantity**			**Main flow losses**		**Main flow fate / uses**	
							WM	**MC**	**DM**	**WM**	**DM**	**DM**	**Specification**
							-03						
		Input	301	Component	K in pruning	kg	4.779E -03						
		Input	301	Component	C in pruning	kg	0.500						
		Input	302	Energy	Diesel	kg	4.87 E-04						
		Output	302	Main flow	Pruning	kg	1.69	40%	1.02	0.0847	0.0508	0.97	Particle board industry
		Output	302	Direct emissions	GHG	kg CO2-eq	1.56 E-03						

Table 19: Extended table for particle board production from pruning (part B: Processing industry)

Process stage	**Description**	**Input/ Output**	**Flow number**	**Flow characterization (Level 1)**	**Material specification (Level 2)**	**Measuring unit**	**Available quantity**			**Loss**			Residues for energy
							WM	**MC %**	**DM**	**WM**	**Water**	**DM**	**DM**
PB-100	Upstream	Inputs	101	Main flow	Pruning	kg	1.614	40%	0.969				

	(On site storage)	Outputs	102	Main flow	Total	kg	1.614	40%	0.969	0.0081	0.0032	0.0048	-
PB-200	Pretreatment (Cutting, Drying, Screening)	Inputs	102	Main flow	Total	kg	1.614	40%	0.969				
			201	Energy	Electricity	kWh	0.114						
			202	Energy	Diesel	L	0.061						
		Outputs	203	Main flow	Total	kg	0.962	2%	0.943	0.645	0.616	0.029	0.027
			204	Emissions (direct)	GHG	kgCO$_2$-eq	0.1611						
			205	Emissions (indirect)	GHG	kgCO$_2$-eq	0.0473						
PB-300	Main process (Mixing with glue, Forming of panel)	Inputs	203	Main flow	Total	kg	0.962	2%	0.943				
			301	Energy	Electricity	kWh	0.0324						
			302	Raw material	Adhesives mixture	Kg	0.0963						
			303	Resources	Water	Kg	0.0193						
			304	Raw material	Additives	kg	0.0193						
			305	Raw material	Sawdust	Kg	0.0516						
		Outputs	306	Main flow	Total	kg	1.126	6.5%	1.053	0	0	0	-
			307	Emissions (indirect)	GHG	kgCO$_2$-eq	0.0133						
PB-400	Downstream (Cold pre-press, Hot press, Trimming)	Inputs	306	Main flow	Total	kg	1.126	6.5%	1.053				
			401	Energy	Electricity	kWh	0.0647						
			402	Energy	Diesel	m^3	1.84E-05						
			403	Raw materials	Sawdust	Kg	0.0155						
		Outputs	404	Main flow	Particle Board	kg	1	6%	0.9400	0.121	0.002	0.118	0.113

			405	Emissions (direct)	GHG	$kgCO_2$-eq	0.0489	
			406	Emissions (indirect)	GHG	$kgCO_2$-eq	0.0267	

3.4 Case study 4: Västernorrland, Sweden

3.4.1 System boundaries

Representative value chains of the forestry sector are studied in Västernorrland County in Sweden. Sweden has a leading role in the forest-based industry. More specifically, Sweden is the country with the largest forest coverage in Europe, amounting to 28 million hectares, followed by Finland and Spain. Sweden's forest cover per capita is 2.8 ha (Hannerz Mats & Ekström Håkan, 2023). Forests occupy approximately 70% of the country's surface while sustainable forest management constitutes a key priority. It is reported that only 1% of the forest land is felled annually and for each tree harvested, at least two trees are planted (Swedish Forest Industries, 2024) Also, forestry constitutes a sector of vital importance for the Swedish economy as it accounts for 11-13% of the total employment, turnover and added value, and for 11% of Sweden's export (Swedish sawmills, 2012). In total, Swedish forest industries produced approximately 12 million t of pulp (of which 4.3 million t are market pulp), 11.3 million t of paper, and 18.3 million cubic meters of sawn timber in 2018 (Kumar et al., 2021).

The Västernorrland County, it is located in the middle of Sweden (Figure 23), has a population of 245,000 inhabitants and the main cities are Sundsvall, Örnsköldsvik and Härnösand.

Figure 23: Västernorrland County (sourced from Global Forest Watch)

According to data derived from the Official Statistics of Sweden (Sveriges officiella statistic) it is reported that 1.65 million hectares of productive forest area are in the region of Västernorrland, being the fourth most important region in terms of forest land, while it corresponds to 7% of the country's total. In the region, 32.1% of the trees are pine, 28% spruce and 26.1% coniferous. 53% of the forest land is owned by companies and 42% is property of individual owners. The growing stock reported in the area is 146 m^3sk/ha (includes the tree stem volume above the felling cut, comprising the bark and top of the tree, but not the branches). The volume of dead wood generated per hectare is 15.6 m^3/ha. All data are provided as a mean value for the time period of 2019-2023 (Official Statistics of Sweden & Swedish University of Agricultural Sciences, 2024).

In particular, the residual biomass streams that are analysed in the context of BioReCer derive either from the forest management practices or from the processing of roundwood in sawmills and pulp and paper industries of the region. The residual biomass considered comprises (BioReCer, 2024):

- **GROT** refers to branches and treetops that are left as residue when the harvester cuts the logs.
- **Bark** is the outer protective layer of a tree, and during industrial processing, it is separated from the wood.
- **Sawdust** consists of fine wood particles that are created during the cutting or milling of timber.
- **Fiber sludge** consists of fibers that remain unused in the pulping process.

Forest management generates substantial volumes of residual biomass. In the Västernorrland County, an estimated quantity of 282,000 t_{dm} of tops and branches is generated. A very important element of the forest-based industry of the region is the sawmill industry. In the Västernorrland County, the total annual quantity of sawn wood produced amounted to 1,488,000 m^3 for the year 2019. Within the context of a sawmill operation, an estimated 50% of the roundwood inflow becomes sawn wood products, 10% bark, 20% chips (Persson, 2021). Therefore, from the operation of the sawmills in the region, approximately 134,000 t of bark and 262,000 t of woodchips are generated annually. Additionally, in the region, it is estimated that 125,000 t of sawdust is produced (SWEDISH WOOD, 2025).

With regard to the pulp and paper industry, approximately 1.9 Mt of pulp was produced in 2023 within the region under study (Skogs Industierna, 2023). This amount of primary product corresponds to the generation of 37,560 dry t of fiber sludge. In the context of the pulp and paper mills operation, large quantities of bark are generated as well, that originate from the wood handling and processing stage. The bark produced 2023 was in the range of 600 kt (dry mass), assuming that the bark accounts for 15% of the tree dry weight and an average kraft pulping yield of 45%.

3.4.2 Definition of the value chain

An overview of the value chain that is assessed in the context of BioReCer is presented in Figure 24.

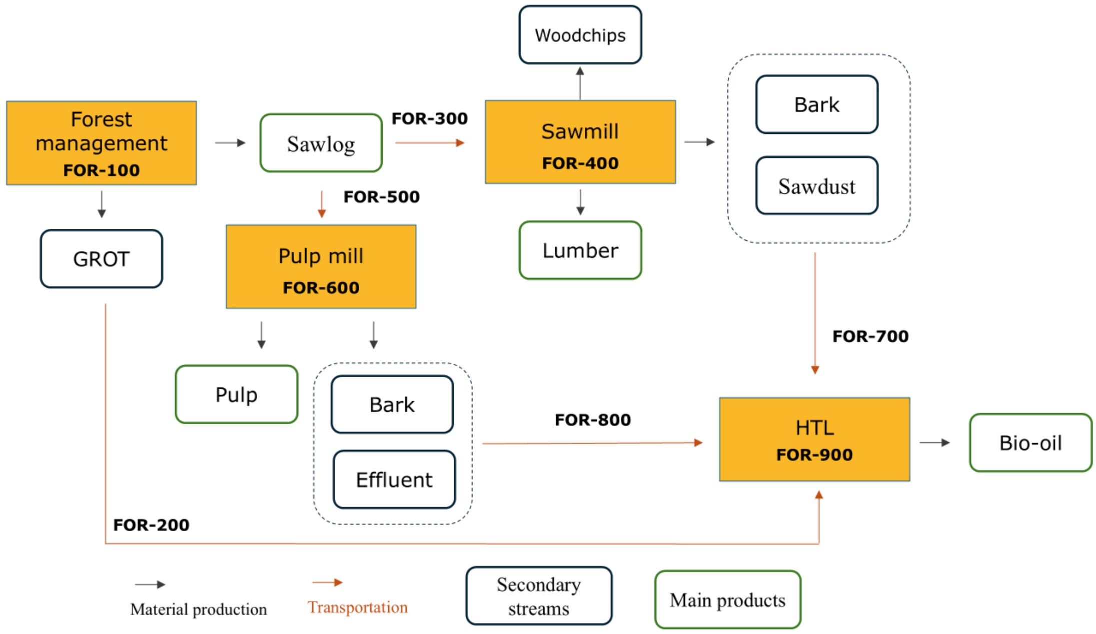

Figure 24: Overview of CS4 value chain

Within the value chain, the valorization of GROT, bark, sawdust and fiber sludge is examined. The first step of the value chain encompasses the forest management stage. The primary product of this activity are the sawlogs produced that are subsequently transported to the sawmill, and the pulp industry to produce added value products, including lumber and pulp, respectively. Forest management includes practices such as sawing, harvesting and skidding, and leads to the generation of GROT as a secondary stream. Part of the GROT is collected and utilized as a biofuel. Furthermore, for the BioReCer scenario, additional GROT is collected and transported to the final processing unit of the bio-oil production. Sawmill is the first intermediate processing unit of the value chain. Sawmilling is a manufacturing setting equipped with machines, transporters and handling mechanisms for the conversion of logs into sizable and merchantable lumber and other wood-based products (Rawat et al., 2023). Throughout its operation large volumes of by-products are generated (approximately 50% of the inflow volume) including woodchips, sawdust and bark. These by-product streams are conventionally used as feed for the pulp and paper industry and for energy production applications. However, within the BioReCer case study, a part of these residues is diverted to a bio-oil facility to be used as feedstock for an alternative product. The pulp and paper industry (PPI) constitutes an additional intermediate processing unit encountered in the value chain that receives pulpwood and woodchips to produce pulp. The first stage of the PPI operation includes pulp making, in which the raw materials are subjected to preparation, debarking and cutting into small pieces. Then, the pulp cooking process under high temperatures and pressure is conducted by employing mechanical, chemical or thermo-mechanical methods, followed by the bleaching process, pulp washing and removal of the bleaching agents and other hardly biodegradable compounds. Finally, the treated pulp is dewatered, and the resulting sheets are dried using air or heat (Esmaeeli et al., 2023). The PPI processing generates various by-product streams, including fiber sludge and bark that are assessed within the BioReCer value chain. It is highlighted that only 3% of the totally generated effluent needs to be sent to the bio-oil facility. The remaining quantity is burned as a waste management option. On the contrary, around ~8% of the total amount of bark is sent to the bio-oil facility. The final module of the forestry case study includes the bio-oil production plant that operates based on hydrothermal liquefaction (HTL) technology. HTL is a thermochemical process that is conducted in an aqueous medium at high pressure (5-20 MPa) and at temperatures ranging from 250 and 370 ^{o}C. In these sub-critical conditions, the complex structures of biomass decompose to smaller molecules with high energy density through hydrolysis and re-polymerization reactions. A major advantage of this method is the utilization of biomass without the need for drying it first (Mathimani et al., 2019). Along with the bio-oil production, the generation of gas and hydrochar is attained.

3.4.3 Data collection and assumptions

A valuable source of data was the Official Statistics of Sweden (Sveriges officiella statistic) that provided a comprehensive report on the characteristics of the forests of Västernorrland County. Having it as a starting basis, an extensive review of the literature and reports has been conducted with the aim to acquire specific information about the relevant industries of the area. Special emphasis was placed on acquiring data regarding the capacity and productivity of the sawmills and the pulp mills of the region that constitute the intermediate companies of the value chain. The information related to the materials and energy consumption for the stages of the value chain depicted in Figure 24 have been retrieved from credible databases such as the Ecoinvent database and consultation of RISE partners that are the forestry case study leaders and experts on the processes under study with a good overview of the local industry. Also, specific emission factors tailored to the Swedish energy mix, described in Section 2.2, are utilized.

An important point for consideration is the capacity of the bio-oil production facility that is directly linked to the quantity of by-products that are sent to the BioReCer value chain. The main fate of the investigated by-product streams is the bioenergy production which constitutes a highly competitive established use for this kind of by-products. Also, it should be taken into consideration that the bio-oil production process is not a mature technology applied on a large scale. Therefore, the portion of the by-products that are allocated for the bio-oil production as an alternative utilization route compared to the traditional energy generation option, is defined based on an assumption. In this context, a realistic scenario is the utilization of 7% of the generated GROT residues within the BioReCer value chain, in order to ensure that the established uses are not impacted. Also, due to the small-scale nature of the HTL facility, the valorization of by-products deriving from a typical sawmill and a typical pulp mill is examined. Another important point relates to the site of the HTL unit. A typical practice, especially regarding the valorization of side streams, is to establish industrial synergies and construct the processing unit in close proximity to the industry that produces the side stream. Therefore, it is assumed that the HTL unit is located near the PPI and the activities take place within a radius of 50 km. Finally, the biogenic emissions from the utilization of residual biomass for energy production are excluded from the scope of the analysis.

3.4.4 Results and interpretation

All the information associated with the material, energy flows and emissions of the investigated value chain is presented in the forestry Extended Table (Table 20) and provides data tailored to the specific region, as described in Sections 3.4.1-3.4.3. The quantitative information is given on the basis of 1 kg of final product (bio-oil) and therefore this database can be utilized as a basis for conversion factors that could be applicable for different capacities or similar systems. Additionally, the Sankey diagram for the production of 1 kg of bio-oil is presented in Figure 25.

Table 20: Extended table for bio-oil production

Process stage	Description	Input/ Output	Flow number	Flow characterization (Level 1)	Material specification (Level 2)	Measuring unit	Total quantity WM	Relevant only to the main flow MC %	DM	Other use WM	Specification
FOR-100	Forest management	Inputs	101	Resource	Land	m^2	29.27				
			102	Energy	Diesel	L	0.0041				
		Outputs	103	Primary product	Sawlog	kg	13.30	50%	6.65		
			104	Main flow	GROT	kg	0.68	50%	0.34	0.26	Energy
			105	Emissions (direct)	GHG	$kgCO_2$-eq	0.015				
FOR-200	Transportation Of GROT to the HTL facility	Inputs	201	Energy	Diesel	L	0.0003				
		Outputs	202	Emissions (direct)	GHG	$kgCO_2$-eq	0.0014				
FOR-300	Transportation Of sawlogs to the sawmill	Inputs	301	Energy	Diesel	L	0.0012				
		Outputs	302	Emissions (direct)	GHG	$kgCO_2$-eq	0.0043				
FOR-400	Sawmill	Inputs	401	Main flow	Sawlog	kg	2.055	50%	1.027	0	-
			402	Energy	Electricity	kWh	6.79E-07				
			403	Raw materials	Lubricating oil	kg	3.75E-09				
		Outputs	404	Primary product	Lumber	kg	0.900				
			405	Main flow	Bark	kg	0.261	50%	0.13	0	-
			406	Main flow	Sawdust	kg	0.179			0	-
			407	By-product	Woodchips	kg	0.715				
			408	Emissions (indirect)	GHG	$kgCO_2$-eq	1.02E-011				

FOR-500	Transportation Of sawlogs to the pulp mill	Inputs	501	Energy	Diesel	L	0.006				
		Outputs	502	Emissions (direct)	GHG	$kgCO_2$-eq	0.023				
FOR-600	Pulp mill	Inputs	601	Main flow	Sawlog	kg	11.242				
			602	Raw materials	NaOH	kg	0.320				
			603	Raw materials	O_2	kg	0.223				
			604	Raw materials	ClO_2	kg	0.269				
			605	Raw materials	H_2O_2	kg	0.074				
			606	Resources	Water	m^3	0.158				
			607	Energy	Steam	GJ	0.076				
			608	Energy	Electricity	MWh	5.569				
		Outputs	609	Primary product	Pulp	kg	9.28				
			610	Main flow	Effluent	kg	164.28	0.6%	0.986	0.955	Production of methane
			611	Main flow	Bark	Kg	2.181	50%	1.09	0	-
			612	By-product	Black liquor	kg	10.045				
			614	Emissions (indirect)	GHG	$kgCO_2$-eq	0.083				
FOR-700	Transportation Of sawmill by-product to the HTL facility	Inputs	701	Energy	Diesel	L	0.0002				
		Outputs	702	Emissions (direct)	GHG	$kgCO_2$-eq	0.0009				
FOR-800	Transportation Of pulp mill by-product to the HTL facility	Inputs	801	Energy	Diesel	L	0.0041				
		Outputs	802	Emissions (direct)	GHG	$kgCO_2$-eq	0.0152				

FOR-900	HTL facility	Inputs	901	Main flow	Bark	kg	2.442				
			902	Main flow	Effluent	kg	5.065	0.6%	0.030		
			903	Main flow	GROT	kg	0.680				
			904	Main flow	Sawdust	kg	0.179				
			905	Energy	Natural gas	kg	0.274				
			906	Energy	Electricity	kWh	0.0003				
			907	Raw material	Dewatering polymer	kg	0.028				
			908	Raw material	Quicklime (CaO)	kg	0.878				
			909	Raw material	Cooling water make up	kg	0.168				
			910	Resource	Water	kg	6.484				
		Outputs	911	Main product	Bio-oil	Kg	1				
			912	Co-product	Syngas	kg	0.074				
			913	Co-product	Hydrochar	kg	0.432				
			914	Waste	Wastewater	kg	6.602				
			915	Emissions (indirect)	GHG	$kgCO_2$-eq	5.0E-09				
			916	Emissions (direct)	GHG	$kgCO_2$-eq	7.69E-07				

The main flows of the biological resources utilized for the production of 1 kg of bio-oil are schematically presented in the Sankey diagram of Figure 25.

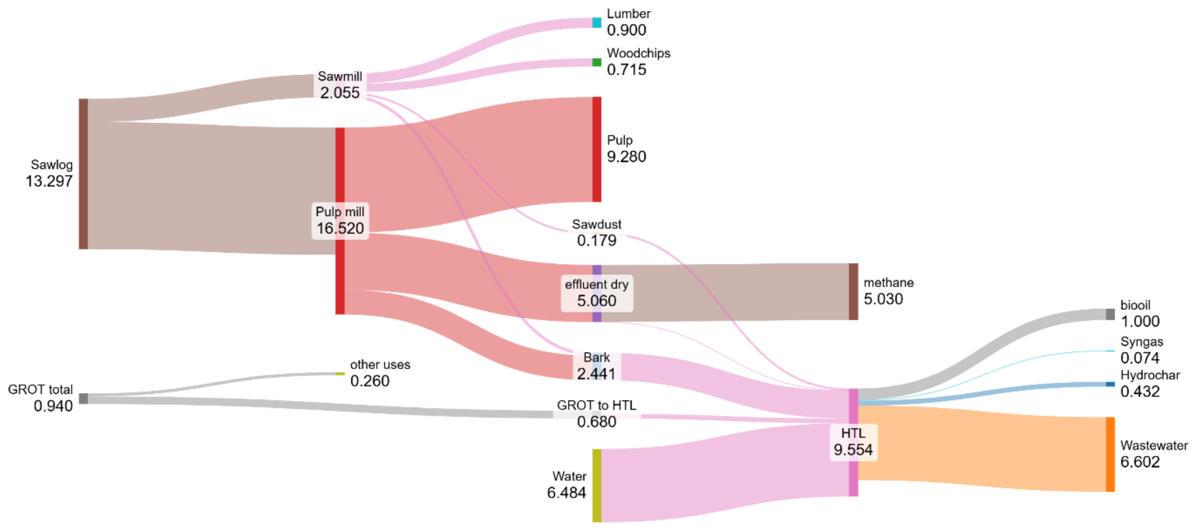

Figure 25: Sankey diagram for CS4 (production of 1 kg bio-oil); quantities in kg FM

Overall, the by-products are utilized in an efficient way within the established value chain and any residue that is generated is used for energy production applications, either directly (e.g. combustion of sawdust) or by implementing conversion technologies. Starting from the first stage of the value chain (forest management), 29.27 m^2 of forest land produces the amount of residues that should eventually be supplied to the HTL facility. On the value chain under study, approximately 11% of the sawlogs harvested are sent to sawmills, while the rest is supplied to pulp mills. Since large quantities of different biomass feedstocks must be transported, transportation is a major hotspot in terms of GHG emissions. To this end, it is highlighted that the electricity derived from the Swedish energy mix is characterized by a small impact while also in every facility of the value chain energy is produced by the residual biomass or by applying appropriate conversion technologies. The introduction of the HTL facility constitutes an efficient and alternative way to valorize the large quantities of the residues of the forestry sector. The main biomass input to the HTL facility derives from the pulp mill by-products and especially the bark generated.

4 Conclusions

The information presented in Deliverable 2.4 provides a comprehensive description of BioReCer case studies. The case studies are examined with the use of a material flow approach in order to shed light on the circulation of flows within the value chains. This analysis contributes to the detection of the most resource intensive stages, the hotspots in terms of emissions and to the more efficient utilization of the biomass feedstocks. D2.4 also provides an in-depth analysis of the material flow analysis (MFA) of various bio-based value chains that are considered in the four case-studies of BioReCer project. The deliverable offers valuable insights into their resource efficiency, environmental impact, and potential for circular bioeconomy implementation. Through case studies covering diverse sectors such as fisheries, urban and industrial environments, and regional agricultural systems, the report sheds light on key challenges and opportunities associated with biomass utilization and waste valorization.

A common theme emerging across all case studies is the importance of integrating circular economy principles into bio-based industries. Efficient utilization of biological feedstocks, combined with optimized waste management strategies, contributes to reducing environmental footprints and enhancing resource sustainability. The results underline the importance of adopting data-driven decision-making approaches to maximize material recovery and minimize losses throughout value chains.

In the fisheries sector (Case Study 1), the findings highlight the potential for enhanced valorization of by-products and algae into bio-based products such as fish oil, collagen, and polysaccharides. The integration of innovative processing techniques can contribute to a more sustainable seafood industry, reducing waste while creating high-value bio-based products. Similarly, the case study on urban and industrial environments (Case Studies 1 and 2) demonstrates how wastewater treatment by-products, particularly sewage sludge, can serve as valuable resources for bio-refineries. The production of volatile fatty acids (VFAs) and biopolymers (PHA) from sludge presents an environmentally viable alternative to conventional disposal methods.

The regional case studies in Greece and Sweden further illustrate the importance of localized approaches in bioeconomy strategies. In Greece (Case Study 3), the utilization of agricultural residues, such as wheat straw, tree pruning and peach pulp, for biofertilizer and particle board production, showcases effective pathways for closing material loops. Meanwhile, in Sweden (Case Study 4), the forestry sector presents promising prospects for sustainable biomass exploitation, reinforcing the role of circular practices in maintaining economic and ecological balance.

Another common conclusion in most case studies under investigation is that a major part of the greenhouse emissions takes place during the production stage of the primary product (e.g. fishing, crops' cultivation) or during the wastewater treatment. However, these emissions should be mainly allocated to the primary product either in a mass-balance base or in an economic-value base. In either cases the allocation of these emissions to the final bio-based product will be a small fraction of the total reported emissions during these stages, and thus the environmental impact to the bio-based product is expected to be low. The proper allocation of these emissions is a critical step during the calculation of the circularity indicators for the bio-based products under consideration.

Despite the comprehensive analysis conducted in this deliverable, certain limitations should be acknowledged. The accuracy of the material flow analysis (MFA) relies on the availability and reliability of primary data, which varies across regions and industries. Some data gaps were addressed using literature sources and expert consultations, but further validation through direct measurements and real-time monitoring would enhance robustness. Additionally, assumptions related to conversion factors, process efficiencies, and emission factors introduce uncertainties that may impact the comparability of results across case studies. A deeper examination of policy and economic incentives for circular bioeconomy implementation, coupled with lifecycle assessment (LCA) studies, would provide valuable insights for decision-makers aiming to enhance resource efficiency and sustainability in bio-based value chains.

A key takeaway from this analysis is the need to encourage incentives for industries to invest in innovative processing technologies, coupled with standardized certification schemes to promote sustainable biomass utilization across different sectors. Moreover, the development of robust data collection and monitoring systems is critical for ensuring the long-term success of material flow optimization strategies. Ultimately, the insights provided in this deliverable contribute to the broader objectives of the BioReCer project, supporting the design of strategies that enhance circularity, sustainability, and economic feasibility in bio-based industries.

The extended database that is provided will be used in subsequent Work-Packages for the calculation/estimation of circularity indicators for the biological feedstocks that have derived in the context of the project. The datasets will be also useful for the overall validation of the BioReCer certification methodologies to strategic sectors of bio-based economy in EU, highlighting the potential strengths and issues during its practical implementation (WP6). The concise presentation of the case studies' data is also an important component of the Project as it constitutes a basis for the estimation of the circularity indicators and the validation of the BioReCer framework.

5 List of abbreviations

AD	anaerobic digestion
BOD	Biochemical Oxygen Demand
CHP	Combined Heat and Power
COD	Chemical Oxygen Demand
CoM	Covenant of Mayors
CS	Case Study
DM	Dry Mass
EF	Emission Factor
ELSTAT	Hellenic Statistical Authority
Eps	Emerging Pollutants
EWI	EcoTransIT World Initiative
GHG	Green House Gas
GWP	Global Warming Potential
IGE	Instituto Galego Estatistica
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre
K	Potassium
LC	Life Cycle
MC	Moisture Content
N	Nitrogen
NCV	Net Calorific Value
NEEFE	National and European Emission Factors for Electricity
OFMSW	Organic Fraction of Municipal Solid Waste
P	Phosphorus
PPI	Pulp and Paper Industry
PS	polysaccharides
RCM	Region of Central Macedonia
SCB	Official statistics of Sweden

SMEs	Small and medium-sized enterprises
SS	Sewage sludge
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solids
WM	Wet Mass
WWTP	Wastewater treatment plant

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