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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
Panagiotis Saliakellis	CERTH	psaliake@certh.gr
Panagiota Petsi	CERTH	petsi@certh.gr
Sotiris Patsios	CERTH	patsios@certh.gr
George F. Banias	CERTH	g.banias@certh.gr

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Lead beneficiary

CERTH (Stamatia Skoutida, Anthoula Karanasiou, Maria Batsioula, Sotiris I. Patsios, George F. Banias)

Contributing beneficiaries

CETAQUA (Lucía González Monjardin, Pedro Villanueva Rey), ANFACO (David Alonso Baptista de Sousa), UNIVPM (Elisa Blumenthal), PROCESSUM (Anneli Sundman), Unitelma (Annarita Colasante)

Internal reviewer(s)

Name	**Organization**	**Email**
Lucía González Monjardin	CETAQUA	lucia-jimena.gonzalez@cetaqua.com
Pedro Villanueva Rey	CETAQUA	pedro.villanueva@cetaqua.com
Annarita Colasante	Unitelma	annarita.colasante@unitelmasapienza.it
Isabel Burdallo	RISE	isabel.burdallo@ri.se
Fredrik Östlund	RISE	fredrik.ostlund@ri.se
Anke Schwarzenberger	NOVA	anke.schwarzenberger@nova-institut.de
David Alonso Baptista de Sousa	ANFACO	dalonso@anfaco.es
Elisa Blumenthal	UNIVPM	e.blumenthal@pm.univpm.it
Nadja Wulff	NOVA	nadja.wulff@nova-institut.de
Sofía Estévez Rivadulla	USC	sofia.estevez.rivadulla@usc.es

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Publishable executive summary

Deliverable 2.1 presents an approach to identify, describe, and evaluate current available data and information for biological feedstock flows applicable at the European level. In particular, the aim of this document is to compile a set of credible and quantitative information in a systematic manner, thus facilitating measuring and monitoring the circular bioeconomy status in the European Union. The document describes the methodological approach for conducting a Material Flow Analysis (MFA) for different case studies selected in the context of BioReCer. The focus is placed on four highly promising sectors (i.e., fishery, forestry, agricultural and the urban and industrial sectors, such as the Organic Fraction of Municipal Solid Waste (OFMSW) and Sewage Sludge) with regard to the supply of secondary biological raw materials that normally are underutilized and exit the value chain.

The goal and scope of the analysis, as well as the boundaries of the systems under consideration, have been defined in the current deliverable. In addition to this, important definitions, terms, and legislation for all feedstocks are defined and described to develop harmonised understanding and terminology, and in parallel shedding light to the barriers that hampers their vast application in existing industrial value chains. To better understand the processes and sub-processes, as well as key biological flows (inputs and outputs) and stocks between them, process specification and activity mapping were undertaken for all four systems of study. The approach for data collecting has been also defined, and relevant research draws on existing literature and national statistics for a database development.

The MFA in this study has been run for the situation in which the bio-based material and products are being produced using secondary raw materials and residual biomass flows. In particular, this analysis delivers a complete and consistent set of information about main biological flows and stocks for studying and optimising closed-loop processes of fishery by-products wood and agricultural residues as well as secondary materials from urban and industrial activities. Through balancing inputs and outputs, the different flows and environmental loadings become visible, and their sources can be identified.

The key outcomes are summarised in the following points: (i) the quantity of the available residual biomass of the examined sectors is non-negligible, despite that only a tiny fraction is valorised to higher-value bio-based products; (ii) fishery waste and by-products are mainly treated through landfill disposal, anaerobic digestion or composting, while a small fraction is used for the production of fishmeal and fish oil mainly for aquaculture and animal

husbandry, as well as other uses such as direct human consumption, pet feed, nutraceuticals, and carrier for pesticides, in paints and in leather production; (iii) concerning the OFMSW, the most popular recovery routes are composting and anaerobic digestion, whereas only 2% is destined to the bio-based industry as secondary raw material; (iv) a significant fraction of the available sewage sludge (37%) is valorised in agriculture, due to its high nutrient content, while a fraction around 10% is used for compost and other applications. The amount of destined to the bio-based industry still remains low (0.3%) with many prospects of development since many technologies are headed for commercialization; (v) even though considerable quantities of agricultural and agro-industrial residues are generated, only 22% of them is collected and even lower volumes are used in the bio-based industry and mainly as a raw material for the production of bio-based products such as organic fertilizers, cosmeceuticals and surfactants; (vi) finally, despite the fact that the wood and forestry industry generate annually substantial amounts of by-products, only a small portion (corresponding to less than 3%) of the available forestry by-products proceeds for further valorisation in bio-based industries as agrochemicals (including bio-fertilizers), bio-plastics and bio-composites. This category does not include the recirculation of woody by-products in panel industry and pulp and paper mills, which constitute an established system.

1 Introduction

1.1 Background of the BioReCer project

The transition to a bio-based economy is expected to deliver substantial environmental, economic and social benefits. However, bio-based production systems still come with significant environmental challenges (e.g., seasonality and high spatial distribution of available resources, variability on critical physicochemical properties etc.), and there is a need for assessment methods that are adapted for the specific characteristics of these systems. The 2018 EU Bioeconomy Strategy aims to develop a circular, sustainable bioeconomy for Europe, strengthening the connection between economy, society, and environment.

BioReCer aims to ensure the environmental performance and traceability of the biological feedstock used by the bio-based industries, deploying guidelines to strengthen the current certification schemes (Figure 1). Within this approach, the added value, the use, as well as social acceptance of bioproducts will be increased. To reach this goal, BioReCer is structured in three main technological pillars: i) to develop a multidimensional assessment framework for an aggregated analysis on the biological feedstocks and their associated supply chains; ii) to create a BioReCer Innovation ecosystem living-lab with a multi-agent approach, testing the framework in 4 bio-based systems supply chain cases of study; and iii) to use all this knowledge to complement current certification schemes including new criteria for certifying biological resources' sustainability, origin, and traceability, and ensure applicability at EU and global scale. Specifically, BioReCer assesses the impact of current and adapted certification schemes on consumers and bio-based industries stakeholders' willingness-to-pay along with industries and consumers' acceptance of new bio-value chains from biological feedstocks, including residual feedstock and waste. The project proposes first to design and develop a multidimensional framework to analyse and define the assessment of the environmental performance of biological resources and traceability that is validated in 4 full bio-based systems and applicable to a wide range of bio-based value chains. This approach will be unfolded by the joint creation of two levels of interaction: a physical one through the creation of a BioResources Stakeholders Platform (BRSP) and a "digital" one through a BioReCer ICT tool (BIT) to amplify the "scope" of the project.

Figure 1: Schematic representation of BioReCer Project

1.2 Scope and objectives of the Deliverable

The goal of the current Deliverable is the compilation of credible quantitative information in a systematic approach so as to measure and monitor the circular bioeconomy status in the European Union (EU). It constitutes an endeavour to measure the physical material flows and capture the status of the bio-based economy and the circularity of materials in the EU. Additionally, it serves as a basis for the estimation of pivotal indicators for the EU robustness and prosperity, covering environmental, economic, and social aspects. The focus is placed on key, highly promising sectors regarding the supply of secondary raw materials that normally are underutilized and are not usually considered as part of the value chain.

1.3 Structure of the report

Deliverable 2.1 is organised and presented in 5 Sections:

- **Chapter 1:** The general approach and objectives of BioReCer are presented as well as the specific purpose and objectives of D2.1. The outline of the deliverable and the methodological approach are also presented.
- **Chapter 2:** The main biological feedstocks in the scope of BioReCer and specifically D2.1 are defined, as well as their main characteristics – such as their composition, seasonality, relevant legislative framework(s) for their valorisation, among others.
- **Chapter 3:** The general MFA methodology and the steps that should be followed for its application in the context of biological feedstocks is described.
- **Chapter 4:** The four case studies that constitute the implementation of the MFA approach and methodology are presented in this chapter to analyse the status of the bio-based economy and the circularity of the selected feedstocks in the EU.
- **Chapter 5:** Conclusions are drawn by taking into consideration the collected data, the analysis presented and the developed Sankey diagrams.

Finally, six annexes are included. More particularly, in Annex A additional information about agricultural feedstock flows is presented, while in Annex B relevant data about their composition are given. Also, Annexes C – F presents the database created from the mapping process of the biological feedstock flows under study. Finally, References are provided at the end of this deliverable.

1.4 Methodological approach

The focus of Task 2.1 is to map the main biological feedstock flows for industrial bio-based systems. To this end, and in order to identify opportunities for bio-based applications and promote circular bioeconomy in the frame of BioReCer, a MFA approach has been adopted in order to possess a comprehensive understanding of the complete bio-based system, its value chains as well as the ways in which biomass stocks and flows are used. The biological feedstocks selected are mainly secondary biomass, in line with the scope of the project as well as the HORIZON-CL6-2021-ZEROPOLLUTION-01-05 call, which focuses on i*ndustrial bio-based systems apart from "…food/feed, biofuels, bioenergy and cultural/recreation sectors…"*; sectors that mainly use primary biomass as feedstock. Further justification/detailing for this selection is provided in Section 2.1. The approach adopted in Task 2.1 follows a logical sequence of three main activities.

It starts with desk research, identifying the available biological feedstocks, their type and origin, as well as their seasonal production, and fluctuations in critical physicochemical properties, among other related factors. On the basis of the desk research's outcomes, a deeper understanding of the available biomass and its uses, its trade-offs and the interconnections and dependencies with international markets is sought by means of data collection. By balancing inputs and outputs, the potential feedstocks for bio-based industries were quantified. In addition, based on available data and by taking into consideration any gaps and inconsistencies, the remaining amounts of each flow are estimated, measuring the input-output materials. The pathways of each material flow within the whole system are examined. Finally, the proposed methodology is implemented for four selected biological *residual streams* (i.e., fish industry and sewage sludge, forestry biomass, organic fraction of municipal solid waste, and urban sludge, and biomass from the agri-food sector), identifying the most promising locally available biological feedstocks. In parallel, Sankey diagrams are used to represent the material flows in the selected supply chains, shedding light on the categorisation of biological feedstock resources and their potential uses and applications in a circular bioeconomy setting, also enabling the comparison of biomass flows between different regions and countries. A more detailed description of how the three above mentioned steps were structured and executed can be found in each of the dedicated sections and sub-sections.

1.5 Relation to other Tasks and Deliverables

The deliverable provides a general overview of the biological feedstocks under study in the project in terms of source, trade flows, seasonality, and fate at EU level. This deliverable is closely related to other Work Packages (WP) and Tasks. Thus, the outcomes of this deliverable are the basis to better contextualise and increase the knowledge over the feedstocks addressed. More specifically, the quantities of the biological flows will shed light on the current status of biomass valorisation, capturing a complete image of the European bioeconomy and indicating the level of circularity. Therefore, it is directly related to T2.2 T2.3, T2.4, and T2.5, as well as to the activities performed in the framework of the WP3, WP4, WP5 and WP6. Likewise, the execution of the MFA along with the outcomes derived from this deliverable will serve as input for other project deliverables such as D2.2 Modified Assessment Methodologies, D2.3 Circular indicators, D2.4 Main biological feedstock flows updated, D2.5 Guidelines for integration to bio-based certification schemes, and D6.1 Mid-report about case studies.

2 Biological feedstock flows and the bio-based sector

Biological feedstocks (BFS) refer to renewable organic material/biomass that originate from plants, animals and microorganisms, which can be used to produce energy, biofuels, biochemicals, and bio-based materials that are usually derived from fossil fuel resources. BFS play a critical role in facilitating the shift towards a bio-based economy that relies on biological resources and processes to produce sustainable and circular products. The total biomass supply (in global scale) from agriculture and forestry is estimated to be approx. 12 billion tons of dry matter annually, of which 61% w/w is produced by agriculture and 39% w/w by forestry [1]. Potentially, all products that are based on fossil fuels, which account for approximately to 10 billion tons of fossil carbon, can be produced from renewable BFS providing environmental, economic, and social benefits. In 2015, the total biomass supply in the EU accounted for 1.1 billion tons of dry matter, accounting for roughly 9 % of global biomass production; it was estimated that approximately 67% w/w of BFS was used in the feed and food sector, 20% w/w for biomaterials and the rest for bioenergy production, either for heat or for biofuels [2]. Biomass feedstocks are essential for the production of bio-based products because they provide the carbon and energy that are needed for the synthesis of bio-based compounds and materials. However, given that the majority of biomass is used as food and feed it is important that the BFS for bio-based products do not compete with food; therefore, BFS by-products and waste streams or BFS originating from marginal land or from the marine sector are of higher importance as BFS for the bio-based sector.

2.1 Feedstock selection

The biological feedstocks that are considered in the current analysis are in total compliance with the definition of biomass, as the biodegradable fraction of products, waste and residues of biological origin, originating from agriculture (including vegetal and animal substances), forestry and related industries, fisheries and aquaculture, and the biodegradable fraction of industrial and municipal waste [3]. Additionally, it should be noted that BioReCer Project deploys four case studies utilizing biomass from these four fundamental biomass pillars. The detailed description of the case studies is provided in D6.1. In brief, the four case studies correspond to the fishery, urban waste, agricultural and forestry sectors, are located in four different regions, and focus on specific final products that are generated within bio-based industries with established operating lines that utilize secondary biomass as feedstock. Therefore, the MFA performed in Task 2.1 and presented in this Deliverable intends to shed light on the current uses of the secondary biomass related to these sectors, measure the extent of utilization and detect the unutilized streams. The objective is to acquire a broader picture of the biomass investigated within the case studies which constitute a promising candidate for valorization in the frame of an evolving bioeconomy.

Additionally, the scope of the MFA is the estimation of biological feedstocks quantities that are allocated to uses other than food, feed and energy in order to be aligned with the objective of the call (HORIZON-CL6-2021-ZEROPOLLUTION-01-05). Therefore, the main focus is placed on the biomass uses that exclude these applications, considering mainly the bio-based industry as the primary destination that addresses this scope. Focusing on the biomass categories, it can be deduced that in the case of agriculture and fishery sectors, the primary biomas is mainly used for food and feed or bioenergy applications. According to Camia et al., 2018, the "food and feed" destination constitutes up to 80% approximately of the agricultural biomass supply[4]. On the contrary, the residual biomass streams that are related to these sectors despite generated in large quantities, they are not appropriate for food and feed applications and are majorly underutilized as they are subject to conventional management practices. Therefore, the investigation of the current uses of residual biomass is more compatible with the objective of the call and the formation of the case studies while it demonstrates heightened interest for the enhancement of the circular and sustainable bioeconomy in the EU [5]. Finally, the focus on secondary biomasses for other bio-based uses apart from food and feed aligns with the ethical hierarchy that primary biomass from the agriculture and fishery sector should preferably by used for human consumption.

With regard to the forestry sector, the primary harvested biomass is directed mainly to material manufacturing and pulp and paper industries. A special characteristic of the forestry sector is the established role and impact of mature certification schemes. In this context, two internationally recognized systems, namely FSC and PEFC, issued in 1994 and 1999 respectively, ensure the responsible forest management and its supply chain. On a global level, almost 11% of the world's forests, or one billion hectares, have been certified [6] while in Europe approximately 6% (or 70,416,000 ha) of the overall forest area at European level is certified under the FSC scheme and about 7% are certified under the PEFC scheme [7]. Since there is an augmented interest in the certification of the forest areas and the existing certification schemes are robust and well-established, the main focus of the research and the market is placed on the by-products of the forestry-related industries.

Finally, the urban waste sector is by definition associated with the residual biomass. Therefore, as clearly mentioned in the BIORECER project DoA, it is a common approach for the four different sectors under analysis, to investigate the major streams of residual biomass including their generation, imports, exports and current uses and in parallel to prioritize the bio-based industry application. In specific cases of biological feedstocks, when both primary biomass and secondary biomass are mixed and could not be distinguished (e.g. fish-meal or fish-oil), primary biomass flow is taken into consideration in the MFA analysis. The available biomass that has been considered in the analysis include:

(i) The regionally produced biomass (at a European and country level),

The regionally produced biomass refers to the biomass streams that are generated both at a European and at a country level. In particular, the sources of generation are identified and then the quantities are calculated either based on data retrieval from primary products and estimations based on conversion factors for the generated residues or by extracting directly data from official databases (if this level of detail is provided).

(ii) Biomass imports and exports (estimated wherever applicable)

It is important to complement the regionally produced biomass with the flows that are imported to and exported from the system boundaries. To address this, official databases are screened and the imported and exported quantities of the investigated biomass streams are integrated in the analysis. At an EU level, the transported biomass, i.e., the quantities that enter and exit the EU system boundaries, are taken into account in the MFA for each case study (Section 4). Additionally, extensive information regarding imports and exports on a country level is provided at the Annexes (Tables C-1, D-2, D-3, D-4, D-5, D-6, D-7, D-10, D-11, D-12, D-13, D-14, D-15, E-6, F-3, F-4 and F-5). It should be highlighted that the transported biomass streams are not applicable for all the feedstocks that are analysed in this Deliverable (e.g., it is not a common practice to transfer fruit pomace within different countries since it is a stream with high moisture content, low economic value and which is quickly spoiled/biodegraded). The feedstocks that are transported and included in the MFA correspond to specific product and waste codes that are elaborately described in each sector.

2.2 Available biomass from fishery sector

The fisheries sector is characterized by a set of activities including commercial fisheries, recreational fishing, aquaculture, and the processing of fisheries products, as stipulated by the directives of Regulation (EU) 2017/1004. According to the definition provided by the Food and Agriculture Organization (FAO), the fishing industry includes both recreational, subsistence and commercial fishing, and the harvesting, processing, and marketing sectors [8].

2.2.1 Type of available biomass

According to the FAO, the trajectory of fish production has been characterized by a consistent and incremental growth, with an annual escalation of 3.0% per year since 1961, reaching a total global production of 214 million tons in 2022 [9]. The popularity of fish and its products has surged in recent years due to its affordability compared to other animal protein sources. Within the European countries the top producers are Norway, Spain, the Netherlands, and Iceland (Figure 2). Fish is widely recognized as a healthy alternative to beef, pork, and poultry. It offers a plethora of essential micro and macronutrients, including calcium, phosphorus, iron, vitamin D, iodine, and long-chain polyunsaturated fatty acids (PUFA). This nutritional profile contributes to its appeal as a valuable dietary option.

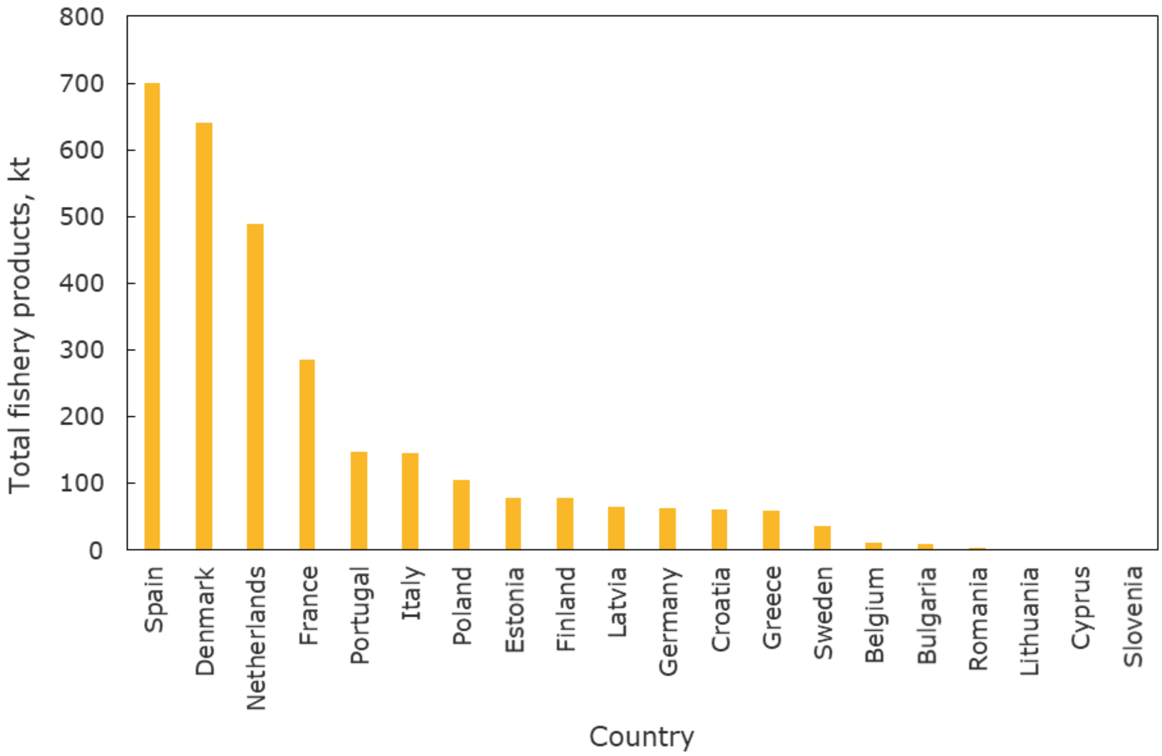

Figure 2: Landings of fishery products in EU27 countries (2021); Eurostat (Online data code: FISH_LD_MAIN; Last updated: 28/02/2023)

The fishery products which are not destined for human consumption are mainly fishmeal and fish oil. **Fishmeal**, a coarse brown flour, is derived from the process of cooking, pressing, drying, and grinding fresh raw fish or shellfish. Practically, any fish or shellfish found in the sea can be used to produce fishmeal. Most of the world's fishmeal is derived from whole fish, with pelagic species being the most commonly utilized for this purpose. It

is typically made from small fatty species such as anchovy, sprat, herring, and krill. When a catch is exclusively designated for the fishmeal industry, it is referred to as an "industrial fishery". This product serves as an excellent source of protein primarily utilized as feed for aquaculture species and livestock. When processing fatty fish into meal, **fish oil** is produced as a fish by-product (FB). This marine oil is 100% derived from fish and contains a high concentration of omega-3 fatty acids. Fish oil predominantly serves as a primary input for the formulation of feed designed for cultivated fish and for refinement in order to be used for human consumption, frequently encapsulated for convenience. In adherence to a common pattern, about 100 kilograms of raw fish materials yield roughly 21 kilograms of fishmeal and a variable quantity of fish oil, typically ranging between 3 to 6 kilograms.
Denmark stands as the leading fishmeal producer among European Union (EU) Member States, contributing approximately 50% of the EU's total fishmeal production. The country's production primarily relies on the catch of small pelagic species, including blue whiting, sandeel, Norway pout, and sprat. In terms of production volume, Spain follows as the second largest producer, accounting for 15-18% of the total output. Spain's fishmeal and fish oil production predominantly utilize waste and trimmings derived from the processing industry. In all the stages of the fishing industry (fin cutting, head and bone removal, washing etc.) challenging waste streams are generated, which consist of significant amounts of organic substances, soluble proteins, carbohydrates, oils, small flesh particles, faeces, and pesticides [10, 11].

2.2.2 Indicative composition

The nutritional value of fish and FB varies depending on factors such as the fish species, age, fishing area, harvesting season, and dietary intake [12]. Studies have reported that FB consists of crude protein content, ranging from 8% to 35% [13], lipids, such as omega-3 (ω-3) fatty acids, oils, fat-soluble vitamins, squalene, phospholipids and cholesterol. The viscera of fish typically contain 19% to 21% lipids [14]. Skin is considered the primary protein source in meagre and gilthead sea bream, particularly in terms of mitochondrial Nicotinamide Adenine Dinucleotide (NADH) dehydrogenase and mitochondrial cytochrome b-c1 complex. On the other hand, the head, intestine, and bones are rich sources of fatty acids, such as oleic, palmitic, linoleic, and eicosanoid acids. Trimmings, scales, and bones are abundant in hydroxyapatite, a valuable source of calcium [14]. The head of the fish (approximately 9-12% of the fish) is a notable source of proteins that offer exceptional nutritional value surpassing proteins found in other animal and plant sources. Moreover, the fish head is abundant in beneficial fats and a variety of vitamins, notably vitamin A, known for its positive effects on eye health and brain development [14]. Fish scales constitute approximately 2% of the total body weight of the fish, and they are comprised of a layer composed of hydroxyapatite and calcium carbonate, enveloping a collagen core. The strong bond between collagen and hydroxyapatite makes it challenging to separate these components. Additionally, the management of fish scales presents difficulties due to the presence of poorly biodegradable materials like keratin and enamel. However, despite these challenges, fish scales possess significant nutritional value. They are a valuable source of nutrients, including nitrogen and organic components such as fat, collagen, lecithin, and scleroproteins, as well as various vitamins. Fish scales also exhibit relatively modest levels of calcium, magnesium, phosphorus, sodium, and sulphur [12]. The remaining parts of fish are skin and bones, accounting for a significant portion of its total weight (30%) and containing abundant valuable compounds such as collagen, gelatin, and hydroxyapatite[15]. Fish bones are rich in minerals, constituting around 60-70% of their composition, with calcium, phosphorus, and hydroxyapatite being the major components. The viscera of fish, comprising 12-18% of the whole fish, form the second major fraction of FB and serve as an abundant source of proteolytic enzymes with high catalytic activity and efficiency, even at low concentrations and temperatures [16]. Table 1 summarises the data discussed so far. The composition of each FB depends on the species, size and season. Gilthead Sea Bream was chosen as a statistically relevant reference species.

Table 1: Mean data for the nutrient composition of by-product samples from Gilthead Sea Bream; adapted from [14]

Parameter	Head	Gills	Viscera	Trimming	Bones	Skin
Moisture (% wt)	57.3±0.7	66.6±0.3	67.1±1.0	48.6±0.1	53.3±0.7	53.0±0.5
Ash (% wt)^{db}	18.1±1.2	16.6±0.4	3.6±0.1	45.8±2.3	26.6±0.1	6.0±0.2
Protein (% wt)^{db}	32.40±0.45	31.5±0.4	37.2±0.8	41.9±1.0	34.0±1.0	43.2±0.9
Fat (% wt)^{db}	37.08±4.19	37.5±1.2	43.2±0.4	5.5±0.1	30.6±0.1	46.4±3.5
Carbohydrates (% wt)[1]	12.41±4.39	14.5±1.3	16.0±0.8	6.9±2.5	8.8±1.0	4.4±3.6

[1]Calculated by difference

2.2.3 Seasonality

The fish raw material can be established as stable from an annual quantity point of view. In terms of fish waste generation there are a variety of sources in the seafood sector, particularly depending on the level being studied. Waste volumes, value and quality can vary from species to species, between regions and at different stages of the supply chain. For example, in freshwater finfish aquaculture, the use of pond systems is extensively applied and comprises the majority of freshwater aquaculture systems across much of the world [17].

Species distributions can change due to fluctuations in the environment throughout different seasons and shifts in the abundance of prey resources, migration patterns, and environmental conditions. These variations impact the overall availability of fish resources and subsequent FB generation. Seasonal changes occur in marine ecosystems worldwide, but their length and strength vary depending on location. Generally, these changes are more noticeable in tropical waters than in temperate waters [18].

However, the long-term trend in total world catches has been relatively stable since the late 1980s, with catches generally being fluctuating between 86 million metric tons and 93 million metric tons per year. Total marine catches have remained relatively stable since the mid-2000s, fluctuating between 78 million and 81 million metric tons per year, following a decline from peak catches from peak catches in the late 1990s [16]. Although there has been a relatively stable trajectory in total marine catches, the catches of primary species have witnessed notable fluctuations over the years, alongside variations in the catch levels among major producing In addition, the vast diversity of climatic and environmental conditions in locations around the world where aquaculture is practiced has led to the utilization of a wide and varied range of species in various types of freshwaters, brackish water, marine, and continental saline aquaculture production practices.

The European Union (EU) ranks as the sixth-largest producer of fishery and aquaculture products globally, contributing approximately 3% to the total production, following countries like China, Indonesia, India, Vietnam, and Peru. Although EU production has remained relatively consistent over the past decades, its position in the industry is noteworthy. The processing and distribution of seafood products highly dependent on raw material supplies from the primary sector. With heightened consumption and increasing demand for seafood products, coupled with stagnation in primary sector growth, these activities are becoming more reliant on imports from non-EU countries. This reality positions the EU as the world's largest seafood importer. The EU's self-sufficiency in meeting its escalating seafood product demand from internal waters stands at approximately 30%, implying that EU citizens consume more than three times what is domestically produced [19].

In 2020, the supply of fishery and aquaculture products for human consumption within the community totalled 12.89 million tons in live weight equivalent (LWE), showing a drop of nearly 180,000 tons LWE from 2019. This decline was one of the lowest recorded figures during the 2011-2020 decade. Between 2019 and 2020, imports, aquaculture production, and capture fisheries all experienced declines. The decrease in capture fisheries was the major contributor to the overall supply decrease. Imports amounted to 8.84 million tons LWE, aquaculture production was 1.09 million tons LWE, and capture fisheries produced 2.96 million tons LWE. Community aquaculture production decreased by 3%, resulting in a loss of over 38,300 tons LWE, while community catches intended for human consumption saw a significant reduction of 15%, equivalent to almost 540,000 tons LWE. Import volume decreased by 2%, or 200,000 tons LWE. Exports also dropped by 2%, totalling nearly 60,000 tons LWE, reaching 2.48 million tons LWE. As a result, the apparent community consumption in 2020 was 10.41 million tons LWE, one of the lowest quantities recorded from 2011 to 2020. Furthermore, the 6% decline compared to 2019 indicated a decrease of over 720,000 tons LWE [19].

2.2.4 Relevant legislative frameworks

The available European policies, legislation and standards regarding the management of **fish biomass** and related activities are listed in Table 2.

Table 2: Available European legislation and standards regarding the management of fish biomass

Relevant legislative framework	Overview
Common Fisheries Policy (CFP)	The CFP is a fundamental framework for fisheries management in the European Union (EU). It establishes rules and regulations for sustainable fisheries, including measures to prevent overfishing, protect fish stocks, and promote responsible fishing practices.
Regulation (EU) 2017/1004	Establishment of a Union framework for the collection, management and use of data in the fisheries sector and support for scientific advice regarding the common fisheries policy and repealing Council Regulation (EC) No 199/2008 (recast)
Regulation (EC) 1069/2009 on Animal By-Products	This regulation sets rules for the handling, processing, and utilization of animal by-products, including fish by-products. It aims to ensure the safe and environmentally sound management of these materials, including the prevention of disease transmission.

Relevant legislative framework	Overview
Regulation (EU) 1380/2013 on the Common Fisheries Policy	This regulation focuses on the conservation and sustainable exploitation of fisheries resources, promoting responsible fishing practices, and establishing measures to achieve a balance between fishing activities and the marine environment.
Regulation (EU) 508/2014 on the European Maritime and Fisheries Fund	This regulation provides financial support for the implementation of the CFP objectives, including measures to support sustainable fisheries, improve fishing practices, and enhance the value of fishery products.
Directive 2018/2001/EU on the Promotion of the Use of Energy from Renewable Sources (recast) - RED II	This regulation promotes the use of renewable energy sources, including bio-based products, to reduce greenhouse gas emissions. It establishes sustainability criteria for the production of bio-based products and sets requirements for their certification and labelling.
European Standard EN 16785:2015 on Bio-based Products	This standard provides guidelines and requirements for the assessment and verification of bio-based products, including criteria for the determination of biomass content and environmental performance.
Regulation (EU) 2019/1241	The regulation focuses on the conservation of fisheries resources and the protection of marine ecosystems through technical measures.
Regulation (EU) 2019/472	The regulation stablishes a multiannual plan for stocks fished in the Western Waters and adjacent waters.

Although European legislation and standards cover various aspects of fish biomass management and the use of bio-based products, the following issues have been detected that need attention:

1. Specific Regulations for FB: There is a lack of specific regulations focused solely on the management and utilization of FB. Clear guidelines and standards regarding the processing, handling, and valorisation of FB could help maximize their potential and reduce waste.
2. Harmonization of Standards: Ensuring harmonization and alignment among existing standards and regulations related to bio-based products would facilitate a more coherent and efficient approach to their utilization. Harmonization efforts could streamline certification processes and promote market acceptance.
3. Sustainability and Environmental Criteria: While regulations such as RED II include sustainability criteria, there is room for further development and refinement of these criteria to ensure the sustainable sourcing and utilization of fish biomass for

bio-based products. Enhancing environmental considerations and life cycle assessments could improve the overall sustainability of these products.

4. Promoting Innovation and Research: Continued support for research and innovation in the field of fish biomass utilization is essential. Encouraging collaboration between industry, academia, and policymakers can lead to the development of new technologies, processes, and standards that maximize the value and minimize the environmental impact of fish biomass.

Addressing these issues will contribute to a more comprehensive regulatory framework and facilitate the sustainable management and utilization of fish biomass for bio-based products within the European Union.

2.3 Available biomass from urban and industrial environment

The Urban Agenda for the EU is an integrated and coordinated approach to deal with the urban dimension of EU and national policies and legislation. By focusing on concrete priority themes within dedicated Partnerships, the Urban Agenda seeks to improve the quality of life in urban areas. One of the Fourteen Partnerships defined is circular economy [20].

2.3.1 Type of available biomass

The available biomass from urban and industrial environment, investigated in this deliverable, comprises the Organic Fraction of Municipal Solid Waste (OFMSW) and the sewage sludge, including the ones originated by co-treatment of municipal wastewater and water-based non-hazardous waste (e.g., septic tanks and agro-industrial waste). Both biomasses are clearly mentioned in the Updated Bioeconomy Strategy "A sustainable bioeconomy for Europe: strengthening the connection between economy, society and the environment" which is reporting "the treatment of waste and residues for energy production, including the production of biogas through anaerobic digestion (AD) of biowaste and waste waters, as well as the integrated production of chemical products and bioenergy in biorefineries" [21].

According to EU/EUROSTAT guidance on municipal waste data collection [22], **municipal solid waste (MSW)** comprises of household waste and similar waste, bulky waste (e.g. white goods, old furniture, mattresses), and yard waste, leaves, grass clippings, street sweepings, the content of litter containers, and market cleansing waste, if managed as waste. It originates from households, commerce and trade, small businesses, office buildings and institutions (schools, hospitals, government buildings). It also includes waste from selected municipal services i.e., waste from park and garden maintenance, waste from street cleaning services (street sweepings, the content of litter containers, market cleansing waste), if managed as waste. It is collected by or on behalf of municipalities, door-to-door through traditional collection as mixed household waste, or through door-to-door collection and/or through voluntary deposits as separate fractions for recovery operations. The definition also includes waste from the same sources and similar in nature and composition which are collected directly by the private sector (business or private non-profit institutions) not on behalf of municipalities (mainly separate collection for recovery purposes) and originate from rural areas not served by a regular waste service, even if they are disposed by the generator. The definition of MSW excludes waste from municipal sewage networks and treatment and municipal construction and demolition waste.

In the EU, **OFMSW** is defined as the mixture of the wastes derived from parks, gardens, kitchen, and restaurants. However, its definition is different depending on the region and the nation. The OFMSW is characterised by high moisture and biodegradability, and it represents one of the main reasons of adverse environmental impacts and risks in traditional landfilling, due to odours, groundwater contamination by leachate etc. [23]. According to the Updated Bioeconomy Strategy, "every year, almost 300 megatons of biodegradable household and household-like wastes, industrial wastes and other wastes are generated in the EU and remain largely unexploited. Among this waste, 140 megatons (90 megatons in dry matter) are municipal waste. About 82% of municipal solid waste is generated by households, the rest coming from commerce and trade, small businesses, yard, and garden waste etc." [21].

Sewage sludge results from wastewater treatment [24]. Wastewater from households, industries, rainfall, and urban runoff is received by wastewater treatment plants (WWTP) aiming to eliminate contaminants and safely returning treated water to the environment. Wastewater undergoes physical, chemical, and biological operations, achieving the removal of settleable solids, organic forms of carbon, nitrogen, and phosphorus. The resulting products generated during these treatment processes are recovered water and wastewater sludge, which is composed of solids and biosolids, typically in a liquid or semi-solid form [25].

Sewage sludge and OFMSW can be processed in biorefineries for obtaining renewable products such as struvite (slow-release fertilizer) and volatile fatty acids (VFA). The latest can be converted into biopolymers (e.g., PHA - Polyhydroxyalkanoates). All these secondary raw materials can be used by different industries producing fertilisers (from struvite), chemicals (from VFA) and bioplastic (from PHA) [26-29]. For VFA production, the used substrate must be characterised by a high level of carbon source. Sewage sludge and the OFMSW are considered suitable, due to the high COD content (> 4000 mg/L) and because the ammonium content does not exceed 5000 mg/L [30, 31], as outlined in the following section.

2.3.2 Indicative composition

The composition of **OFMSW** is influenced by different factors such as climate, season, geographic location, number of inhabitants and their social condition and regional food. For instance, in Italy pasta is among the major waste components, while the waste in Finland contains mainly coffee rests and tea bags [30]. Green waste from parks, gardens etc. usually includes 50-60% water and more wood (lignocellulose) and kitchen waste contains no wood and up to 80% water [32]. Considering its chemical composition, OFMSW consists of carbohydrates, proteins, and lipids [23]. Table 3 depicts the indicative composition of OFMSW.

Table 3: Indicative composition of OFMSW [33-38]

Parameter	Range (average)
Moisture (%wt)^{ar}	22.5-70.5 (53.9)
pH	4.9-7.3 (6.5)
TS (%wt)^{ar}	22.5-40 (34.4)
VS (%wt)^{ar}	60.4-85.6 (74.7)
Ash (%wt)^{db}	6.0-8.3 (6.9)
Fat and waxes (%wt)^{db}	15.6-31.9 (23.8)
Pectin (%wt)^{db}	13.0-18.8 (17.1)
Lignin (%wt)^{db}	6.8-10.1 (8.7)
Glucan (%wt)^{db}	34.2-45.0 (39.7)
Xylan (%wt)^{db}	0.2-2.4 (1.1)
Protein (%wt)^{db}	8.3-10.4 (9.5)
Starch (%wt)^{db}	3.2-6.2 (5.0)

Parameter	Range (average)
Elemental analyses	
Carbon (%wt)^{db}	38.5-49.4 (45.7)
Oxygen (%wt)^{db}	29.5-36.6 (32.0)
Hydrogen (%wt)^{db}	5.3-7.5 (6.1)
Nitrogen (%wt)^{db}	1.8-3.0 (2.3)
Sulfur (%wt)^{db}	0.2-0.3 (0.2)
C/N (%wt)^{db}	15.4-24.2 (19.5)
Nutrients	
TKN (g/kg)^{db}	23.5-25.8 (24.7)
TP (g/kg)^{db}	2.7-3.5 (3.1)
TK (g/kg)^{db}	9.8-10.2 (10.0)

^{ar} as received, ^{db} dry basis

Sewage sludge composition and contamination may vary depending on the local household habits, the sewer collection, the regional legislation, the season, and the process used by the considered WWTP [39]. Along with energetically desirable components, wastewater sludge also contains organic, inorganic, and biological impurities in soluble, insoluble, and colloidal forms. The organic fraction of wastewater sludge typically ranges from 45% to 60%, and its components include PAHs, PCBs, organochlorine pesticides, dioxins, furans, adsorbed and extracted chlorinated derivatives, phenols, phthalates, etc. [40]. The inorganic fraction of wastewater sludge includes constituents such as calcium, magnesium, iron, potassium, and sodium, as well as toxic heavy metals like cadmium, chromium, copper, lead, mercury, among others. Heavy metals concentration in sewage sludge may vary considerably depending on its origin [24]. The typical chemical composition of primary and secondary sludge is given in Table 4 and the typical metal content in wastewater solids is given in Table 5.

Table 4: Typical chemical composition of primary and secondary sludge [25, 41]

Parameter	Primary sludge range (typical)	Secondary sludge range (typical)
Total solids (TS), %	1-9 (3)	0.4-1.2 (0.8)
Volatile solids (VS), % of TS	60-85 (75)	59-85 (70)
pH	5-8 (6)	6.5-8.0 (7.1)
Alkalinity (mg/L as $CaCO_3$)	500-1500 (600)	580-1100 (790)
Organic acids (mg/L as Hac)	200-2000 (600)	1100-1700 (1350)
Energy content (kJ/kg VSS)	23,000-29,000 (25,000)	19,000-23,000 (20,000)
Structural compounds		
Cellulose (% of TS)	8.0-15 (10)	7.0-9.7 (-)
Protein (% of TS)	20-30 (25)	32-41 (36)
Grease and fats (% of TS)	5.0-35 (6)	5.0-12 (8.0)
Nutrients, minerals and metals		
Nitrogen, % of TS	1.5-4 (2.5)	2.4-5.0 (3.8)
Phosphorus (P_2O_5), % of TS	0.8-2.8 (1.6)	0.5-11.0 (5.5)
Potassium (K_2O), % of TS	0.0-1.0 (0.4)	0.5-0.7 (0.6)
Iron (not as sulfide), % of TS	2-4 (2.5)	-
Silica (SiO_2), % of TS	15-20 (-)	-

Table 5: Typical metal content in wastewater solids [25]

Metal	Range
Arsenic (As) $(mg/kg)^{db}$	1.2-49.2
Cadmium (Cd) $(mg/kg)^{db}$	1.2-11.8
Chromium (Cr) $(mg/kg)^{db}$	6.74-1160
Cobalt (Co) $(mg/kg)^{db}$	0.87-290

Metal	Range
Copper (Cu) (mg/kg)^{db}	115-2580
Iron (Fe) (mg/kg)^{db}	1575-299,000
Lead (Pb) (mg/kg)^{db}	5.81-450
Manganese (Mn) (mg/kg)^{db}	34.8-14,900
Mercury (Hg) (mg/kg)^{db}	0.17-8.3
Molybdenum (Mo) (mg/kg)^{db}	2.5-132
Nickel (Ni) (mg/kg)^{db}	7.4-526
Selenium (Se) (mg/kg)^{db}	1.1-24.7
Tin (Sn) (mg/kg)^{db}	7.5-522
Zinc (Zn) (mg/kg)^{db}	216-8550

2.3.3 Seasonality

The composition of **OFMSW** is influenced, among the other, by seasonality [30]. Some studies reported that the amount of food waste generation increases during autumn and summer [42, 43]. The composition of sewage sludge may vary depending on the season as well [39]. Moisture, pH, quantity, and impurity characteristics of sewage sludge may vary greatly due to the wide variation in water quality and treatment operations. For instance, Spanos et al.[44], investigating heavy metals occurrence and chromium species in WWTPs during different seasons, noticed that, on average, in summer months (dry season) metal concentrations are lower than the ones occurring in spring and winter (wet seasons). In addition to seasonal variations, the composition of sludge differs from one plant to another [45].

2.3.4 Relevant legislative frameworks

The available European directives, regulations and certification schemes regarding the management of **OFMSW** and **sewage sludge** and their use as secondary raw materials are listed in Table 6.

Table 6: Available European legislation, standards and certification schemes regarding the management of OFMSW and sewage sludge and their use as secondary raw materials.

Relevant legislative frameworks	Overview
Directive 2008/98/EC	This Directive lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of *waste* and by reducing overall impacts of resource use and improving the efficiency of such use.
Directive 1999/31/EC, Landfill Directive	The Landfill Directive defines the different categories of waste (municipal waste, hazardous waste, non-hazardous waste, and inert waste) and applies to all landfills, defined as waste disposal sites for the landfilling of waste onto or into land.
Directive 1986/278/EEC (and on-going revision), Sewage Sludge Directive	The purpose of the Sewage Sludge Directive is to regulate the use of sewage sludge in agriculture in such a way as to prevent harmful effects on soil, vegetation, animals, and man, thereby encouraging the correct use of such sewage sludge. The directive establishes rules for sludge application and determines criteria based on the contaminating elements present in the sludge.
Directive 1991/271/EEC (and ongoing revision)	The objective of the Directive is to protect the environment from the adverse effects of *urban wastewater discharges*. This has a clear impact on the quantity and quality of sewage sludge, as well as indirect impact on its use.
Directive 2010/75/EU, Industrial Emissions Directive	The Industrial Emissions Directive aims to achieve a high level of protection of human health and the environment taken as a whole by reducing harmful industrial emissions across the EU. As municipal wastewater treatment plants can also treat agro-industrial and organic water-based liquid, they can be subject to the IED for permits and operation and Best Available Techniques application.
Regulation (EU) 2019/1009	Laying down rules on the making available on the market of EU *fertilising products* and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003.

Relevant legislative frameworks	Overview
	The document promotes the increase and use of recycled nutrients to further aid the development of the circular economy and allow a more resource-efficient general use of nutrients, while reducing Union dependency on nutrients from third countries. It requires sewage sludge to meet specific requirements before being considered products with fertiliser potential.
Waste Shipment Regulation (EC), No 1013/2006	On supervising and controlling shipments of waste within EU borders and to/from EFTA, OECD, and Basel Convention countries. The Waste Shipment Regulation stipulates a procedure of prior written notification and consent (notification procedure) before cross borders shipments of: all hazardous waste other types of waste, including certain non-hazardous wastes that are destined to certain non-OECD countries
Classification, Labelling and Packaging (CLP) Regulation (EC) 1272/2008	The CLP Regulation contributes to the UN Globally Harmonised System (GHS) aim that the same hazards will be described and labelled in the same way all around the world
Commission Decision 2014/955/EU	Amending Decision 2000/532/EC on the *list of waste* pursuant to Directive 2008/98/EC of the European Parliament and of the Council
COM (2008) 811 final GREEN PAPER **On the management of bio-waste in the European Union**	It aims to explore options for the further development of the *management of bio-waste*. It summarises important background information about current policies on biowaste management and new research findings in the field, presents core issues for debate, and invites stakeholders to contribute their knowledge and views on the way forward. It aims to prepare a debate on the possible need for future policy action, seeking views on how to improve bio-waste management in line with the waste hierarchy, possible economic, social, and environmental gains, as well as the most efficient policy instruments to reach this objective.

Relevant legislative frameworks	Overview
Communications from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions Towards a circular economy: A zero waste programme for Europe (2014) Closing the loop - An EU action plan for the Circular Economy (2015)	The goal of the document is to establish a favourable, common, and coherent strategic framework at European level to promote *circular economy*. With these two documents, European Commission defines its strategic path towards the following points: • Common goal to recycle 65% of urban waste and 75% of packaging by 2020. • Goal to reduce waste disposal in landfill to 10% by 2035. • Homogeneous definitions for levels of recycling • Concrete measures to promote reuse and favour industrial symbiosis, by transforming by products of an industry in raw materials for another one. • From waste to resource: support the market of secondary raw materials (phosphorus recover, valorisation of agro-food waste) and reuse of treated wastewater
Bioeconomy strategy	Europe’s Bioeconomy Strategy addresses the production of renewable biological resources and their conversion into vital products and bioenergy. It aims at focusing Europe’s common efforts in response to increasing populations, depletion of natural resources, impacts of increasing environmental pressures and climate change
Circular Economy Package	The CE package contributes to ‘closing the loop’ of product lifecycles through increased recycling and re-use. The plans aim at extracting the maximum value and use from all raw materials, products, and waste, fostering energy savings and reducing greenhouse gas emissions. The new Fertilising Products Regulation is the first legal act coming out of the CE package
Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) Regulation (EC) 1907/2006	Concerning the establishment of a European Chemicals Agency, amending Directive 1999/45/EC and repealing Council Regulation (EEC) No 793/93 and Commission Regulation (EC) No 1488/94 as well as Council Directive 76/769/EEC and Commission Directives 91/155/EEC, 93/67/EEC, 93/105/EC and 2000/21/EC

Relevant legislative frameworks	Overview
ECN-QAS	It presents an independent quality assurance scheme and includes fundamental requirements for national quality assurance organisations (NQAO) for compost and digestate and basic requirements for a European compost and digestate standard in the first instance.
Real Decreto-ley 11/1995 (developed through its Real Decreto 509/1996) (ES)	It promotes the use of appropriate technologies and sets requirements for the quality of treated water, indirectly influencing the generation and management of sewage sludge.
Biosolids Assurance Scheme (BAS) – UK [46]	The purpose of the UK Biosolids Assurance Scheme (BAS) is to provide food chain and consumer reassurance that BAS Certified Biosolids can be safely and sustainably recycled to agricultural land. In consultation with food chain stakeholders the UK Water Industry has introduced the Biosolids Assurance Scheme that includes sludge treatment and biosolids recycling to agricultural land. Member organisations are audited by an independent third-party Certification Body with UKAS accreditation to ensure that they conform to the scheme standard.
Bundesgütegemeinschaft Kompost e.V. (BGK) – Germany [46]	BGK is the carrier of the RAL quality labels for compost, digestate, sewage sludge and sewage sludge compost. The system includes the RAL GZ 258 for AS Humus compost (sewage sludge compost) and the RAL GZ 247 for AS Düngung (sewage sludge for fertilisation) for sewage sludge. The BGK has defined a general quality standard for each RAL quality label and established a nationwide system for external monitoring of composting and digestion plants and of compost and digestion products
QLA-System – Germany [46]	A quality assurance system for the agricultural utilisation of sewage sludge and other organic waste. A system that guarantees high requirements for soil and groundwater protection and thus increases confidence and acceptance of sewage sludge utilisation in agriculture. The system has three categories: 1. Input, 2. Product, 3. Utilisation

Relevant legislative frameworks	Overview
Kompost & Biogas Verband Österreich (KBVÖ) – Austria [46]	KBVÖ is in charge of Quality assurance systems for compost. Quality assurance systems are based on legislation and national compost standards (ÖNORM S2200).
NFU 44-095 normative standards – France [46]	Sludge compost used for agricultural application can move out of waste status by complying with NFU 44-095 normative standards according to their characteristics. In this case, traceability is no longer mandatory, and compost has become a finished product that can be traded. Composts from sewage sludge cannot be used in organic farming because they are not listed in Annex IIA of Regulation No. 2092/91, specifications for organic farming.
Directive (EU) 2018/851 of the European Parliament and of the Council	The objective is to improve and transform waste management into sustainable material management, with a view to protecting, preserving and improving the quality of the environment, protecting human health, ensuring prudent, efficient and rational utilization of natural resources and promoting the principles of the circular economy.

Currently, PHA recovery from wastewater treatment plants as secondary raw materials for bioplastics production is not governed by any regulation, directive or standard. Moreover, according to JRC [47], scoping possible further EU-wide end-of-waste and by-product criteria, PHA recovery from wastewater and sewage sludge seems to be not in the priority list to be eligible for the end-of-waste criteria evaluation.

2.4 Available biomass from agricultural sector

The total agricultural biomass production in the EU is projected at 956 million tons of agricultural biomass annually. In terms of economic productivity, 54% are primary goods (grains, fruits, roots, tubers, etc.) and 46% are secondary biomass, such as leaves and stems [48]. Residual biomass streams are generated from agricultural practices as well as from agro-industry. Agro-industry is a broad concept that refers to the establishment of linkages between enterprises and supply chains for developing, transforming and distributing specific inputs and products in the agricultural sector [49].

2.4.1 Type of available biomass

The type of available secondary biomass related to the agrifood sector can be divided into two large categories, namely the agricultural waste and the agro-industrial waste.

2.4.1.1 Agricultural waste

Agricultural waste corresponds to 7.5-17.5% of the overall waste originating from the Food Supply Chain [50]. Agricultural waste includes the by-products that are generated through management and harvesting practices in the agricultural production cycle.

Straw and stems: Cereal straw consists of the senesced leaves (sheath and blade) and stems (node and internode) material remaining after grain harvesting and contains approximately two-thirds stem and one-third leaf (56% internodes, 7–8% nodes, 23% leaf sheaths, 14% leaf blades). The generated straw is discharged from conventional combines and falls to the field ground [51]. Stems constitute the main structural axe of a vascular plant that supports leaves, flowers and fruits, transports water and dissolved substances and produces new living tissue.

The current pathways regarding straw management encompass soil enhancement activities, such as disposal on field to retain organic carbon, nitrogen and nutrients. Besides, agricultural residues are extensively incinerated in situ. Conventionally, a substantial portion of the straw is destined for on-farm applications such as bedding or animal feed as it constitutes a source of long fibre ingredient for ruminants, in particular for cattle farms [52]. The established management is severely unfavourable since it exacerbates global emissions due to the greenhouse gases (CO_2, CO, CH_4, N_2O, SO_2), particulate matter and smoke emitted during the incineration and decomposition stages [53]. Additionally, agricultural residues constitute a potential source of soil pollution, soil leaching and underground water pollution. From an economic perspective, the management of agricultural residues generates little or no worth to the farmers. Furthermore, surplus amount of straw has ignited environmental and public health concerns attributing to the inefficiency of the conventional straw disposal or utilization methods [54].

Overall, the improper management of agricultural residues has negative repercussions on the environmental, economic, and social pillar, highlighting the need for the adaptation of alternative solutions that will pave the way for the circular management and extended retention of the resource in the value chain, maximizing its efficiency. Even though straw upcycling into high-value products is a profoundly beneficial strategy, it should be highlighted that several challenges remain hampering its full potential. The most important obstacles encompass the productive potential, quality of feedstock, feedstock delivery, challenges in the breakdown of the cell wall polymeric structure, as well as the complex conversion processes.

The flows of straw that will be investigated originates from the following crops: wheat, barley, oats, triticale, rye, soybeans and rice due to their abundant production, economic importance for the region and wide geographical distribution. With regard to stems, maize, sunflower and rapeseed will be examined. Further information about wheat and maize production and residues are provided indicatively, as the most characteristic examples of straw and stems sources respectively. Also, information about the other cultivations that straw and stems are sourced are provided in Annex A.

Wheat: Wheat (*Triticum aestivum L.*) is one of the most important commodities traded globally and a staple for the nutrition of billions of people. Wheat's unique ability to be transformed into a wide variety of products, agronomic adaptability, ease of storage, nutritional value and flour quality have contributed to its establishment as a principal product of alimentation [55]. The total production of wheat amounted to 766 million tons in 2021, with Europe's contribution at 147 million tons. Wheat straw, which is the main residual biomass of wheat grain harvesting, is the second most abundant lignocellulosic material in the world [54]. The main fractions of wheat straw are nodes, internodes, and leaves, as depicted in Figure 3. An indicative composition of wheat straw includes internodes (68.5%), leaf-sheath (20.3%), leaf-blade (5.5%), nodes and fines (4.2%) and grains and debris (1.5%) [56].

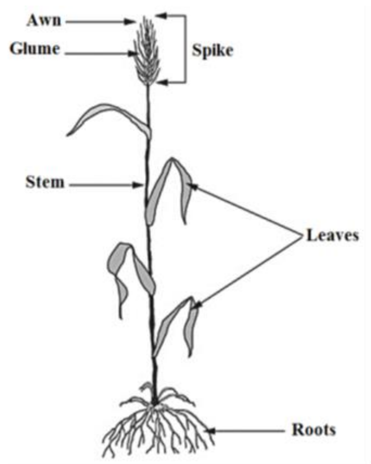

Figure 3: Morphology of wheat plant [56]

Currently, wheat straw is used as animal feed and bedding, as supporting materials, as raw material for pulp and paper production, and as a substrate for biogas, bioethanol, and mushroom production. Wheat straw is also burnt as a fuel and is added to soil for its maintenance [54].

Maize: Maize (*Zea mays* L.) is one of the most significant and widespread crops in the world. Maize can be processed into a wide range of industrial products, including starch, sweeteners, corn oil, beverages, glue, industrial alcohol, and fuel ethanol. The former use accounts for approximately 40% of the total USA maize production [57]. Approximately, 26 million hectares of maize are cultivated each year in the EU; the total estimated value of all the downstream maize products is more than 32 billion euro. Maize stover is the main product originating from maize collection and more specifically refers to husks (8%), cobs (15%), leaves (28%), and stalks (48%) that are left on the farm after harvest. Maize stover approximately makes up half of the maize plant and thus can be considered a prolific byproduct. The current uses of maize stover include its use as fuel, litter for animals, soil conditioner, and as fodder for ruminants, despite their relatively low nutritive value [58]. The morphology of the maize plant is demonstrated on Figure 4.

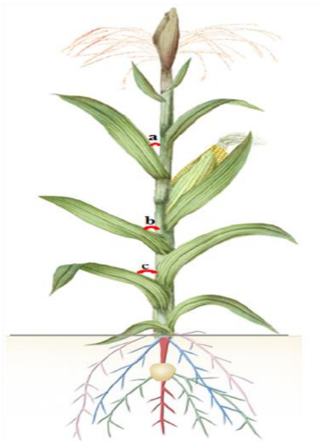

Figure 4: Morphology of maize plant [59]

Prunings: Tree pruning constitutes a fundamental horticultural practice that assures the healthy maintenance of the orchards and ameliorates the production levels of the cultivations. More specifically, pruning contributes to the enhancement of the light conditions for fruit development within the crown, improves the distribution of nutrients and regulates the vegetative growth of a tree. The negligence or improper execution of the pruning process can render the orchard more susceptible to diseases, degrade crop quality and lead to irregular yields through consecutive harvesting periods [60, 61]. Overall, the pruning process contributes to the qualitative and quantitative amelioration of the crops' yields. Currently, prunings are mainly used as mulch for soil-enhancement, incinerated on-field or landfilled.

2.4.1.2 Agro-industrial by-products

Agro-industrial by-products encompass the by-products generated from food processing industries [62]. More specifically, fruit processing is a major contributor to waste generation. The employed processes necessitate the removal of parts such as the core, peel, pips, and kernel [63]. The most important agro-industrial by-products that will be studied in the scope of BioReCer are briefly described in the following subchapters.

Kernels

Peach kernel: Peach (derived from *Prunus persica L.*) is an important fruit with remarkable production globally, amounting to 26.43 million tons in 2020. Peach is predominantly consumed as fresh fruit, concentrated juice or canned peaches [64]. Peach processing produces large quantities of waste with their conventional management including landfilling, animal feed, incineration, or use in energy production [65].
A major by-product is the kernel (endocarp), which is formed by the seed covered by a hard shell. Peach kernels constitute 5% to 10% of the total fruit weight, depending on the variety [66] and contain almost 50% wt of oils [67]. Currently, the utilization of peach kernels in a closed-loop context is still restricted mainly to large-scale facilities. In this scope, the industries proceed to the combustion of kernels as an ecological biofuel with high calorific value, aiming to the production of energy to cover the unit's energy needs [68]. Kernel's combustion emits 30% less CO_2 and 6 to 15 times less sulfur oxides compared to the combustion of brown or stony coal. The crushing of stones and the subsequent recovery of the seeds is a very promising resource for the extraction of oils for pharmaceutical applications due to their oil content and bioactive compounds [69].

Olive kernel: Olive trees (*Olea europaea L.*) cultivation is a key component for the cultural heritage and rural economy of Mediterranean countries and olive oil is a staple in Mediterranean alimentation [70]. The organoleptic properties along with the substantial health benefits have contributed to olive oil's introduction to people's eating trends [71]. Olive oil industries generate substantial quantities of by-products, including olive stones (kernels). Typically, olive stones represent 10% of olive fruits [72]. Olive stones are produced in the olive oil extraction process after oil separation [73]. The olive stone wooden residues constitute a high-quality combustible fuel [70].

Pomace

Peach pomace: An additional by-product of peach processing industries is peach pomace. Peach pomace is equal to 15-28% of transformed raw material, depending on the process conditions. More specifically, for the juice industry, pomace corresponds to 24% of the fresh fruit feedstock. Peach pomace is an extraordinary source of multiple beneficial substances, including phenolics, proteins, alkaloids, and sugars [74].

Apple pomace: Apple (derived from *Malus* domestica) is one of the most widely cultivated fruits in temperate regions, with its production amounting to 87 million tons in 2021 [75]. Approximately, 25–30% of the total amount of apples is processed into several value-added products such as juices, jams, ciders, wine, vinegar, distilled spirit, jelly, and dried products. Apple pomace is the main solid residue generated from apple process industries, which is generally composed of skin and flesh (95%), seeds (2% to 4%), and stems (1%) [76]. Apple pomace represents approximately 30% of the fresh fruit and originates from the fruit pressing process [77]. It is currently managed as a low-value by-product with potential adverse environmental impact, since it contains high levels of moisture and biological and chemical oxidation demand [78]. Currently, the by-products from apple processing industry are managed in traditional ways, such as landfilling, incineration, composting and a small proportion is utilized as low-quality animal feed for ruminants, land spreading, added at soils as fertilizers, agro-based fuels, or coal [79, 80].

Grape pomace: Grapes are one of the most important commodities globally, traded as table grapes, wine, juice, vinegar, or raisins. Grape cultivation (*Vitis vinifera L.*) and winemaking constitute a pillar of the European culture and economy, occupying a leading role in the global production of grapes (37%) and wine (279 million hL). Grape pomace (marc) is the basic solid organic by-product deriving from the winemaking industry. It accounts for 20-30% of the total weight of grapes processed. Grape marc consists of seeds (38-52%), skin (38-52%), residual pulp and stems (2-10%) [81]. Due to the lower fibre content of grape pulp, it is the grape by-product with the best nutritional value for livestock. The conventional uses of solid wine by-products are animal feed and fertilizer/compost without or with little further processing [82].

Olive pomace: Olive-oil industry is a major pollutant since huge quantities of by-products (kernels, olive pomace, olive mill wastewater and two-phase olive mill wastewater) are generated during the different processes, while these streams are characterized as deleterious due to their high organic content and phytotoxicity [72]. The traditional management practices encompass incineration, field disposal for soil-enhancement purposes, discharge into nearby water bodies and storage/evaporation in lagoons [71, 72]. Olive oil pomace constitutes the main solid by-product from the olive oil extraction corresponding to 35–40% of the total weight of the olives processed in the mill. This biowaste is composed of crushed olive stones, pulp and skins and variable amounts of water depending on the extraction system used for the oil recovery [72].

Orange pomace: Orange is a very important fruit crop, which is widely consumed as fresh fruit, while the juice industry is well-established as well. Orange juice global production was estimated at 1.7 million tons in 2020 [63]. The production of orange juice is a multi-step process. During juice extraction most of the solid residue is generated, which contains peel (60–65%), internal tissues (30–35%) and seeds (0–10%) and has high levels of soluble sugars, pectin, proteins, hemicelluloses, and cellulose fibres. Overall, pomace is a waste stream that causes several problems to the industry that generates it since it is possible to provoke clogging of the floatation tank, while its disposal is an issue of concern as well. The prevalent management practices include pomace's conversion to livestock feed, as a poultry bedding material, to essential oils or proceed to carotenoids extraction from peels [83].

2.4.2 Indicative composition

Agricultural wastes/residues are mainly lignocellulosic biomass consisting of cellulose, hemicellulose, and lignin, with cellulose being the main component. Small quantities of extractives, such as ash and proteins are also contained [84]. In Table 7 the indicative composition of various types of straws is depicted showing that there are no substantial differences in cellulose, hemicellulose, and lignin content. Detailed compositional data of straw is given in Annex B.

Table 7: Indicative composition of straw; range (mean value)

Parameter	Wheat	Barley	Oat	Rye	Soybean	Rice	Ref.
Moisture (% wt)^{ar}	0.0-17 (9.3)	3.8-12 (9.2)	8.2	8.97	12 (stalks)	6.6-12 (8.3)	[85] Rye: [86] Soya: [87]
Ash (%wt)^{db}	1.3-22 (9.0)	2.2-11 (8.6)	2.6-7.8 (5.9)	1.2-10 (4.1)	6	12-22 (18.5)	[85]

Parameter	Wheat	Barley	Oat	Rye	Soybean	Rice	Ref.
Cellulose (%wt)^{db}	28-52 (6.3)	33-46 (41.2)	37	28-5 (36.9)	38-41 (39.5)	28-41 (35.7)	[85]
Hemicellulose (%wt)^{db}	11-39 (5.2)	22-26 (23.6)	24.9	11-28 (22.5)	16	22-27 (23.7)	[85]
Lignin (%wt)^{db}	8.0-30 (5.2)	15-23 (18)	15.4	2.0-20 (11.40)	16	9.9-21.6 (14.0)	[85]
Crude protein (%wt)^{db}	3.6-4.2 (3.9)	3.8	3.6	2.5-6.7 (4.1)	5.5 (just protein)	2.4-6.8 (4.2)	[88] Soya: [85]

By the indicative composition of stalks (Table 8), it can also be concluded that the main components are cellulose, hemicellulose and lignin. Detailed compositional data of stalks is given in Annex B.

Table 8: Indicative composition of stalks; range (mean value)

Parameter	Corn stalks	Sunflower stalks	Ref.
Moisture (% wt)^{ar}	8.02	9.2	[85]
Ash (%wt)^{db}	3.0-7.0 (5.5)	4.6	[85]
Cellulose (%wt)^{db}	38	35.0-38.5 (36.8)	[85]
Hemicellulose (%wt)^{db}	26	33.5	[85]
Lignin (%wt)^{db}	11	17.5	[85]
Crude protein (%wt)^{db}	1.8-11.5 (3.9) (for dry maize stover)	1.8-11.2 (7.3)	[88]

Respectively, the composition of pruning residues of various trees is summarized in Table 9. Detailed compositional data of prunings is given in Annex B.

Table 9: Indicative composition of representative prunings; range (mean value)

Parameter	Grape	Olive tree	Almond tree	Apple tree	Orange tree	Cherry tree	Ref.
Moisture (% wt)[ar]	43.7[1]	4.6-14 (8.4)	11.4	5.1	31.1	26[2]	[85] Grape: [88]
Ash (%wt)[db]	2.2-3.0 (2.6)	13.3	1.63	-	4.4 (at 815°C)	1.3[2]	[85]
Cellulose (%wt)[db]	-	30.3	-	36.2	40.5	42.0[2]	[85] Orange: [89]
Hemicellulose (%wt)[db]	-	17.9	-	25.1	29.3	34.0[2]	[85] Orange: [89]
Lignin (%wt)[db]	10-25 (17.1)[1]	21 (acid insoluble) 3.1 (acid soluble)	-	11.9	20.8	24.0[2]	[85] Grape: [88] Orange: [90]

[1]Grape branches and leaves, fresh, [2]cherry wood

Agro-industrial by-products are rich in functional compounds, such as carotenoids, phenolic compounds, dietary fiber, polyunsaturated fatty acids, etc. This is why they have many prospects for valorisation [91, 92]. In Table 10 a typical composition of peach and olive pits is depicted. Detailed compositional data of peach and olive pits is given in Annex B.

Table 10: Indicative composition of peach and olive pits; range (mean value)

Parameter	Peach pits	Olive pits	Ref.
Moisture (% wt)[ar]	20.0[1]	6.1-12.1 (8.7)	[85] Peach: [68]
Ash (%wt)[db]	1.0-1.1 (1.1)	0.4-3.2 (2.3)	[85]
Structural compounds			
Cellulose (%wt)[db]	-	28.1	[85]
Hemicellulose (%wt)[db]	-	37.1	[85]

Parameter	Peach pits	Olive pits	Ref.
Lignin (%wt)[db]	-	25.3-31.2 (28.2)	[85]
Crude protein (%wt)[db]	26.7[1]	31.0-33.0 (32.0)[3]	[88] Peach: [93]
Carbohydrates (%wt)[db]	16.0 [1] 12.9[2]	-	Peach: 1. [93] 2. [65]
Reducing sugars (%wt)[db]	7.1[1]	-	Peach: [93]
Bioactive compounds			
Total phenolic content	8.1 g/100g [1]	61.4% [1]	Peach: [66] Olive: [72]

[1] kernels, [2] peach seeds, [3] olive kernels, exhausted.

In Table 11 the indicative composition of by-products derived from the processing of olives and fruits is depicted. Detailed compositional data is given in Annex B.

Table 11: Indicative composition of olive cake and apple, peach, grape and orange pomace; range (mean value)

Parameter	Olive cake	Apple pomace	Peach pomace	Grape pomace[5]	Orange pomace	Ref.
Moisture (% wt)[ar]	6.4	5.7[2]	94.1	60.3	82.5[6]	[85] Peach: [94] Grape and Citrus: [88]
Ash (%wt)[db]	10.9	2.8[2]	2.1	4.2-9.5	3-9.2 (4.4)[6]	[85] Peach: [65] Citrus: [88]
Carbohydrate (%wt)[db]	-	48-85	25.9 *(water soluble)*	1.6 (starch)	4.4 (starch)[6]	Apple: [76] Peach: [94]
Total sugars (%wt)[db]	-	6.2[3]	-	3.9-31.8 (18.5)	25.8[6]	[88]
Nitrogen (%wt)[db]	1.8	1.0	-	2.0-2.2 (2.1)	1.1[8]	[85] Orange peel: [95]

Parameter	Olive cake	Apple pomace	Peach pomace	Grape pomace[5]	Orange pomace	Ref.
Phosphorus (g/kg)[db]	0.9-1.6 (1.3)[1]	0.1-1.6 (1.1)[3]	2.2[2]	2-3 (2.5)	0.3-2.0 (1.5)[6]	[88] Peach pulp: [96]
Potassium (g/kg)[db]	6.7-14.2 (10.5)[1]	6.0-7.4 (6.8)[3]	0.4[2]	-	5.1[6]	[88] Peach pulp: [97]
Bioactive compounds						
Total extractable polyphenols (g GAE/kg) db	13.9	-	-	-	-	Olive Cake: [98]
Phenolic acids (mg/kg)[db]	-	523–1542		-	560[7]	Apple and orange: [99]
Phenolic compounds (mg GAE/g) db	-	-	2.0[4]	30.7-48.8	-	Peach pomace: [100] Grape pomace: [101]
Flavonoids (mg/kg)[db]	-	2153–3734	320 QE[4]	-	55 Flavones[7] 22,298 Flavanones[7]	Apple and orange: [99] Peach pomace: [100]

[1]Olive oil cake, crude, without stones, [2]pulp, [3]fresh apple pomace, [4]frozen peach pomace, [5]fresh grape pomace, [6]fresh citrus pulp, [7]orange peel and pulp.

2.4.3 Seasonality

Crops can be broadly divided into two categories: annual and perennial. Annual crops are those that do not last more than two growing seasons and normally only one. Perennial crops (e.g., fruit trees and vines) are also termed as permanent crops and last for more than two growing seasons, either dying back after each season or growing continuously.

Annual crops can be more elaborately categorized in winter crops and spring-summer crops. Winter crops are sown in autumn and harvested in the summer of the following year. Spring and summer crops are sown and harvested in the same year. Regarding EU agriculture, wheat, rapeseed, rye, and triticale are typically winter crops, whereas maize, sunflowers, rice, soybeans, potatoes, and sugar beet are summer crops. Barley is common in both its winter and spring varieties [102]. Tree pruning in Europe typically occurs at the end of winter and beginning of spring and more specifically during the months of February and March. Therefore, the largest volumes of available prunings are massively generated during this period.

Olive oil production exhibits substantial fluctuations throughout the year, as it is reflected in the European Commission's report that presents the monthly production of olive oil for season 2022/2023. It is observed that the largest amounts of olive oil are produced from October to February, accounting for 97.5% of the annual production. More specifically, in October 8.7% of the total production is generated and analogously for the other months: November (29.2%), December (32.7%), January (21.5%), February (5.3%) [103]. With reference to fruit processing and juice-making industries, the most intense production period is the hot and dry period, usually from May to September [69]. Grape harvesting period typically takes place between August and October for the countries of the Northern Hemisphere and thus, this is the period when the wine by-product generation culminates [104].

2.4.4 Relevant legislative frameworks

Generally, the EC has turned its interest to bio-based products and set this sector as a priority. For this reason, EC has proceeded to reform and adapt relevant policies in a more sustainable and environmentally friendly direction. In Table 12 the relevant European legislation framework for the biomass management is summarized. Since now, the directives are referred to general waste management, to renewable energy targets and to emissions limits. Furthermore, the EU with the common agricultural policy (CAP) 2023-2027 has reformed older policies and strategies with orientation to greener food and farming systems until 2027. However, EU regulations relevant to the treatment of the agricultural and food industry residues/by-products have not been detected. There are not specific regulations regarding:

1. The burning of crop residues, a common practice, during which greenhouse gases (GHG) are emitted and air pollution is caused.

2. Good practices regarding the management of fruit and vegetables during processing. The common methods used are on site storage, returning them to the field, using them for livestock, giving them to local food banks, composting, separation of juice and pulp and landfilling [105]. During disposal options issues may arise, such as methane emissions. For this reason, a proper framework should be set regarding these management options and novel methods for the valorisation of agri-food by-products.

Furthermore, omissions exist in legislation concerning the valorisation of agri-food by-products.

Table 12: Available European legislation regarding the management of biomass from agricultural sector and their use as secondary raw materials

Relevant legislative framework	Overview
Common Agricultural Policy (CAP) 2023-27 *(entered into force on 1 January 2023)*	Legislation framework focussing on ten key objectives related with social, environmental, and economic sectors of the agricultural activities.
Directive 2008/98/EC	This Directive lays down measures to protect the environment and human health by preventing or reducing the adverse impacts of the generation and management of waste and by reducing overall impacts of resource use and improving the efficiency of such use. In Annex II it defines R10 "Land treatment resulting in benefit to agriculture or ecological improvement" as a viable waste recovery operation.
Directive 2018/2001/EU on the Promotion of the Use of Energy from Renewable Sources (recast) - RED II	This regulation promotes the use of renewable energy sources, including bio-based products, to reduce greenhouse gas emissions. It establishes sustainability criteria for the production of bio-based products and sets requirements for their certification and labelling.
Directive 2010/75/EU, Industrial Emissions Directive	This directive is focused on the control and prevention of the emissions produced from the food industry into air, water, and soil recipients. In Annex V Part 1 and 2, the maximum emissions limits are defined.
Directive 1999/31/EC, Landfill Directive	The scope of this directive is to tighten the legislation regarding the waste and landfills and comply with the Directive 75/442/EEC and especially Article 3 and 4. Specifically, it includes stringent instructions regarding the technical requirements that should fulfil the landfill operation, in order to prevent environmental pollution.

Relevant legislative framework	Overview
Directive 2009/128/EC establishing a framework for Community action to achieve the sustainable use of pesticides	The specific directive establishes a framework regarding the reduction of chemical pesticides, in order to eliminate the risks and impacts of their use in human health and the environment. It is focused on the integrated management of pesticides and the promotion of alternative solutions regarding the replacement of the hazardous pesticides.
COM (2019)/640 European Green Deal	The European Green Deal strategy has set goals for a more sustainable future until 2030. Two main objectives are a toxic-free environment and a healthier and environmentally friendly food system.
Regulation 2021/2115 on the sustainable use of plant protection products and amending Regulation (EU)	This is a new legislation proposal for revising the Directive 2009/128/EC. The main purpose is to replace the regulations of the Sustainable Use of Pesticides Directive 2009/128/EC (SUD) in order to align with the European Green Deal COM (2019) 640 strategy.
Regulation (EU) 2019/1009	Laying down rules on the making available on the market of EU *fertilising products* and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003. The document promotes the increase and use of recycled nutrients to further aid the development of the circular economy and allow a more resource-efficient general use of nutrients, while reducing Union dependency on nutrients from third countries. It requires sewage sludge to meet specific requirements before being considered products with fertiliser potential.

2.5 Available biomass from forestry sector

European forests and the forest-based sector play a crucial role in a bioeconomy. They provide material (wood and non-wood), bioenergy and a plethora of other regulating and cultural ecosystem services [106]. Forest land occupies 159 million hectares (reported for 2020), which corresponds to 39% of European land [107].

2.5.1 Type of biomass

The forestry sector comprises pulp and paper mills, sawmills and bioenergy companies [108]. Conversion of forest biomass can be broadly divided into three main areas of applications; *sawlogs* resulting in sawn timber, which is utilised in applications such as housing, furniture and interior, *pulpwood* which is utilised to produce pulp resulting in pulp and paper products, and finally *biofuel* in the form of liquid biofuels, electricity, heat, and wood pellets [109].

Forest products industries generate residues during the process of manufacturing timber, plywood, and particleboard, collectively known as wood manufacturing residues. Residual streams from wood processing industries comprise saw dust, bark and wood chips. For example, sawmills aim to produce rectangular pieces of timber from round logs, thereby generating residues [110].Also, the pulp and paper mills reject various waste streams, at different stages, such as woody and barky residues, particles, black liquor, and wastewater sludges [111]. The definitions of the major residual streams of forestry sector are briefly presented:

Wood chips are small- to medium-sized pieces of wood formed by cutting or chipping larger pieces of wood such as trees, branches, logging residues, stumps, roots, and wood waste. Sawdust is the fine particles of wood that are a by-product of woodworking operations such as sawing, sanding and milling. **Bark** constitutes the external covering of the woody stems, branches, and roots of plants. These widely available and low-cost residues are predominantly used as solid fuel for the production of energy and heat or for horticultural use, despite the high chemical potential that this lignocellulosic biomass might offer [112]. These streams are also recycled as feedstock in the material industry for the production of wood panels and in the pulp and paper industry as well.

Pulp and paper mill sludge refers to the material generated by the initial clarification of raw paper/pulp mill effluent via flotation or sedimentation. To reduce the volume, chemical oxygen demand and biochemical oxygen demand, the primary sludge may undergo further treatment [113]. An additional stream generated in pulp and paper mills is **black liquor**. Black liquor is the spent liquor from the Kraft process in which pulpwood is converted into paper pulp by removing lignin and hemicellulose constituents and other extractable materials from wood to free the cellulose fibers [114].

In the EU, Sweden is one of the most important countries in terms of forestry land (63% of the country's area) and thus it is purposeful to provide a brief outline of basic flows detected in Swedish wood industry. In Sweden, approximately 10% of the employed population is active within the forest industry. In some other countries, the number is even higher, there the forest industry accounts for at least 20% of the industrial employment.

According to statistics from the Swedish Forest Industries Federation, 67.2 million m^3fub was taken from the Swedish forest in 2017. Almost equal volumes were shared between sawn timber and pulpwood, resulting in 10 million m^3fub of wood chips from the sawmill industry to the pulping industry. Valorisation of residual streams from the forest industry is increasing, e.g., conversion of sawdust to bio-oil [115], isolation of valuable compounds from birch bark (e.g., [116] and [117], isolation of sugar rich hydrolysates for use in the personal care business [118] and valorisation of lignin (e.g., [119-122]). Tops and branches comprise one residual stream which is currently poorly exploited [123].

2.5.2 Indicative composition

The chemical composition of wood varies by parameters such as species, part of the tree, geographical location, climate, age, potential storage time and season [124]. It comprises three main components: cellulose, hemicellulose and lignin, see the tables below. Hence, that is the approximate composition of residual streams such as tops and branches, saw dust, wood chips and fibre sludge. In addition to the main components, the biomass also contains extractives which comprise low molecular weight components. Two such examples are tall oil and turpentine which are commercially available residual streams from the kraft pulping process of softwood, e.g., both Södra and Stora Enso sell turpentine and tall oil [125, 126]. Bark is especially rich in extractives. It has been reported to contain 20-40% of lipophilic and hydrophobic extractives [127]. The indicative composition of forest biomass based on hardwood and softwood are displayed on Table 13 and Table 14 respectively. Representative bark composition for spruce, pine and birch bark samples are shown in Table 15, Table 16 and Table 17. Finally, representative composition for residual streams from the forest industry is added in the last table of this section, namely Table 18, Table 19 and Table 20.

Table 13: Indicative composition of forest biomass based on hardwood [128]

Parameter	Range
Cellulose (%)	45-55
Hemicellulose (%)	24-40
Lignin (%)	18-25

Table 14: Indicative composition of forest biomass based on softwood [128]

Parameter	Range
Cellulose (%)	45-50
Hemicellulose (%)	25-35
Lignin (%)	25-35

Table 15: Indicative composition of forest biomass based on spruce bark [129]

Parameter	Average
Glucan (%)	23.1
Xylan (%)	3.6
Galactan (%)	0.,8
Arabinan (%)	4.3
Mannan (%)	3.4
Acid soluble lignin (%)	13.3
Acid insoluble lignin (%)	20.5
Extractives (%)	28.2
Ash (%)	2.2

Table 16: Indicative composition of forest biomass based on pine bark [130]

Parameter	Average
Glucan (%)	17.5
Xylan (%)	1.8
Galactan (%)	2.2
Arabinan (%)	5.2
Mannan (%)	1.8
Acid soluble lignin (%)	6.3

Parameter	Average
Acid insoluble lignin (%)	28.5
Extractives (%)	23.7
Ash (%)	3.6

Table 17: Indicative composition of forest biomass based on birch bark [130]

Parameter	Average
Glucan (%)	8.1
Xylan (%)	3.3
Galactan (%)	1.2
Arabinan (%)	2.5
Mannan (%)	0.8
Acid soluble lignin (%)	3.1
Acid insoluble lignin (%)	47.1
Extractives (%)	27.4
Ash (%)	1.9

Table 18: Indicative composition of residual streams from the forest industry, e.g., wood chips, saw dust and other residues [85, 131]

Parameter	Range
Cellulose (%)	47.4
Hemicellulose (%)	21.4
Lignin (%)	24.6
Extractives (%)	6.1-24.3
Ash (%)	0.27-0.95

Table 19: Indicative composition of pulp and paper mill sludge [113]

Parameter	Range
Dry matter (%w/w)	15-57%
Ash (% solids)	10-15%
Nitrogen (ppm)	450-2800
Phosphorus (ppm)	100-600
Potassium (ppm)	200-900
C:N ratio	111:1–943:1

Table 20: Physicochemical properties of black liquor [132]

Parameter	Range
Lignin (%)	29-45
Hydroxy acids (%)	25-35
Extractives (%)	3-5
Formic acid (%)	~5
Acetic acid (%)	~3
Methanol (%)	~1

2.5.3 Seasonality

Wood industry exhibits fluctuations in the production quantity throughout the year. However, these fluctuations refer mostly to smaller industries since the larger ones operate for larger periods producing more even quantities throughout the year. On the contrary, at small sawmills, sawing is concentrated in the early part of the year. The goal of getting the sawn wood dry early enough for shipments in the summer causes a seasonal peak at early spring [133]. Also, the forest industry's seasonality is correlated with the transport from the forest to the mills as exemplified in the case study by Sjölling et al. [134]. In brief, the inflow of material to the rail terminals was higher in the winter and lower towards spring, i.e., typical of northern areas. Finally, with reference to pulp and paper mills, the vast majority of them operate 365 days and 24 hours per day. In few exceptions, the manufacturing process takes place 5 days and 10 hours per day, according to the type of mill [135].

2.5.4 Relevant legislative frameworks

The new EU 2030 forest strategy plays an important role for the forest industry and aims at improving forest quality and quantity. Furthermore, the strategy aims at strengthening the forest's resilience, protection, and restoration. Additionally, the new EU Deforestation Regulation (Regulation (EU) 2023/1115) also plays an important role via legislative measures against deforestation and forest degradation. Other significant legislative frameworks regarding forestry resources are presented on Table 21.

Table 21: Available European legislation regarding the management of forestry biomass

Relevant legislative framework	Overview
Regulation (EU) 2023/1115	The aim is to minimize the Union's contribution to deforestation and forest degradation worldwide (imported deforestation), thereby contributing to a reduction in global deforestation. Also, it aims to reduce the Union's contribution to greenhouse gas emissions and global biodiversity loss. The Regulation covers seven commodities and certain products that contain, have been fed with, or have been made using commodities: palm oil, soya, wood, cocoa, coffee, cattle, and rubber.
Forest Strategy 2021-2030	The objective is to "set a vision and concrete actions to improve the quantity and quality of EU forests and strengthen their protection, restoration and resilience". The Strategy places forest demands in the context of changing environmental conditions due to climate change and meeting socio-economic needs [136].
Timber Regulation (EU) No. 995/2010 (EUTR)	The Regulation prohibits illegally harvested timber from being placed on the EU market and sets out preconditions for the marketing of timber and timber products in the EU.
Forest Law Enforcement, Governance, and Trade (FLEGT) Action Plan	It aims to reduce illegal logging by strengthening sustainable and legal forest management, improving governance and promoting trade in legally produced timber.

Relevant legislative framework	Overview
Renewable Energy Directive (RED II)	RED II introduces sustainability for forestry feedstocks as well as GHG criteria for solid and gaseous biomass fuels.
Common Agricultural Policy (CAP)	CAP Strategic Plans foresee funding of forestry interventions aimed at protecting the forest, making it more resilient to climate change, safeguarding its multiple functions, including the provision of environmental services, as well as supporting investments, innovation and training to the benefit of the rural economy.

Additionally, the sustainable management of forest resources is the subject of various Certification Schemes. Two of the most recognized Certification Schemes are those issued by the international, non-profit organizations the Forest Stewardship Council (FSC) [137] and Programme for the Endorsement of Forest Certification (PEFC) [138]. In brief, the FSC label indicates responsible forestry, i.e., zero deforestation, that fair wage and work environment has been followed, protection of plant and animal species and that community rights are respective. Similarly, the PEFC works to advance responsible forestry. Another example is the International Sustainability & Carbon Certification (ISCC), which not only applies to forest biomass, but all bio-based feedstocks within different sectors: energy, food, feed, and chemicals. Also, the Roundtable of Sustainable Biomaterials (RSB) is a significant Certification Scheme. The Certification Schemes are briefly described on Table 22.

Table 22: Important Certification Schemes for forestry sector

Relevant legislative framework	Overview
ISCC	The ISCC comprises one of the world's largest certification systems and there are currently more than 8000 valid certificates globally. It covers all sustainable feedstocks and focuses on sustainability in the following three areas: environmental, social, and economic.
FSC	FSC is an international, non-governmental organisation that confirms that the forest is being managed in a way that preserves biological diversity and benefits the lives of local people and workers, while ensuring it sustains

Relevant legislative framework	Overview
	economic viability. FSC-certified forests are managed to strict environmental, social and economic standards.
PEFC	PEFC is an international non-profit, non-governmental organization, dedicated to promoting sustainable forest management through independent third-party certification.
RSB	RSB 's approach, at its core recognises the importance of conserving forest ecosystems whilst unlocking certain limited types of woody biomass for use in fuels, energy and materials.

2.6 Bio-based sector

The demand for bio-based products is constantly increasing in the European market and the bio-based industry is gaining momentum. Even though the market share of bio-based products is still relatively low, society is increasingly conscientious of sustainable biomass sourcing and endorses this kind of production patterns. However, major obstacles still exist, hampering the proliferation of the market, with the most important being the higher production costs, lack of funding, insufficient infrastructures, and maturity [139]. In this context, it is important to provide some key definitions for the bio-based sector.

Bio-based products refer to non-food products derived from biomass (plants, algae, crops, trees, marine organisms and biological waste from households, animals, and food production). Bio-based products may range from high-value added fine chemicals such as pharmaceuticals, cosmetics, food additives, etc., to high volume materials such as general biopolymers or chemical feedstocks. The concept excludes traditional bio-based products, such as pulp and paper, and wood products, and biomass as an energy source [139].

Biorefining is broadly defined as the processing of biomass into a spectrum of marketable bio-based products, which could include co-production of food and feed, chemicals and materials and bioenergy (power, heat/cold, fuels) [140]. It constitutes one of the key-enabling strategies of the circular economy, closing the loop in raw biomass materials (reuse of forestry, agricultural, aquatic, processing, and postconsumer residues), minerals, water and carbon [141].

The bio-based feedstocks indicate the type and/or the source of biomass that is processed in the biorefinery and are categorized as [140]:

Primary biomass feedstocks: It refers to biomass originated via artificial or natural photosynthesis, capable of capturing and storing carbon during the growing period. It may be produced for dedicated use or purpose, and it is obtained from forest, agricultural land, and aquatic systems or specialised bioreactors. It includes oil crops, starch crops, sugar crops, and aquatic biomass, lignocellulosic biomass from croplands and grasslands and lignocellulosic wood.

Secondary biomass feedstocks: It refers to biomass produced during the processing, conversion or decomposition of primary biomass and organic material and essentially is a side-products and residues category that has already been part of current industrial ecosystems, production, and consumption chains. It includes microbial biomass, residues from agriculture, residues from aquatic biomass, residues from forestry and forest-based industry, residues from nature and landscape management, residues from recycled bio-based products and other organic residues.

Within the biorefinery concept, further classification criteria are widely used, such as conversion processes and platforms, which are out of the scope of the current study. The emphasis is placed on criteria that are relevant to the origin and type of the product. More specifically, the feedstocks that are investigated in the current analysis fall in the **secondary biomass** category.
Regarding the products generated in bio-based industry, they are divided in the following generic categories:

- **Bio-based chemicals:** including platform chemicals, solvents, polymers, paints, coatings, inks, surfactants, cosmetics, adhesives, lubricants, plasticisers, stabilisers, enzymes and agrochemicals, among others.
- **Liquid biofuels:** including bioethanol, biodiesel, and bio-based jet fuel among others.
- **Bio-based composites and fibres:** including wood-plastic composites, natural fibres composites and different types of fabrics, among others.
- **Other type of energy from biomass:** including electricity, heat, and gas, among others

Overall, bio-based products are a promising avenue for the substitution of fossil-based materials, the elimination of resource dependence and strengthening of sustainability of the EU economy. However, monitoring the development of the bio-based economy constitutes an intricate task, since there are no official databases focusing on bio-based products and offering detailed information about their production, especially with respect to bio-based chemicals and bio-based materials [142, 143]. Essentially, the bio-based products are not separately registered in official statistical classifications and therefore, it is not possible to easily extract information about their quantities. For example, in PRODCOM, there are not any separate codes about the bio-based products in most cases. Also, the official databases do not foresee any distinction of products based on the raw materials from which they originate [143, 144].

To address this knowledge gap, the BioMAT [61] model has been conceptualized and constructed. The BioMAT model collects data from official databases, such as PRODCOM and COMEXT. The retrieved data are subjected to imputation techniques, complemented with additional information and experts' assumptions so as to capture the bio-based market and map the production of bio-based chemicals. Noteworthily, the BioMAT database has been included in the recent JRC report that investigates "Biomass production, supply, uses and flows in EU" [61], as well. Detailed quantities about the production of bio-based chemicals in EU28 are presented on Table 23.

Table 23: Production quantities of bio-based products in EU28 for 2018

Bio-based products	Quantity (kt)	Data source
Biofuels	15,668	[61]
Agrochemicals (including bio-based fertilizers)	7,747	[61]
Surfactants	4,691	[61]
Cosmetics	2,199	[61]
Food & feed	2,184	[61]
Adhesives	1,242	[61]
Polymers for plastics	780	[61]
Paints & Coatings	724	[61]
Pharmaceuticals	695	[61]
Man-made fibers	647	[61]
Solvents	418	[61]
Resins	432	[139]
Lubricants	291	[61]
Building blocks for	230	[145]

Bio-based products	Quantity (kt)	Data source
chemicals		
Flavors & fragrances	174	[146, 147]
Construction	165	[61]
Plasticizers	67	[139]
Other	270	[61]

Another product category of paramount importance for the bio-based industry is the bio-based composite materials. The production of bio-based composites in Europe reached 410,000 tons in 2017, as documented in NOVA's report "Natural fibre-reinforced plastics: establishment and growth in niche markets ". The bio-composites represent an emerging market in the EU, with a yearly growth rate equal to 3%. Bio-composites are destined to a wide field of applications ranging from technical applications over furniture up to consumer goods [148].

2.7 Existing barriers that hamper the use of available biological feedstock in bio-based value chains

A barrier is defined as "a problem, rule or situation that prevents somebody from doing something, or that makes something impossible". This definition was considered to identify potential barriers in the deployment of bio-based feedstocks. Six distinct barrier dimensions were identified (cultural, economic, environmental, governance, structural, technical).

The use of biological feedstocks involves 4 main actors along the whole value chain: *biomass producers, bio-based industries, end-consumers, and policy makers*. The process of identification of the barriers takes into account the role played by each actor as well as the interlinkages among them. Based on the review of both scientific literature and grey literature, the identified barriers could be grouped in the following categories: Economic, legal, environmental and knowledge and awareness.

a) Economic

Economic barriers affect all the actors involved in the value chain. The first barrier that is worth mentioning is the **lack of profitability** for firms operating in the bio-based as well as in the circular bio-sector [149-152]. The transition from a traditional linear economy towards a circular bio-based economy requires significant changes that results in huge investment to rebuild the production process as well as to hire skilled workers. Even though the manufacture and sale of bio-based will generate significant positive externalities in terms of both environmental impact and economic gains, this benefit will be reached only in the long run and this is incompatible with short-term profitability goals. This aspect is strictly related also to the **high investment risk for bio-based industry** [153-155] given the evidence that producers bear a significant cost in the short run with a probabilistic future revenue. Furthermore, high operating costs to be afforded for skilled workers and R&D activities [156-160] also impact the profitability of firms. The second important economic barrier concerns **consumer acceptance and willingness to pay for green products** [150, 159, 161, 162]. There is, indeed, a two-way link between demand and supply of bio-based products: if there is a not-reliable consumer demand for such products, this may harm companies to shift their business models toward a sustainable production process. Moreover, it is well-known that there exists a green premium for bio-based products (i.e., the price for sustainable products is higher than conventional products) and consumers do not have neither monetary nor other incentives to change their behaviour [163-165]. This will further worsen the incentive for the supply side. The third economic barrier refers to the **different prices between virgin and secondary materials** [152, 157, 166, 167]. This barrier is of central importance for bio-based materials and is also strictly related to the availability of secondary materials in the market, as well as to the perception and acceptance of such materials by stakeholders.

b) Legal

The transition from a fossil-based economy to a bio-based economy is a process that involves all the main actors in the value chain. An important role is played by policies and, more in general, by legal framework. According to the literature (e.g., [154, 168, 169] there is a **lack of alignment between different policies** both between European countries and among different sectors (e.g., agriculture, energy). The main consequences of this lack of alignment are the high uncertainty that bio-industries and feedstock producers face in their investment. Indeed, as explained above, the transition to a bio-based economy requires significant investment that should not be mined by the lack of consistency of public policies. Alongside this, there is also a **lack of policy support** [170, 171], especially for some sectors involved in the transition. It is well-known that, often, the policies related to the environment are not well defined in terms of measurable objectives. The same happens in the bio-based sector. This **inadequacy of policy targets** has a strong negative impact on the sector affecting both producers and consumers: regarding the former category, indeed, it could be challenging for firms to determine the right allocation of resources and, as a consequence, to define targeted initiatives; regarding the latter category, the complexity in determining the policy effectiveness could negatively affect consumers' trust toward bio-based sectors.

c) Environmental

The first important environmental barrier is **lack of data on impacts** [172-174] that hinder the possibility for both producers and consumers to move toward a sustainable path. Indeed, few or poorly reliable data about carbon footprints, impact on biodiversity or biodegradability are available for the current fossil-fuel based production process. This implies that actors involved in the value chain are not able to properly identify the impact of their activities on the environment. This lack of information, together with the above-mentioned high costs, slow down the transition to a bio-based economy. Another important barrier is the lack of traceability - the ability to trace sustainability attributes and reliable information throughout the value chain of a bio-based product. Having reliable information on biological feedstock may have a positive impact on fostering the transition to bio-based products for both industries and consumers. This will also reduce, especially on the demand side, the potential for misuse of certificates to promote greenwashed products.

d) Knowledge and awareness

The barriers included in this set mainly refers to both end-users/consumers and industries. The first identified barrier concerns the **little knowledge of bio-based products** [154, 171, 175, 176]. Studies estimate that overall awareness of the existence of bio-based products is only around 50% [175]. People working on bio-based industries as well as academics are familiar with the specific jargon related to the biological sector and, hence, they are able to identify bio-based products characteristics. This is not the case for the majority of consumers that often misunderstood or do not look at products characteristics and their environmental impact. The most important implication of such incorrect assessment is that consumers are not fully aware of the consequences of their consumption choices and the potential benefits of the use of bio-based products. The literature review indicates two cultural barriers related to education as prevalent obstacles to the transition to circular bio-based systems. These barriers are the **lack of specialised knowledge, skills and expertise in the bio-based production sector** [156, 177, 178]. Indeed, bio-based productions need the development of new knowledge (through R&D and R&I activities) and a specialised workforce. At this stage bio-based industries face two problems: on the one hand, the scholar system is currently not able to provide adequate multidisciplinary background to train workers for working in the bio-based sector; on the other hand, given the poor availability of skilled workers, the cost to find and hire them is very high. Consequently, a shortage of skilled labour slows down the implementation of bio-based production processes. Finally, there are considerable **knowledge gaps for what concerns the monitoring activities** especially on the supply side. Indeed, there exists a variety of standards for calculating differently defined bio-based contents and, especially in the field of bio-based products, additional certification programs for agricultural biomass have been created resulting in a reduction in the transparency of communication [179].

The main barriers that we have identified based on the literature review have also been discussed with a group of stakeholders involved in the BioReCer project during the Focus Groups. These activities have been carried out in the framework of the WP4 joint with other actions useful to build up the BioReCer Stakeholder Platform (BRSP). We collected feedback in four different European countries (i.e., Spain, Italy, Greece, and Sweden) and, during the discussion, one of the most important barriers that was commented on is related to the legal/policy aspects. Furthermore, the lack of knowledge and awareness lead has been reported also for producers that, in some cases, are not aware about the potential use of some materials as a feedstock.

3 Material Flow Analysis methodology

Although not as well recognised as Life Cycle Analysis (LCA), Material Flow Analysis (MFA) is a tool closely related to sustainability and Circular Economy. In general terms, MFA constitutes an environmental management tool focusing on the assessment of hotspots through the analysis of material and energy input and output processes, resources use and stock calculations. In fact, it elucidates the interconnectedness among the sources, and the valorisation routes, from supply to uses - including trade of a material [180, 181], thus enabling to gain useful insights into entire systems and their sub-components in an integrated and holistic way.

MFA describes a model for the "systematic assessment of the flows and stocks of materials within a system defined in space and time" [182]. Thus, its implementation can facilitate the analysis and evaluation of biological feedstock flows at local, national, or global levels, taking also into account different sectors of the bioeconomy [4]. However, an essential aspect of performing a successful MFA and illustrating not only cascading uses, but also the competitions and synergies, as well as the importance of the different sub-sectors, is the quantification of the flows of biomass. At first glance, MFA appears to have nothing in common with LCA, which also describes material and energy stock and flow systems. However, it may act as a starting point for implementing an LCA assessment since it enhances the mapping of material and energy inputs and thus facilitates accounting of carbon footprint and other environmental impacts. To this end, MFA enhances the understanding of the material basis of the economy and the associated economic supply and demand issues. Furthermore, it facilitates the identification of inefficient use of natural resources, energy and materials in process or value chains or the economy in general, that would go undetected in conventional monitoring systems [183].

The overall objectives of MFA can be summarised to the following points:

1. To understand and outline a system of material flows and stocks qualitatively, by utilizing precise and uniform terms with the selected system boundaries.
2. To monitor the material system over time, with a focus on past developments or to anticipate future trends by taking into account assumptions about progress such as new technologies or changing factors like consumer behaviour.
3. To simplify intricate systems while securing a basis for rational decision-making.
4. To implement the mass-balance principle, utilize quantitative terms and point out any sensitivities and uncertainties of the systems investigated.

5. To generate results about the flows and stocks in a reproducible, comprehensible, and transparent way.
6. To interpret the results, with emphasis on the management of resources, the environment and waste, thus serving as a basis for assessment tools supporting the management of resources and wastes, and in parallel contributing to the timely prediction of problems such as future environmental loadings and resource depletions.

According to available standard documents and textbooks, such as ISO 14051, ISO 14052 [184, 185], and the Practical Handbook of Material Flow analysis [186], the general MFA methodology comprises the following stages:

1. Goal and Scope definition
2. System boundaries definition
3. Identification of relevant flows, stocks, and processes
4. Quantification of mass flows, stocks, and concentrations
5. Assessment of total material flows and stocks
6. Presentation of results

The analytical steps applied for an MFA are schematically illustrated on Figure 5.

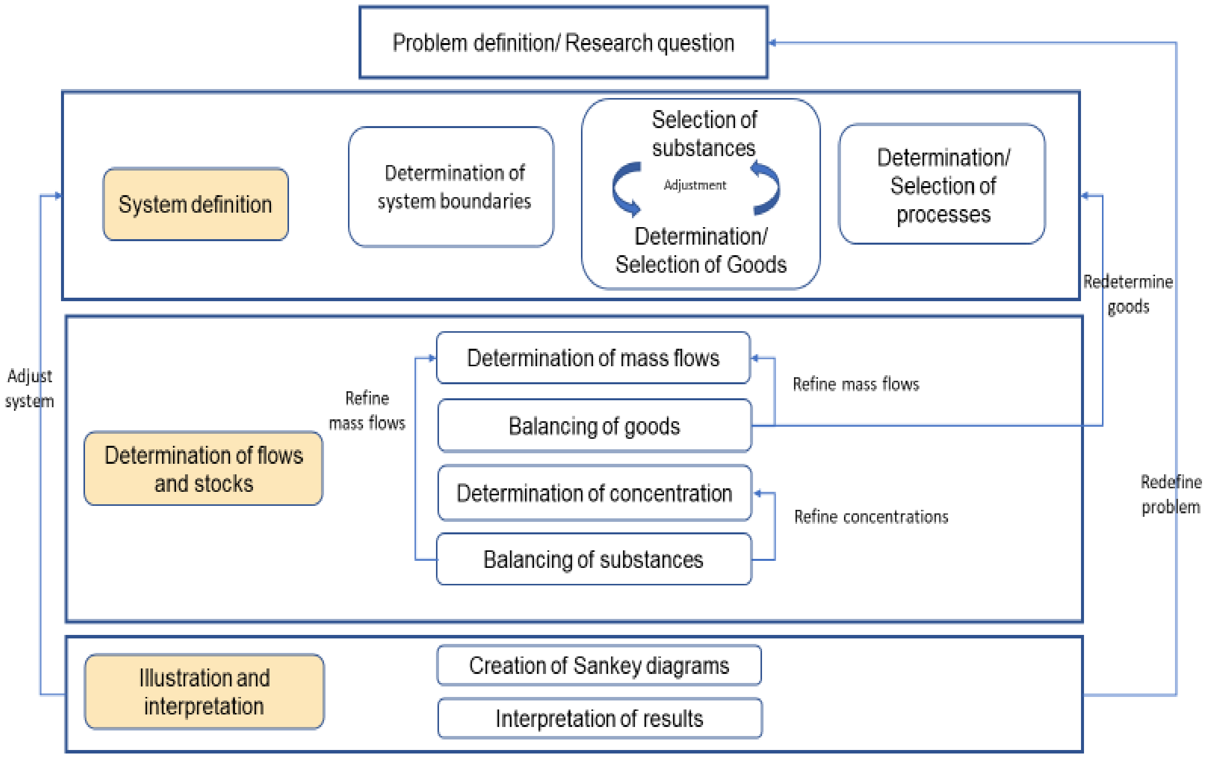

Figure 5 Methodological steps to perform an MFA (adapted from [186])

3.1 Goal and scope definition

MFA starts with defining the problem and setting appropriate goals. More specifically, the main desired results of the study are determined as well as the key assumptions are formed. This step also ensures the compatibility and sufficientness of the study in terms of its scale, depth, and detail with the stated objectives. All in all, the context in which the assessment will take place is established.

3.2 System boundaries definition

The **system** is defined as the basic object of any MFA investigation and is characterized by a group of main elements (such as processes, flows, etc.), the interaction between them, as well as the boundaries between these and other elements in space and time [187]. Thus, system boundaries should be well-defined and comply with the scope of the study. Especially in the case of MFA, the **system boundaries** are defined in both space and time. In particular, they are **spatially** determined by the scope of the project, usually referred to as a geographical boundary. Since data is more systematically and efficiently collected at regional and/or national levels, spatial system boundaries are defined as administrative regions, such as nations, states, or cities. Concerning their **temporal** definition, system boundaries might refer to one or several years [188].

3.3 Identification of Relevant Flows, Stocks, and Processes

Following the selection of substances and the definition of system boundaries, process specification and activity mapping is performed. The number of processes required for describing the system is determined by the study's objectives and the system's complexity. To this end, focus is given on the most relevant flows that address problems of primary interest [189]. The determination of which flow categories are accounted, should be accompanied by:

i. **Examination of the path** of the flows and **identification of the process steps**. It involves identifying those key processes which most efficiently represent and describe the complex system investigated.
ii. **Identification of the factors** that affect these flows.

The relevant processes, goods and substances are defined and linked [190], leading to the creation of a flowchart (Figure 6). Typically, an MFA includes the direct material flows associated with the extraction, processing, use, and end-of-life management phase of a particular material, as well as imports and exports for different life-cycle stages [191]. Also, a first rough balance of goods can be carried out for the system at this stage considering that data is available.

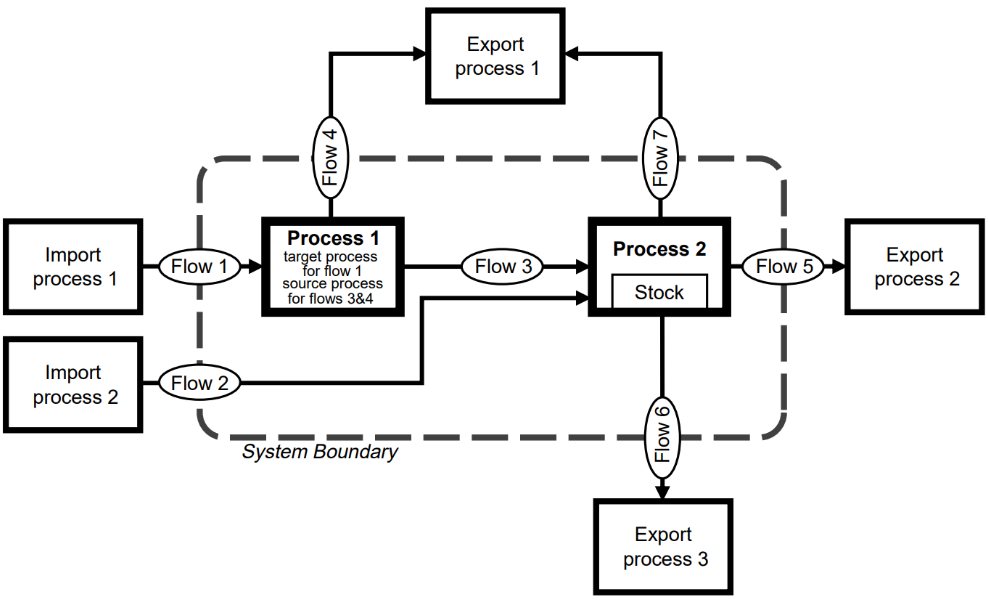

Figure 6: Exemplary MFA system

All in all, this step results in a complete map of the system under investigation, with a comprehensive breakdown of different manufacturing and subprocess processes, including every input and output taken into account.

3.4 Determination of Mass Flows, Stocks, and Concentrations

MFA is intensely data-driven, and consequently this step requires a detailed information collection (inputs and outputs) and examination for processes, subprocesses and streams recognized within the previous step. Thus, every flow and stock of the investigated system should be quantified. **Data retrieval**, evaluation and handling are a crucial parameter for the quality of the research and core tasks in MFA.

In more details, the determination and collection of available input data refers to flows and stocks of goods, substance concentrations, transfer coefficients and characterization of uncertainties. For the execution of the analysis, available production, consumption and trade data in combination with environment statistics are obtained [183]. Usually, primary data measured directly or indirectly on-site is the most valuable information for the one running an MFA, although mass streams might also be taken from secondary sources. To this end, the required information about flows and stocks can be provided from the scientific literature, company or national reports, statistical databases, environmental protection agencies, and other sources [188]. In parallel, some material flows are assessed based on assumptions, or even cross comparisons between similar systems.

3.5 Balancing of Total Material Flows and Stocks

Another focal point of the MFA is the **accounting and balancing of materials**, meaning that the sum of all inputs into the system under study must be equal to all outputs plus changes in stocks (see section 3.5.1). To do so, and based on the process chain, the inputs and outputs of each stage have to be determined quantitatively 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 [187, 189].

An actual material balance of a process or system may be attained only if all input and output flows are known and either equal to zero or can be quantified. If the inputs and outputs do not balance, one or more flows are either missing or were determined incorrectly. An additional factor influencing the balance of the system under study could be inaccuracies in substance concentrations. Balance differences of 10% between input and output are frequent and usually insignificant for drawing conclusions. In addition, since data collected for MFA is typically acquired from sources of different quality, it is subject to uncertainty and might conflict with model requirements. While the majority of model constraints are linear (e.g., mass flow balances of particular processes), nonlinear equations (e.g., concentration or transfer coefficient equations) are used in some circumstances, resulting in nonlinear data reconciliation difficulties [192]. Such inconsistencies can be resolved through data reconciliation, a statistical method that assists with figuring out the most likely values of measured quantities.

3.5.1 Law of mass balance

The MFA lays its foundation 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 physical process [183]. The results of an MFA essentially constitute a simple material mass or energy balance comparing all inputs, stocks, and outputs of a process [186].
For a given system such as production or consumption processes, companies, regions or national economies, the material balance principle is manifested as:

1. **Total inputs = Total outputs + Net accumulation,** meaning that what inserts into the system is either accumulated in the system or is leaving the system again as an output [193].

This principle is described by the following equation:

$$\sum_{i=1}^{j} \dot{m}_i = \sum_{i=1}^{k} \dot{m}_i + \Delta S$$

where j is the number of inputs, k the number of outputs, and $\dot{m}$ is substance or total material flow. ΔS is the change of stock that considers accumulation (ΔS > 0) or depletion (ΔS < 0) of material in the process. It is also schematically illustrated in Figure 7:

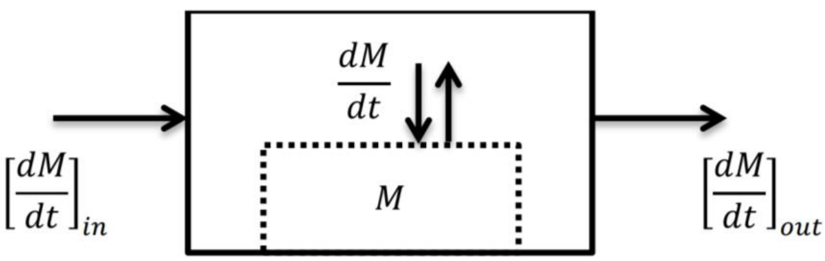

Figure 7: Flows of material M in and out of a system and the change in stock of M through accumulation or depletion [188]

For a given **physical flow,** the material balance entails the following facts:

i. All flows have an origin and a destination, and a breakdown by origin must be exhaustive in the sense that the sum of masses by origin must be equal to the sum of masses by destination.
ii. Matter changes form during production and consumption processes. When this identity is used to establish economy-wide balances for specific material groups (e.g., biomass), the raw materials must be related to the emissions or wastes that are the final destinations of these materials [193].

3.6 Presentation of Results

To maximize the effect of the MFA findings, figures that visualize the results and conclusions are critical. Several typical graphs, such as flowcharts, partitioning diagrams, etc. are effective ways of displaying the results. More specifically, a flowchart represents a diagram that depicts all the processes, stocks, material flows, as well as imports and exports that enter and exit the system. This type of illustration, which is known as the Sankey diagram, is mainly used to depict material, energy, and financial flows. Moreover, it should indicate the system boundaries as well as the units of flows and stocks. This presentation approach supports the reader to understand at a glance if materials are accumulating or depleting in the system, as well as which sources, pathways, and sinks are most important [186].

3.6.1 Sankey diagrams

As mentioned above, the Sankey diagram constitutes a visual representation of interlinkages in MFA systems. It illustrates all the intricate networking of the investigated system, while directing the attention to the essential points [194]. Sankey diagrams exhibit substantial benefits since they have proven particularly effective for public communications to decision makers in industry and government, to stakeholders and the public as well [194, 195]. In the Sankey diagram, flows are represented by arrows, where the width proportionally indicates the magnitude of the flows. The directed flows are always formed at least between two nodes, indicating, aside from quantities, information about the connections of the system [196]. Color is often utilized therein to aid in referring to particular flows, to indicate additional information such as life cycle stage or to illustrate an additional property of the analysis [195].

3.6.2 MFA interpretation

MFA is widely perceived as a particularly attractive decision-support tool in resource management, waste management, and environmental management. An MFA delivers a complete and consistent set of information about all flows and stocks of a particular material within a system. The results of an MFA indicate the flows of waste and environmental loadings while assisting in the identification of their sources. Additionally, MFA demonstrates the depletion or accumulation of material stocks at an early stage, rendering feasible the timely adoption of measures and policies [186].

MFAs can be evaluated complementarity with other assessment methodologies, such as LCAs, and draw substantial conclusions regarding system analysis and decision-making. However, MFAs are the only tools that:

- Provide a holistic and integrated view of resource flows through the economy.
- Capture flows that do not enter the economy as transactions but that are important from an environmental point of view.
- Aid in understanding how flows of materials shift within countries and among countries and regions, and their effect in the economic and environmental sectors [183].

The application of the abovementioned methodology to the BioReCer project is described in the following section.

4 Material Flow Analysis for the BioReCer project

4.1 General framework of the BioReCer MFA

In this section a framework is given of the MFA, which is going to be conducted for the BioReCer project. General concepts, such as the goal and scope and the system boundaries, which were applied in all case studies are analysed. Furthermore, the databases, from which data were retrieved, and the applied computer interfaces are mentioned. Finally, the general approach followed and the undertaken are determined.

4.1.1 BioReCer MFA goal and scope definition

The MFAs that are conducted in the context of BioReCer Project, primarily aim to shed light on the utilization pathways of the most important secondary biomass feedstocks and by-products of each sector (the primary commodities are not investigated). The goal is to elucidate the fate of the flows by focusing principally on the valorisation of the by-products in the bio-based industry. This information is complemented with data for the conventional uses so as to enable a complete assessment of the valorisation and circularity of each by-product analysed.

4.1.2 System boundaries definition

The system boundaries are common for the four different systems that will be investigated. In the context of an MFA, it is imperative to define the spatial and temporal boundaries. From the spatial perspective, the analysis involves the countries of EU-28. Regarding temporal boundaries, the analysis is conducted on an annual basis, based on the most recent data provided by the databases and literature. In most cases, the mean value of the data is calculated to eliminate time-dependent variations. A generic outline that illustrates schematically the system boundaries and the most important stages, which is applicable to all case studies is illustrated in Figure 8.

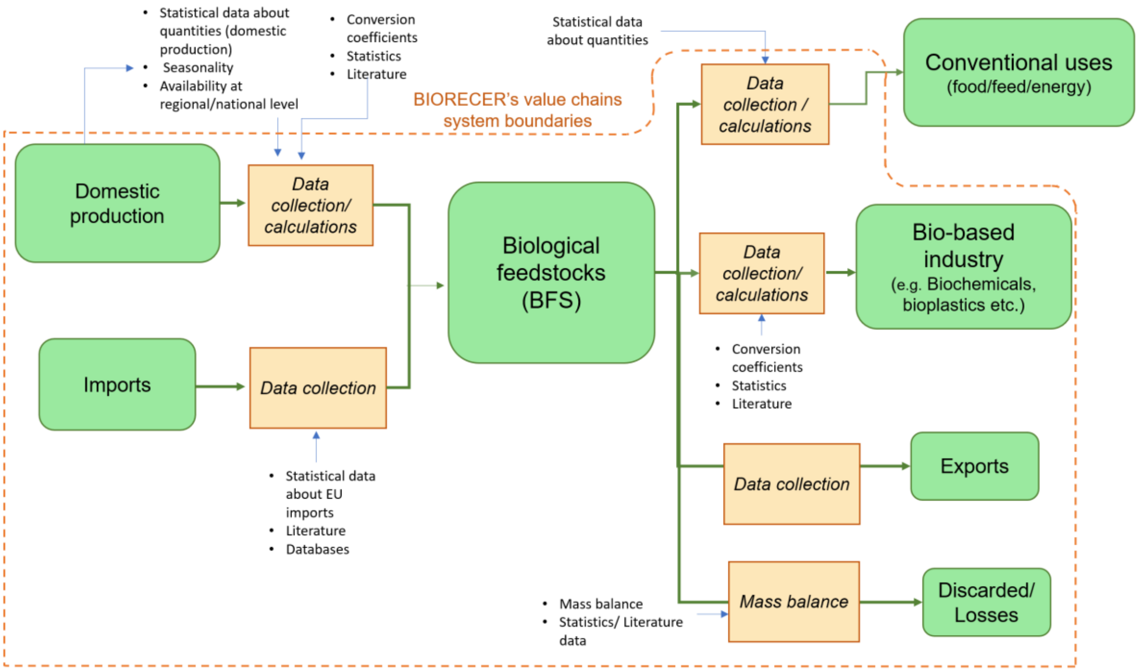

Figure 8: System boundaries of BioReCer case studies

4.1.3 Data collection and facilitated computer applications

The data availability and collection concerning the flows' quantities is the main pillar for the MFA performance. It is critical to acquire high-quality, reliable information from well-grounded, credible sources so as to assure the performance of a robust analysis. The majority of data is acquired from databases, in the context of data mining. The databases provide large volumes of coherent and reliable data. The most basic databases for the performance of the analysis are the following:

4.1.3.1 FAOSTAT

FAOSTAT is a free database managed by FAO and provides in detail a wide range of statistical information related to agriculture, food production and nutrition. The data is available on a country level, and is reported annually, with the most recent data referring to 2021. The database's latest updates occurred in the first quarter of 2023. Available at: https://www.fao.org/faostat/en/#data

4.1.3.2 OECD.Stat

OECD.Stat includes data and metadata for OECD countries and selected non-member economies. The data are provided through the interfaces https://stats.oecd.org/ and https://data-explorer.oecd.org/.

4.1.3.3 EUROSTAT

Eurostat is the statistical office of the European Union and https://ec.europa.eu/eurostat is an official website of the European Union. Its mission is to provide high-quality statistics and data on Europe. Eurostat coordinates statistical activities at Union level and more particularly inside the Commission. It provides a database through a Data Browser interface consisted of a huge variety of datasets, each identified with a unique online data code (e.g., ENPS_ENV_WASTRT for "Treatment of municipal waste").

4.1.3.4 World Integrated Trade Solution

The World Integrated Trade Solution (WITS) is an open database provided by the World Bank that offers information on trade and tariffs (traded values). The information is compiled by several international organizations, namely UN COMTRADE, UNCTAD TRAINS and WTO IDB/CTS. In the context of the MFA, the information retrieved from WITS relates to the import and export quantities that enter and exit the investigated system. The statistics are provided according to the Harmonized System (HS) 6-digit level for every country and year, updated for 2021. (Available at: https://wits.worldbank.org/trade/country-byhs6product.aspx?lang=en)

4.1.3.5 Data-Modelling platform of resource economics

Data-Modelling platform of resource economics, or DataM, is a website (https://datam.jrc.ec.europa.eu) that acts as a knowledge and data hub about the research carried out by the European Commission and partners in resource economics and sustainability. Resource economics is a branch of economics that studies how natural resources are allocated, used, and managed in relation to human activities and well-being.

4.1.3.6 JRC database for biorefineries

The JRC database provides extremely useful data for the execution of the current study since it is one of the very few organized and systematic records concerning the accumulation and visualization of information about the bio-based sector in the EU. The database covers the whole spectrum of biorefineries operating in EU-27, while a similar database exists for other countries of interest, including the UK. More specifically, the biorefineries that are incorporated in the database have a TRL of at least 8 or 9, implying that these facilities generate commercial products. In total 298 facilities were detected (July 2023). However, it is noted that the database may not contain all the innovative biorefineries existing in the EU (and selected non-EU countries) due to limited availability of information and implementation of new developments. In a general context, the creators of the database highlight the underlying difficulties that are inherent in endeavours that necessitate the collection and maintenance of reliable biorefinery-related information that is also time-consistent and commercially applicable [197]. (Available at: https://knowledge4policy.ec.europa.eu/visualisation/chemical-material-biorefineries-eu_en)

It is noted that the Biorefinery database does not provide data regarding the quantities of the raw materials or products. The information provided is limited to the number and distribution of biorefineries which are categorized according to their feedstocks and outputs. The data is filtered to delineate Europe's bio-based sector in the most representative way.

4.1.3.7 BioRefineries Blog

BioRefineries Blog includes a list/map of advanced bio-refineries at commercial scale in Europe (https://biorrefineria.blogspot.com/p/listado-de-biorrefiern.html?m=1).

4.1.3.8 European Technology and Innovation Platform

European Technology and Innovation Platform includes a list of global bioenergy plants (https://www.etipbioenergy.eu/databases/production-facilities). In installations reported in this platform, bio-chemicals are produced, which are not exclusively used for bioenergy.

4.1.3.9 IEA Bioenergy Task 42

IEA Bioenergy Task 42: Biorefining in a Circular Economy - BioRefinery Plant Portal (http://webgis.brindisi.enea.it/bioenergy/maps.php).

Complementarily, a systematic review in the Publications Office of the European Union showed the abundance of reports concerning the bio-based sector such as [61, 198-200].

The above mentioned reports and databases are extensively used in the analysis and provide a solid frame for data accumulation and processing. The creation of the inventory

is primarily the combination and processing of the data retrieved by these official sources. Since statistical information cannot be retrieved for every flow considered in the analysis, the missing information was complemented with data from reports, scientific literature, and studies from relevant Associations. Finally, to bridge the gap of missing data, the resort to assumptions and estimations is inevitable. However, it is accentuated that the assumptions were formulated based on concrete evidence and are meticulously described in Section 4.1.4 and subsequently in each case study.
For data processing and the creation of Sankey diagrams, SankeyMATIC was used, a web-based tool available online at https://sankeymatic.com/.

4.1.4 General assumptions applied to all case studies

The phenomenon of data scarcity is particularly common in studies that explore the residual biomass in terms of quantification [61]. The problem is further exacerbated in the case of information retrieval about the bio-based industry, as it was analysed in Section 2.5. Analogously, these issues arose in the BioReCer Project as well. Since the bio-based industry is still in a nascent stage and the bio-based products are generated in relatively small quantities compared to their fossil-based conventional counterparts, there are very few organized endeavours that review systematically the industry's volumes. It is noted that the official databases do not provide separate information for the bio-based products. Also, there is limited information regarding the fate of by-products.

Therefore, it is challenging to acquire detailed information for specific characteristics of interest, such as the quantities of the different raw materials that are utilized in the bio-based industry. To tackle the issue of data scarcity and to conduct a coherent analysis, the following assumptions and hypotheses have been stipulated.

- The focus of the current study is placed on the production of high value bio-based products (chemicals and materials) which are produced in bio-based industries, excluding conventional applications, such as food, feed, or energy. However, in some cases, as analysed in the following chapters, conventional uses were also taken into account, in order to determine the quantities destined to the bio-based industry.
- To address any temporal-related inconsistencies, the mean values of the reported data (last 3 years) for each biological feedstock are extracted (wherever applicable according to the availability of data in the databases examined).
- The aggregation of different feedstocks when examining the valorisation routes of the available biomass is implemented since data for the management of separate

feedstocks is scarce. For instance, data reported for the category of agricultural residues or secondary agricultural biomass is more prevalent as opposed to specific BFS such as straw or stems. Another paradigm is the consideration of MSW or bio-waste as the OFMSW, where applicable.

- The investigated system boundary is "cradle-to-gate", meaning that the analysis extends from the raw material extraction to the manufacturing stage. The investigation of the end-of-life phase is excluded from the analysis since it is out of the scope of the current Deliverable.
- In most cases, it is not possible to detect quantitative data regarding the bio-based industries' feedstocks. In parallel, there are few reports that offer insight on the total quantities of bio-based products produced in EU. More specifically, the total quantities encompass bio-based products formulated by all possible feedstocks (in terms of sectors). Also, there is no distinction between primary and secondary biomass feedstock used in the reported bio-based products' volumes.
- To quantify bio-based sector feedstocks, two approaches were followed, each one appropriate for each sector.
    - Investigation of available quantitative feedstock data of every industry. This information is referred to in platforms and constitutes a direct way to measure the bio-based industry's flows.
    - A "bottom-up" approach and use of appropriate conversion factors, which is further analysed in each CS study. The approach adopted, is to define the share of the bio-based products that derive from the feedstocks of interest (for each examined case). Since this share cannot be extracted directly from volumes due to lack of data, a dashboard presenting chemical and material biorefineries in the EU [201], provided by DataM is utilized. The information acquired from this database relates to the number of bio-based facilities. In this context, a representative image of the bio-based industry in the EU is acquired and is used to make estimations about the share of the bio-based feedstocks that correspond to each bio-based product. The estimations are then applied to the EU-level data that are available for each product category, to transfer the analogy to the EU scale.
- It is highlighted that by following the abovementioned approach, the quantities of products that exit the industrial plant are calculated. The volume of feedstock supplied to the industry is estimated by applying a suitable conversion factor derived from literature. It is noted that the utilization of coefficients and percentages is an established method to cope with data unavailability and determine the shares per

product category with reference to the bio-based industry. This method facilitates a satisfactory representation of the wide image of the bio-based sector [144].

- The "bottom-up" approach is a widely accepted strategy adopted by practitioners of MFA, offering a satisfactory level of assurance about the research results. The "bottom-up" approach implies that the data is collected from individual components and subsequently inferences are made for the larger system [202].
- It is worth mentioning that in the Sankey diagrams and the balance sheets, the quantities refer to the amount of required bio-based feedstocks (input) that will be processed, and not to the volumes of final products.

Specific parameters, data sources and assumptions tailored for each case will be further elaborated in the corresponding case studies presented in Sections 4.2 - 4.3.

4.2 Case Study 1: Fishery sector

In the following chapters the MFA of the BFS from the fisheries sector is presented.

4.2.1 Goal and scope definition

In the last decades the EU Commission has paid attention to the valorisation of waste produced from the Fishery sector, aligning their strategies and objectives with the general concept of circular economy and zero wastes discharge. Generally, almost 70% of total fisheries and aquaculture production is processed before their release at the market, discharging a significant amount of solid wastes/by-products, like fish heads, fins, skin etc. [203]. Some of them consist of valuable proteins that can be exploited in a variety of commercial products like cosmeceuticals, pharmaceuticals etc. [204, 205]. However, this discharge poses a risk of disrupting the natural food web and affecting the diversity of benthic organisms and planktonic communities. Although approximately 20% of FB undergoes processing and utilization, the majority is disposed of through dumping, incineration, or discharge into marine environments as waste, resulting in adverse consequences for health, environment, and the economy. Thus, it is crucial to categorize and process this waste effectively to protect the environment and ensure the sustainability of fish resources [10]. Additionally, the fishmeal and fish oil derived from the fishery industry are also rich in proteins and long chain polyunsaturated fatty acids of Omega-3 [206]. Consequently, it is important to annually record and supervise the fate of the FB. The MFA will contribute to the mapping of the FB and the identification of gaps at the existing data.

4.2.2 System boundaries definition and assumptions

The system boundaries for the fishery sector were the EU-27 from the spatial perspective. Appropriate assumptions and estimations were made, wherever it was necessary. Regarding the temporal boundaries the annual quantities of each country of the EU-27 and of the total EU-27 were taken into consideration. The average of the most recent three years with available data was estimated for each country.

From the investigation of DataM (section 4.1.3.5), and the literature [207], the following diagram for the fisheries sector and prospects for by-products utilization has been formulated (Figure 9). It should be stressed that limited data exist for the destinations to which the BioReCer project focuses, i.e., the bio-based sector. This may be attributed to limited reporting of the specific data or to the fact that these prospects have not reached commercialization yet.

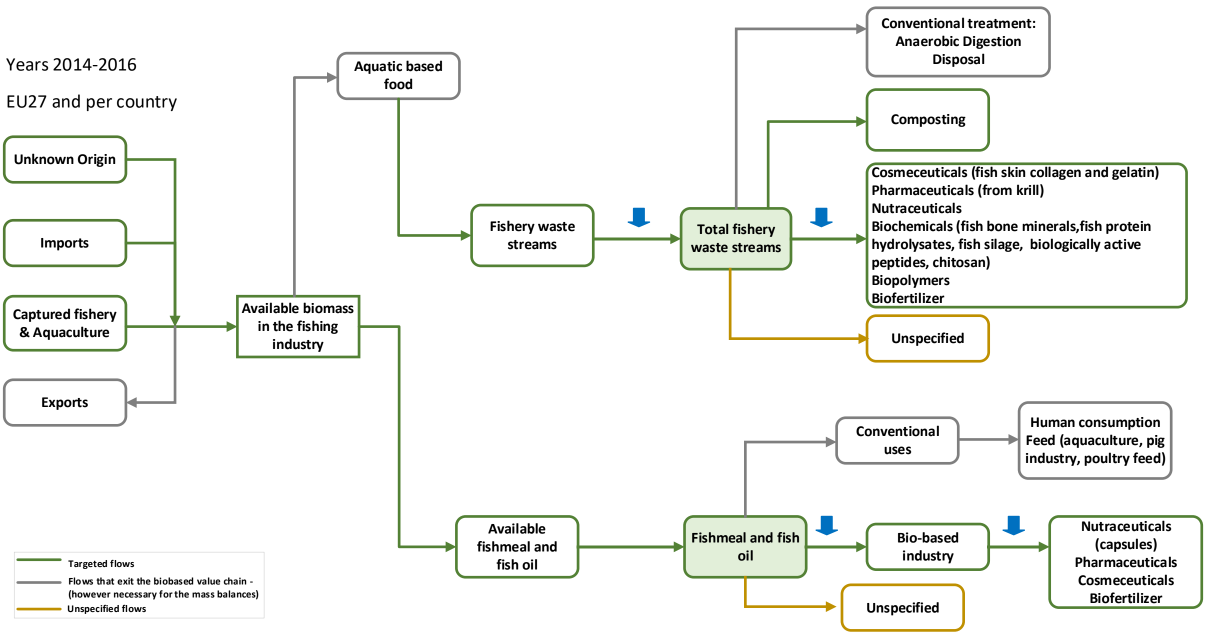

Figure 9: Generation and destinations of FB from the fishery sector; the blue arrows indicate the flows with limited quantitative data

The definitions of the sources and destinations of fisheries biomass, as given by DataM, are the following:

- **Biomass supply:** Biomass from fisheries and aquaculture origin of any type available for consumption or processing. It includes domestic production and imports.

- **Aquaculture** is the cultivation of fish and other aquatic animals in control by human growth conditions like, quality of water, oxygen supply, feeding, etc. The cultivation can be built either in the land (onshore aquaculture) or in open water bodies like sea, lakes etc. away from the coasts (offshore aquaculture).
- **Capture fishery** is the harvest for human consumption and industrial purposes of fish and other aquatic organisms directly from the aquatic ecosystem with different techniques like trapping, netting etc.
- **Unknown Origin** is the amount of the fish and aquatic organisms calculated by JRC, due to the difference in the mass quantities between the sources and the final products.
- **Imports** are considered the quantities be imported in EU-27, of fish and seafood of any origin, raw or processed and also the fishmeal and oil extracted from fish.
- **Exports** of any type of fisheries & aquaculture biomass. For the EU-27, this refers to exports from Extra-EU countries.
- **Aquatic-based food:** Food of fisheries & aquaculture origin consumed by humans.
- **Fishmeal & oil:** Production of fishmeal (cooked, pressed and ground fish) & oil extracted from fish.
- **Fishmeal & oil for animal husbandry:** Fishmeal & oil used for feeding farm animals, except in aquaculture.

Additionally, the **following assumptions/considerations** have been made:

- The total fisheries biomass in the fishing industry has been determined by adding the Biomass supply (as defined in DataM) with the waste streams derived from aquaculture and capture of fisheries.
- 72% of the available fishmeal and fish oil is fishmeal and 28% fish oil [208].

4.2.3 Identification of relevant Flows, Stocks and Concentrations

Due to the nutritional value of fisheries the whole value chain of the fishery industry is considered in order to detect the flows which need special attention. Taking into account the availability of the data the flows identified for conducting the MFA of the fisheries sector are the following:

- The total quantity of fisheries biomass supply derived from imports, exports, captured fishery and aquaculture destined to food and non-food uses.
- The flows concerning the fishmeal and fish oil industry.

- The waste streams derived from all the fisheries activities.

4.2.4 Determination of Mass Flows, Stocks, and Concentrations

In the following paragraphs the identified flows and stocks, as illustrated in Figure 9, were quantified.

4.2.4.1 Quantification of the identified feedstock flows

All the data included in this section were obtained from the DataM platform (chapter 4.1.3.5) frame "JRC - Biomass uses and flows". In Annex C details are given for the data of all the system flows for the average of the quantities for three years of each EU country. *No data for the UK was encountered in DataM, hence it was excluded*. The quantities were considered as the dry net weight. According to the specific database the latest available data were for the years 2014, 2015 and 2016.

4.2.4.1.1 Total supply of the fisheries biomass

According to the DataM platform, the total produced biomass of the fisheries sector is derived from the following sources: Aquaculture, Capture fishery, Unknown Origin, Imports and Exports.
In Table 24 the total fisheries biomass produced by the aforementioned sources is depicted. Details regarding each EU country are presented in Annex C. It should be noted that even though some countries are exporting fisheries biomass, the total exports from the EU, as determined by the JRC, are zero.

Table 24: Total fisheries biomass produced in the fishing industry in EU-27 from each biomass source; DataM platform

Fishing industry					
	Aquaculture, kt ^{db}	**Capture fishery, kt ^{db}**	**Unknown Origin, kt ^{db}**	**Imports, kt ^{db}**	**Total, kt ^{db}**
2014	260	1187	590	1573	3610
2015	263	1173	647	1463	3547
2016	278	1143	614	1555	3590
Mean value	267	1168	617	1531	3582

4.2.4.1.2 Generation of fishmeal and fish oil

According to the flow diagram in Figure 9, the fisheries biomass is destined for human consumption (aquatic-based food), for fishmeal and fish oil production and fishery waste streams. Fishmeal is a flour, rich in proteins, which is produced by milling the whole body of the fish or parts of it. Fish oil is the extracted oil obtained by the fish, which firstly has been cooked and pressed and then the liquid extract was received by centrifugation [209]. In Table 25, the available fishmeal and fish oil for EU-27 is presented, whereas in Annex C the corresponding data for each country are given. Based on the results ~20% of the total fisheries is used for the production of fishmeal and fish oil. Furthermore, the quantities of the biomass destined for aquatic based food, for reasons of consistency.

Table 25: Total available fishmeal and fish oil from the biomass supply in EU27; DataM platform

	Available Fishmeal and Fish oil, kt ^{db}	Available, aquatic-based food, kt ^{db}
2014	689	2368
2015	650	2342
2016	653	2363
Mean value	664	2358

Hence, the annual available fishmeal and fish oil in EU 27 is 664 kt. Taking into account the assumption mentioned in section 4.2.2 the available fishmeal quantity is 481 kt/yr and the fish oil quantity is 183 kt/yr. These amounts originate from domestic production and imports. Fishmeal and fish oil are mainly produced by directly processing fish. However, in recent years, the amount originating from FB is constantly increasing. In fact in 2020 over 27% of the global production of fishmeal and 48% of the total production of fish oil were obtained from FB [210].

4.2.4.1.3 Generation of fisheries waste-streams

In all the stages of the fishing industry (cutting of fins, head and bone removal, washing etc.) waste streams are generated, which are also rich in proteins, fats and minerals [11]. The total amount of waste from the fisheries sector originates from aquaculture and the capture of fisheries, from fisheries processing and the consumption of aquatic based food. Table 26 summarises the quantities of all the waste streams divided according to their origin. In Annex C the corresponding data for each country are presented.

Table 26: Quantities of the waste streams for the EU-27; DataM platform

Fishery waste-streams, EU-27				
Origin	**Fishing Industry**		**Aquatic based food**	
Process	**Aquaculture and capture fisheries, kt^{db}**	**Fisheries processing, kt^{db}**	**Consumption of aquatic based food, kt^{db}**	**Total, kt^{db}**
2014	303	250	313	866
2015	300	255	310	865
2016	294	280	313	886
Mean value	299	262	312	873

By the inspection of Table 24 and Table 26, it can be concluded that a significant fraction (~24%) of the total available fisheries biomass is FB, which is a source of valuable compounds with many prospects of uses, as analysed in sections 2.1.1 and 2.2.2.

4.2.4.2 Quantification of the destinations of biological feedstocks

4.2.4.2.1 Conventional uses

The main consumer of **fishmeal and fish oil is aquaculture**. Fishmeal is also used in animal husbandry and in pet food and fish oil in direct human consumption. Furthermore, unspecified destinations of fishmeal and fish oil exist [208, 210, 211]. Direct use of fish oil in human foods and capsules are increasingly significant outlets [10]. As it can be seen in Table 27 the share of fishmeal used in aquaculture has increased in 2020, compared to 2015 and it is expected to increase more, due to the expected growth of aquaculture in the coming years [211]. It should be noted that in DataM data is given only for the total amount of fishmeal and fish oil destined to animal husbandry and the specific data were not taken into account in the MFA.

Table 27: Global share of the fishmeal and fish oil uses. EU-27

Fishmeal uses			Fish oil uses		
	2015 [208]	2020 [210]		2015 [208]	2020 [210]
Aquaculture	70%	86%	Aquaculture	73%	73%
Chicken	6%	1%	Direct human consumption	21%	16%
Pig	22%	9%	Other	6%	11%
Other	2%	4%			

From the observation of Table 28 it can be assumed that ~5% of the available fishmeal and ~10% of the available fish oil is destined to other/unspecified uses, while the remaining amount is destined to conventional uses, i.e. for direct human consumption and feed (aquaculture, pig industry, poultry feed). The results of the quantitative destinations of fishmeal and fish oil are depicted in Table 28.

Table 28: Destinations of fishmeal and fish oil. EU-27

	Fishmeal	Fish oil
Conventional uses (human consumption and feed), kt^{db}	457	165
Other/unspecified uses, kt^{db}	24.1	18.3

Fishery waste streams: The fishery wastes commonly are disposed to landfills or are treated with anaerobic digestion. According to the DataM platform fishery wastes are also sent for composting. Fishery waste-streams are appropriate feedstock for the production of compost rich in nutrients (C~50%, N~8% and P~5%) [212]. In Table 62 the quantities of the wastes treated with conventional processes (disposal and AD) as well as the quantities of the wastes being composted are depicted. Details regarding each country are given in Annex C.

Table 29: Destinations of fishery waste streams for the EU-27, DataM platform.

	Disposal and AD, kt^{db}	Composting, kt^{db}
2014	659	207
2015	658	207
2016	674	213
Mean value	664	209

As depicted in Table 62 ~ 24% of the total fisheries waste streams is valorised as a compost while the remaining amount is destined to AD or even disposal.

4.2.4.2.2 Utilization in the bio-based industry

Fisheries BP have many prospects of being utilised in the bio-based industry. Fish oil can be used in capsules, carriers for pesticides, in paints, and in leather making [10]. Furthermore FB can be valorised [210]:

- For the production of fish gelatine for the stabilization of emulsions
- In biotechnological and pharmaceutical and biomedical applications
- For the production of leather, detergents and cosmetics

- In bioremediation processes
- For the production of calcium carbonate or calcium oxide, two highly versatile chemical compounds with wide industrial applications
- For handicrafts and jewellery
- For the production of bio-fertilizers

For the retrieval of data on the valorisation of sewage sludge in the biochemical industry the BioRefineries Blog, the European Technology and Innovation Platform and IEA Bioenergy Task 42 were investigated. However, no appropriate data for FB utilization were available. This may be attributed to the fact that the valorisation of FB has not reached commercialization yet.

4.2.5 Balancing of total Material Flows and Stocks

The final step in completing the MFA is the execution of the mass balances for each stage in order to balance the supply and uses of BFS. The objective of this step is to close the gap and illustrate the estimated quantities of materials that:

- Enter the system as flows of unreported sources.
- Exit the system either to conventional destinations, such as in disposal or AD.
- Constitute losses.
- Are headed for other unreported/ unspecified uses.

In Table 30 the balance sheet of the total fisheries biomass is given.

Table 30: Balance sheet of the fisheries biomass MFA; EU-27 (data in kt/yr^{db}), average values of the most recent three years with available data (2014-2016)

Input: Available Fisheries Biomass		Output: Fisheries Destinations	
Aquaculture	267	Aquatic based food	2358
Capture	1168	Fishmeal	481
Unknown	617	Fish oil	183
Imports	1531	Aquaculture and capture waste	299
		Fisheries processing waste	262
Total	3582	Total	3583

In Table 31 the balance sheet of the FB biomass is given.

Table 31: Balance sheet of the FB MFA; EU-27 (data in kt/yr[db]), average values of the most recent three years with available data (2014-2016)

Input		Output	
Fishmeal	481	Conventional uses (human consumption and feed)	457
		Other/Unspecified	24.1
Fish oil	183	Conventional human consumption and feed	165
		Other/Unspecified	18.3
Aquaculture and capture waste	299	Disposal and AD	664
Fisheries processing waste	262	Composting	209
Consumption of aquatic based	313		
Total	1538	Total	1537.4

4.2.6 Presentation of the results

The results of the performed MFA for the fishery sector are presented in Table 20. The production of waste in the fishing industry amounts to ~24% of the available fisheries biomass, while ~20% of the total fisheries is used for the production of fishmeal and fish oil, while the amount of fishmeal and fish oil originating from FB is constantly increasing. Fishmeal and fish oil are mainly used in aquaculture, animal husbandry and are directly used for human consumption. Only a small fraction (~6%) is destined to other/unspecified uses. These destinations may be pet feed, nutraceuticals, and carrier for pesticides, in paints and in leather production. Fisheries waste is mainly treated conventionally through disposal and anaerobic digestion, while ~24% is valorised in composting.

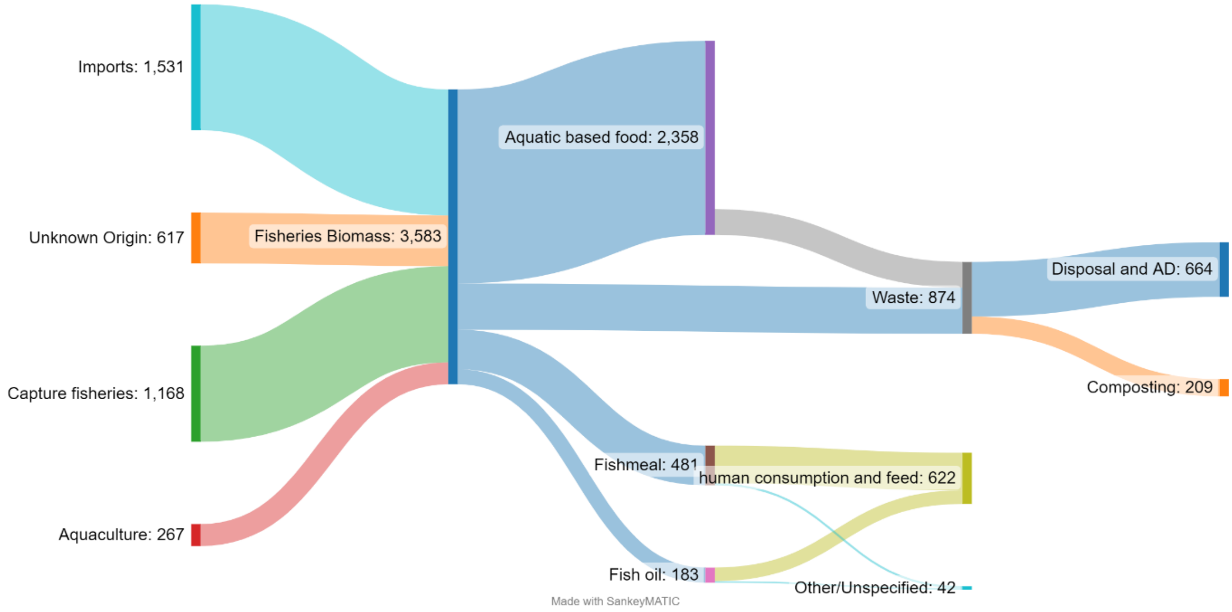

Figure 10: MFA Sankey diagram for fisheries biomass (EU-27); Quantities in kt/yr^{db}, average values of the most recent three years with available data (2014-2016)

4.3 Case Study 2: Urban and industrial sector

In the following chapters the MFA of the BFS from the urban and industrial sector is presented. Specifically, the Organic fraction of municipal solid waste (OFMSW) and sewage sludge were investigated.

4.3.1 Goal and scope definition

The **OFMSW** constitutes a significant fraction of municipal solid waste (MSW). Furthermore, due to its significant organic load, consisting of carbohydrates, proteins, and lipids (Section 2.3.2), if treated properly, it can be potentially valorised for the recovery of useful or even valuable products [213]. However, its management/treatment remains a challenge since the capture and separate collection of these fractions is currently low. According to a report conducted by the Bio-based Industries Consortium (2020) [214] 16% of potentially generated food waste and 32% of potentially generated bio-waste are separately collected in EU27+ (UK and Norway included). The collected OFMSW are usually used for compost and energy recovery. However, there are prospects for the production of products with greater value [215, 216] and it is believed that there is room for these applications, as demonstrated by the MFA.

On the other hand, although conventional methods are applied for the treatment of **sewage sludge** in order improve its unpleasant characteristics and significantly reduce its volume, a large amount of material remains at the end of the treatment, making its management a challenging task with limited available options [45]. The large amount of the produced sewage sludge (10 million tons dry solids in EU27) [217] render it appropriate for resource recovery providing economic and environmental benefits [41]. Some examples for sewage sludge valorisation are the recovery of energy, nutrients, minerals, coagulants, cellulose, metals and many more bio-based substances. However, sewage sludge valorisation remains a challenge due to the presence of contaminants, such as organic (e.g., PAH-Polycyclic aromatic hydrocarbons and PCB- Polychlorinated biphenyl), inorganic contaminants (e.g., metals) and pathogens, like bacteria, viruses etc. For these reasons, the sludge needs to undergo some stabilisation processes which may vary depending on the characteristics of the raw sludge [39]. Assuming water consumption of 125 litres per day, the potential resources that can be recovered from municipal wastewater and examples of their potential end-use in various market segments are given in Table 32 [41].

Table 32: Overview of the potential resources that can be recovered from municipal wastewater and examples of their potential end-use in various market segments [41]

Resource category	Resource	Recovery potential	Examples of potential end-use/market segment
Water	Water	100–400 L/capita/day (depending on daily water consumption per country/region)	Irrigation, non-potable domestic use, industrial use, potable domestic use. Injection to mitigate saltwater intrusion and so on.
Inerts	Sand	0.1–3 kg/capita/yr	Construction industry
Organics	Cellulose	Several kg/capita/yr	Biochemical industry, construction material
	Biosolids	It is nearly impossible to provide accurate numbers on the recovery potential of these compounds as the latter depends on a	Agriculture
	Alginate like substances		Pharmaceutical and food industry
	Biochar		Agriculture

Resource category	Resource	Recovery potential	Examples of potential end-use/market segment
	Volatile fatty acids	multitude of factors. 'Ballpark' figures that can be used are in the order of several kg/capita/yr for each of these resources	Biochemical industry
	PHA		Bioplastic/Agriculture
Energy	Biogas, as electricity	~250 MJ/capita/yr (theoretical) ~33 MJ/ capita/yr (practical)	Reuse onsite, local power grid
	Thermal energy (heat)	~760 MJ/capita/yr (theoretical) ~291 MJ/capita/yr (practical)	District heating/cooling
Nitrogen	Ammonia (NH_3)	1.6–7.4 kg N/capita/yr	Power generation (Denox)
	Ammonium sulphate		Agriculture
	Microbial protein		Agrifood, aquaculture
	Biosolids		Agriculture, landscaping
	Struvite		Agriculture
Phosphorus	Biosolids	0.4–1 kg P/capita/year	Agriculture
	Struvite		Agriculture
	Calcium phosphate		Agriculture
Metals	Large variety of metals in biosolids/ash	In the order of several grams/capita/year (for the sum of all metals)	Metallurgy
Coagulants	Predominantly Fe and Al based	In the order of 1 kg/capita/year	Soil amendment, construction, sulfide removal and odor control

Consequently, sewage sludge is considered a valuable resource, which can be used as feedstock in biorefineries. For this reason, the MFA could assist the routes for its valorisation.

4.3.2 System boundaries definition and assumptions

The system boundaries that define the investigated system from the spatial perspective is the EU27 + UK. Data were collected for EU27, EU28 and for each country separately. Regarding temporal boundaries, available data were collected from three most recent years. In order to eliminate time-dependent variations the mean value of the collected data was determined.

From the investigation of the databases described in Section 4.1.3, and the literature [215, 216, 218-220] the following diagram for the urban sector and prospects for by-products utilization has been formulated (Figure 11). It should be stressed that limited data exist for the destinations to which the BioReCer project focuses, i.e., the bio-based sector. This may be attributed to limited reporting of the specific data or to the fact that these prospects have not reached commercialization yet.

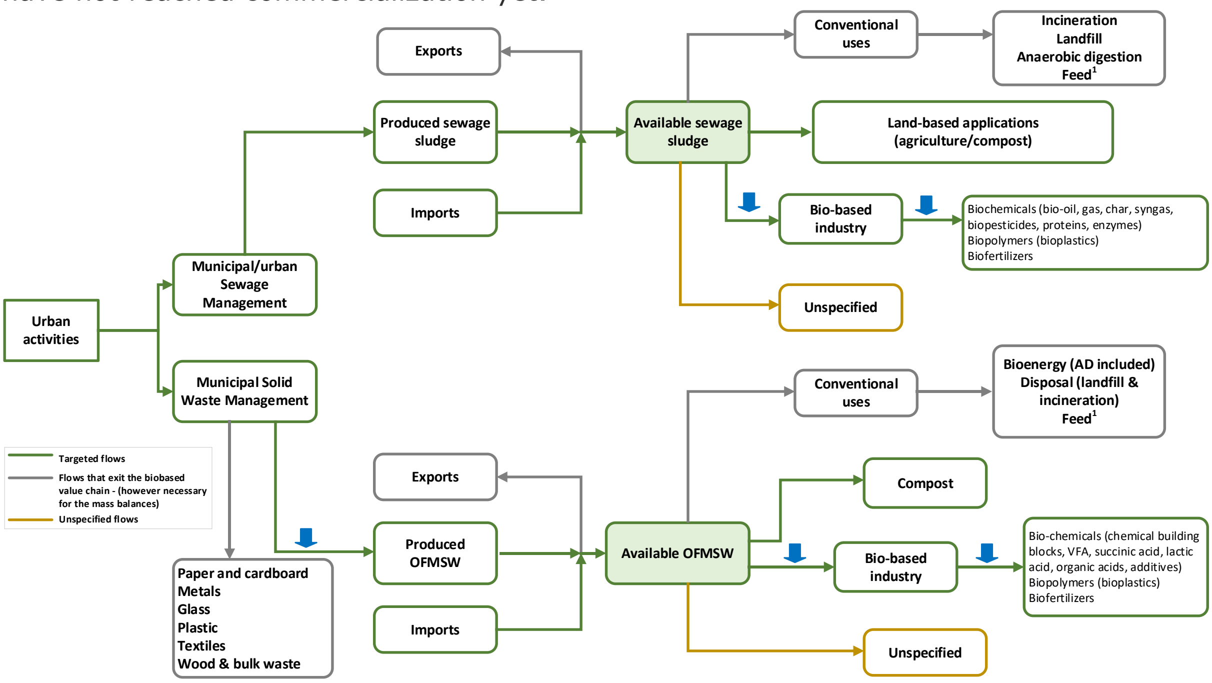

Figure 11: Generation and destinations of BFS from Urban activities; the blue arrows indicate the flows with limited quantitative data. [1] Applied in research [215, 216, 218-220]

The definitions of the MSW treatment operations (illustrated in Figure 11), as given by Eurostat [221], are the following:

Landfill is defined as deposit of waste into or onto land; it includes specially engineered landfills and temporary storage of over one year on permanent sites. The definition covers both landfill in internal sites (i.e., where a generator of waste is carrying out its own waste disposal at the place of generation) and in external sites.

Incineration means thermal treatment of waste in an incineration plant as defined in Article 3(4) or a co-incineration plant as defined in Article 3(5) of European Parliament and Council Directive 2000/76/EC of 4 December 2000 on the incineration of waste. OJ L 332, 28.12.2000, p.91.

Energy recovery is defined as the incineration that fulfils the energy efficiency criteria laid down in the Waste Framework Directive (2008/98/EC), Annex II (recovery operation R1).

Recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations. (Waste Framework Directive, 2008/98/EC*). Composting is excluded from material recycling [22]*.

Composting and anaerobic digestion are processes of biological decomposition of biodegradable waste under controlled aerobic (composting) or anaerobic conditions. It may be classified as recycling when compost (or digestate) is used on land or for the production of growing media (COM (2008) 811 final GREEN PAPER).

Preparing for re-use means checking, cleaning or repairing recovery operations, by which products or components of products that have become waste are prepared so that they can be re-used without any other pre-processing.

The treatment/management operations of **sewage sludge** (Figure 11) are defined as follows [222]:

Agricultural use: all use of sewage sludge as fertiliser on arable land or pastures, irrespective of the method of application.

Compost and other applications: all use of sewage sludge after mixing it with other organic material and composting, e.g., in parks or for gardens.

Landfill: all sludge that is disposed of in tips, landfill areas or special depot sites and that serves no useful function.

Incineration: all sludge that is disposed of by direct incineration or by incineration after mixing with other waste

Fair *assumptions* and estimates were made if data were not available. For the **OFMSW** the assumptions made are summarized below:

- The OFMSW comprises 34% of the total MSW [223, 224].
- The MSW treated by composting and AD is considered to be the OFMSW.
- In the EU-27, 70% of separately collected municipal bio-waste is sent for composting and 30% of separately collected municipal bio-waste is sent for AD [225].
- Data on biorefineries with TRL>8 were drawn.
- Data on biorefineries with productivity>1kt/yr were drawn.
- Biorefineries with no obvious status of operation were considered operational.
- Biorefineries which are planned to operate in 2023 are considered operational.
- The feedstocks of the selected biorefineries are assumed to totally consist of the OFMSW.

For **sewage sludge** the following assumptions were made:

- The available commercial biorefineries were considered.

Details on the assumptions, calculations and conversions are discussed in section 4.3.4.

4.3.3 Identification of relevant Flows, Stocks and Concentrations

By the observation of the composition tables in section 2.3, it can be concluded that the OFMSW and sewage sludge differ in composition and are usually managed as different waste fractions. Furthermore, they are governed by different legislative frameworks. For these reasons separate MFAs have been conducted for the OFMSW and the sewage sludge.

4.3.4 Determination of Mass Flows, Stocks, and Concentrations

In the following paragraphs the identified flows and stocks, as illustrated in Figure 11, were quantified.

4.3.4.1 Quantification of the identified feedstock flows: OFMSW

4.3.4.1.1 Generated OFMSW

Available data on the quantities of total MSW were collected from Eurostat (Online data code: ENV_WASMUN; Last updated: 4/4/2023). Detailed data are depicted in Annex D. In the EU, bio-waste usually constitutes between 30% and 40% of the total MSW. This percentage can range from 18% up to 60% [32], depending on the infrastructure and the income status of each country (low and middle income countries: 50-70%, high income countries: 20-40%) [218]. For the scope of this deliverable, it is considered that the *OFMSW comprises the 34% of the total MSW* [223, 224]. By these means the quantity of the OFMSW was determined, as depicted in Table 33.

Table 33. OFMSW generated in EU-27 and EU-28 (Eurostat last update: 4/4/2023)

	MSW, kt^{db}		OFMSW, kt^{db}	
Year	**EU-27[1]**	**EU-28**	**EU-27**	**EU-28**
2019	225,336	-	-	-
2020	233,206	-	-	-
2021	236,801	-	-	-
Mean value	231,781[2]	262,362[3]	78,806	89,203

[1]Estimated by Eurostat; [2]mean of Eurostat estimation for 2019-2021; [3]sum of data available for each country

4.3.4.1.2 Imports/Exports of OFMSW

Detailed data on waste shipments, regulated by the EC Waste Shipment Regulation (No 1013/2006) are provided by Eurostat [226] (Last updated: 28 October 2022). The data are derived from EU, EFTA (European Free Trade Association) and OECD (Organisation for Economic Co-operation and Development) (non-EFTA) countries.

The data were filtered by type of waste according to the European List of Waste Codes (2014/955/EU: Commission Decision) and for the years 2018-2020 (latest available data). The European waste codes selected are the following:

- 20 01 08: biodegradable kitchen and canteen waste
- 20 01 25: edible oil and fat
- 20 01 38: wood other than that mentioned in 20 01 37* (wood containing hazardous substances)
- 20 02 01: biodegradable waste

Detail data on the filtered results can be found in the Annex D. In the following table (Table 34) data are reported for years 2018-2020. From the information in Table 34 it can be concluded that the quantities of imported and exported OFMSW is negligible compared to the amounts generated in EU-28 (< 0.07%). Consequently, imports and exports will not be considered in the MFA.

Table 34: OFMSW shipments reported by EU, EFTA and OECD (non-EFTA) [226]

	Imports, kt^{db}	Exports, kt^{db}
2018	93	93
2019	52	68

	Imports, kt^{db}	Exports, kt^{db}
2020	40	37
Mean value 2018-2020	62	66

4.3.4.2 Quantification of the destinations of biological feedstocks: OFMSW

4.3.4.2.1 Conventional uses: Recovery/Disposal of OFMSW

MSW, according to Eurostat, is treated/managed with the operations stated in Table 35. The classification follows the definitions for the OECD/Eurostat Joint Questionnaire on waste [22] and the Guidance for the compilation and reporting of data on municipal waste [227]. According to the EU Waste Framework Directive 2008/98, waste related activities are classed as recovery (R) or disposal (D) and their codes are given in Annex D.

Table 35: Treatment operations codes for MSW given by Eurostat [221]

MANAGEMENT OPERATION	EUROSTAT CODE
Landfill / disposal (D1-D7, D12)	DSP_L_OTH
Incineration / disposal (D10)	DSP_I
Incineration / energy recovery (R1)	RCV_E
Material recycling	RCY_M
Composting and digestion	RCY_C_D
Preparation for reuse	PRP_REU

In Table 36 are depicted the quantities of total MSW treated, according to the aforementioned treatment operations. Data was collected from Eurostat (Online data code: ENV_WASMUN; Last updated 4/4/2023) and details are given in Annex D.

Table 36: Treatment operations of *MSW* (Eurostat last update: 4/4/2023)

	European Union - 27		European Union - 28	
	Quantity, kt/yr^{db}	***Reference years***	***Quantity, kt/yr^{db}***	***Reference years***
RECYCLING - COMPOSTING AND DIGESTION	*42,431*	*2019-2021*	*47,524*	*sum of available data*
RECYCLING - MATERIAL	68,618	2019-2021	77,157	sum of available data
R1: INCINERATION ENERGY RECOVERY	59,981	2019-2021	71,112	sum of available data
PREPARING FOR REUSE	976	sum of available data	976	sum of available data

	European Union - 27		European Union - 28	
D10 (INCINERATION WITHOUT EN. RECOVERY)	1,172	2017-2019	1,916	sum of available data
D1-D7, D12: LANDFILL AND OTHER	54,296	2019-2021	60,277	sum of available data

JRC has also reported the main treatment methods for bio-waste, which are the following [228]:

- For source separated bio-waste collection
    - Anaerobic digestion
    - Composting
    - Pyrolysis and gasification
- For mixed waste collection (i.e., bio-waste together with non-organic fractions)
    - Mechanical biological treatment
    - Incineration
    - Landfilling

It is also reported that Pyrolysis and Gasification are much less applied than the other techniques. Consequently, it can be fairly assumed that the quantity of the MSW treated by composting and AD is equal to the quantity of OFMSW. This assumption is also confirmed by literature [213]. Consequently, 42,431 kt/yr in EU-27 and 47,524 kt/yr in EU-28 of MSW are basically OFMSW, which is composted and digested. The quantities determined are in accord with the data reported in the European Compost Network - ECN DATA REPORT 2022 [225], i.e. 38,000 kt/yr of municipal bio-waste composted & digested in the EU27 and 47,000 kt/yr of municipal bio-waste composted & digested in the EU27+ (including CH, NO & UK). Furthermore, in the ECN report the current recycling rate is 17% of MSW (EU-27) through bio-waste collection and treatment, which is in agreement with the current data (18.3% of the total MSW is recycled through composting and AD in EU27).

It is also assumed that the OFMSW, which is used for composting and AD is collected separately, because , as reported by JRC (2011) [228] the risk of contaminated bio-waste is too high when using mixed waste that is separated after collection. Consequently, the following conversion factors from the ECN DATA REPORT 2022 [225] can be used:

- 70% of separately collected municipal bio-waste is sent for composting in the EU-27
- 30% of separately collected municipal bio-waste is sent for AD in the EU-27

By these means, the amount of OFMSW treated with AD and the amount treated with composting are determined (EU-27:12,729 kt/yr and 29,702 kt/yr, respectively). The same conversion factors are also used for the EU-28, i.e., 33,267 kt/yr and 14,257 kt/yr of OFMSW for composting and anaerobic digestion, respectively. The remaining quantities of the OFMSW (EU-27: 36,375 kt/yr, EU-28: 41,679 kt/yr) are subjected to other treatment operations. From the operations defined by Eurostat, landfill and incineration can be used in the OFMSW, but recycling is considered to be referred only to materials such as paper & cardboard, metals, glass, plastic, textiles and wood. In the following sections the existing information on the utilisation of the OFMSW in the bio-based industry will be analysed. The quantities of OFMSW landfilled and incinerated will result from the mass balance.

4.3.4.2.2 Utilization of OFMSW in the bio-based industry

The OFMSW has prospects of being valorised in the production of bio-chemicals (chemical building blocks, VFA, succinic acid, lactic acid, organic acids, additives) and biopolymers (bioplastics) [215, 216]. Currently, no data exist on the use of the OFMSW in bio-plastics production. According to the Total Energies Corbion Whitepaper [229] alternative feedstocks (often referred to as cellulosic feedstocks or second-generation feedstocks) for bio-plastics production include non-food biomass crops, agricultural by-products and waste streams. Specific examples include miscanthus, wheat straw, bagasse, corn stover and wood chips. No specific data is provided on the OFMSW.

For the retrieval of data on the production of bio-chemicals from the OFMSW, BioRefineries Blog, the European Technology and Innovation Platform and IEA Bioenergy Task 42 were investigated. The BioRefineries Blog does not include data concerning MSW or the OFMSW. For data retrieval the assumptions mentioned in section 4.3.2 were made. For the determination of the quantity of BFS, where not reported, the following conversion factors were taken into account:

- In the cases where no data on feedstock or production capacity were reported, a typical quantity of 20 kt/yr of feedstock is assumed.
- For starch waste (bakery waste) the conversion factor to ethanol is considered equal to 0.4 [230].
- For lignocellulosic biomass/waste the conversion factor to ethanol is considered equal to 0.1 (0.4 cellulose/biomass x 0.6 sugars/cellulose x 0.4 ethanol/sugars) [231, 232].

- The methanol to waste ratio is considered ~0.5 [233].
- The yield of hydrotreated vegetable oils (HVO) from various feedstocks is considered ~ 0.85 [234]
- The maximum density of gasification products is considered 1.4 kg/Nm^3 [235].
- The yield of syngas (gasification product) from biowaste is considered 1 Nm^3/kg of biomass [236].

The biorefineries using OFMSW for the production of bio-chemicals are summarised in Table 37. The assumptions mentioned in section 4.3.2 are considered rather inclusive and may lead to overestimation to the quantity of OFMSW destined for biorefineries. However, they give an indication on the current status.

Table 37 Biorefineries assumed to be using OFMSW as feedstock in the EU-28

Name[1]	Country	Feedstock type	Feedstock quantity kt/yr	Main product	Production kt/yr[2]	Status
Waste to Methanol	Italy	RDF, Plasmix	200	Methanol	109.5	Planned 2023
Perseo Bioethanol	Spain	MSW	99	Ethanol	1 - 9.9 (9.9)	N.A.
Versalis / Eni	Italy	Organic residues and waste streams, several biomasses	250	1. Ethanol 2. Lignin (co-product) used in a Biomass power plant	1. 25 2. -	Operational
Süd-Chemie	Germany	N.A.	18	Ethanol	1.8	N.A.
Etanolix Vantaa	Finland	Food Waste bakery waste and process residues, bread waste	5.5	1. Ethanol 2. Liquid animal feed	1. 1 2. 10,000 m^3 (10% Dry Solids)	Operational
Etanolix	Finland	Food	17.5	Ethanol	7	No status

Name[1]	Country	Feedstock type	Feedstock quantity kt/yr	Main product	Production kt/yr[2]	Status
Jokioinen		Waste				
Ethanolix Lahti	Finland	Food Waste food industry waste and process residues, bread waste	5.5	1. Ethanol 2. Liquid animal feed	1. 1 2. 10,000 m^3 (10% Dry Solids)	Operational
Etanolix Hamina	Finland	Food Waste food industry waste and process residues, bread waste	5.5	1. Ethanol 2. Liquid animal feed	1. 1 2. 10,000 m^3 (10% Dry Solids)	Operational
Gela Biorefinery	Italy	Oil residues, fat residues, organic waste, oil crops, aquatic biomass	637.5	HVO	750	Operational
Petrol d.d	Slovenia	Oil residues, fat residues, organic waste	-	Biogas	N.A.	N.A.
Biogázüzem Szarvas	Hungary	Oil residues, fat residues, organic waste	357	Gasification products	100-999 (500)	N.A.

Name[1]	Country	Feedstock type	Feedstock quantity kt/yr	Main product	Production kt/yr[2]	Status
NAFIGATE Corporation	Czechia	Cooking oil	-	Poly-3-hydroxybutyrate (P3HB)	N.A.	N.A.
Lignocellulose – Biorefinery/ LCF Biorefinery	Austria	Cereal residues, forest biomass, forest residues, paper, cellulosic, MSW	-	Nanolignin, bioactives, organic acids, erythritol, fibers	N.A.	N.A.
Orsted pilo	Denmark	MSW	-	Bio-Liquid	N.A.	N.A.
AquaGreen ApS	Denmark	Organic residues and waste streams Sludge (wet)	5	Clean syngas, solid fuels, other (Syngas and Biochar)	N.A.	Operational
		Total	1681			

[1] Data is retrieved from IEA Bioenergy Task 42, available at: http://webgis.brindisi.enea.it/bioenergy/maps.php and the European Technology and Innovation Platform, available at: https://www.etipbioenergy.eu/databases/production-facilities (accessed on 24 July 2023).

[2] unless stated otherwise

RDF (refuse derived fuel): fractions of MSW having a sensible calorific value [237]; Plasmix: the residual mixture of polymers arising from mechanical treatment of solid waste [238].

The total amount of BFS determined, by adding the feedstock of each biorefinery is 1681 kt/yr, which is considered the same for EU-27 and EU-28.

4.3.4.3 Quantification of the identified feedstock flows: Sewage sludge

4.3.4.3.1 Generated sewage sludge

Available data on the quantities of the generated sewage sludge were collected from Eurostat (Online data code: ENV_WW_SPD; Last updated: 10/8/2022] and are depicted in Table 38. The level of production of sewage or wastewater treatment sludge is defined as the quantity of decanted matter resulting from wastewater treatment, including sludge treatment. Depending on the methods of water treatment and sludge treatment, e.g., digestion or filter-pressing, the concentration of dry substance can be very variable. For this reason, data are reported on dry base (db) [222]. By the observation of detailed data in Annex D it can be concluded that for some countries no available or recent data exist. However, in the determination of the quantities the latest available data were considered.

Table 38. Sewage sludge generated in EU27 and EU28 (Eurostat last update: 10/8/2022)

Region	Generated sewage sludge, kt/yr^{db}
EU-27	8,356
EU-28	9,795

^{db} dry basis

4.3.4.3.2 Imports/exports of sewage sludge

Detailed data on waste shipments (Last updated: 12 July 2023), regulated by the EC Waste Shipment Regulation (No 1013/2006), are provided by Eurostat [226]. The data, derived from EU, EFTA (European Free Trade Association) and OECD (Organisation for Economic Co-operation and Development) (non-EFTA) countries, were filtered by type of waste according to the European List of Waste Codes (2014/955/EU: Commission Decision) and for the years 2019-2021 (latest available data).

The European waste code selected is 19 08 05 (sludges from treatment of urban wastewater). Detailed data on the filtered results can be found in the Annex D. In the following table (Table 39) data for years 2019-2020 are summarized. From the information in Table 39, it can be concluded that the quantity of imported and exported sewage sludge compared to the amounts generated in EU28 is ~3%.

Table 39 Sewage sludge shipments reported by EU, EFTA and OECD (non-EFTA) [226]

	Imports, kt/yr^{db}	Exports, kt/yr^{db}
2019	396	387
2020	283	220

	Imports, kt/yr[db]	Exports, kt/yr[db]
2021	266	165
Mean value 2019-2021	315	257

4.3.4.4 Quantification of the destinations of biological feedstocks: Sewage sludge

4.3.4.4.1 Conventional uses: Recovery/Disposal of sewage sludge

Among the conventional applications of wastewater sludge, landfill disposal has been the most common use, as it is the simplest method of management. However, due to limitations in available land and the increasing production of wastewater sludge, this option is no longer as feasible as it used to be, and other uses that can provide greater environmental, economic, and social benefits should be employed [239].

According to a survey conducted by the European Federation of National Associations of Water Services (EurEau) [240] among the EurEau countries, composting, agricultural use and thermal treatment are currently the most popular alternatives for wastewater sludge management. The use of sludge in agriculture, due to the high nutrient content, saves energy that would otherwise be required for the production of industrial fertilisers [241]. The thermal energy content of wastewater sludge can be utilised to substitute fuels in thermal processes [242].

Data were collected from Eurostat (Online data code: ENV_WW_SPD; Last updated: 12/8/2022) on the amounts of sewage sludge destined for agricultural use, compost and other applications, landfill, and incineration (definitions given in section 4.3.2). In Table 40 are depicted the quantities of sewage sludge treated, according to the aforementioned uses. Details are given in Annex D.

Table 40 Treatment operations of *sewage sludge* (Eurostat last updated: 12/8/2022)

	European Union - 27			European Union - 28		
	Quantity, kt/yr[db]	**Reference years**	**%**	**Quantity, kt/yr[db]**	**Reference years**	**%**
Agricultural use	2727.6	*sum of available data*	32.6	3708.9	*sum of available data*	37.9
Compost and other applications	994.5	sum of available data	11.9	994.5	sum of available data	10.2
Landfill	832.8	sum of	10.0	839.5	sum of	8.6

	European Union - 27			European Union - 28		
		available data			available data	
Incineration	2316.4	sum of available data	27.7	2560.7	sum of available data	26.1
Other	767.6	sum of available data	9.2	769.3	sum of available data	7.9
Unspecified[1]	717.4	*From mass balance*	8.6	922.3	*From mass balance*	11.0

[1] Calculated from the mass balance

The results from Table 40 can be compared with the data reported by the European Federation of National Associations of Water Services (EuEau) [240] (Figure 12). EurEau conducted an extensive survey amongst its members in 2020 to explore which is the destination of treated sludge. According to this Survey, 47.5 % of the produced sewage sludge goes to Agriculture, 8.3% to re-cultivation/land reclamation, 27.2% to incineration, 5.6% to landfill and 9.2% to other uses.

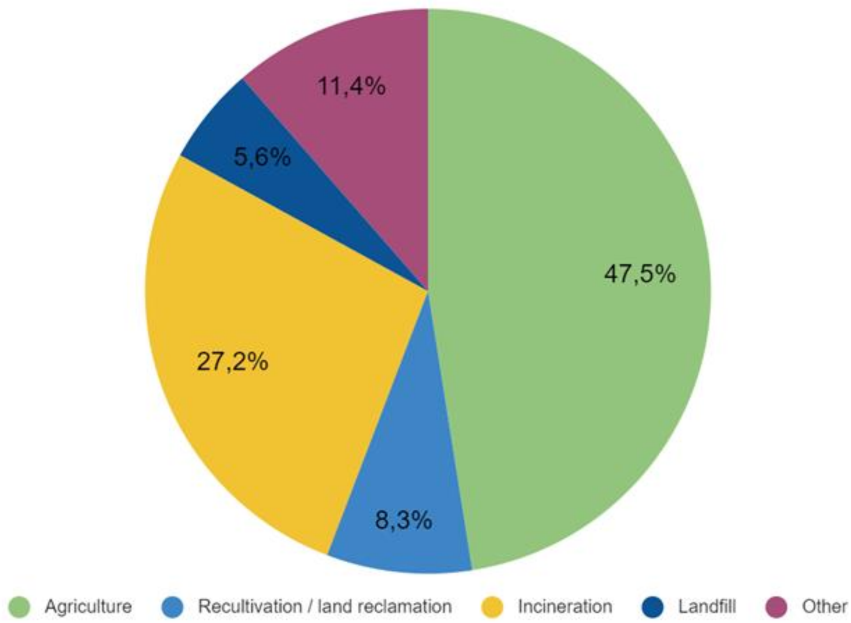

Figure 12 Destination of wastewater sludge production in the member countries of EurEau (based on responses, without extrapolation). Adapted from EurEau (2021) [240]

4.3.4.4.2 Utilization of sewage sludge in the bio-based industry

As also indicated in Table 32 (section 4.3.1) sewage sludge may valorised in the production of biochemicals, construction materials, bioplastic etc. For the retrieval of data on the valorisation of sewage sludge in the biochemical industry the BioRefineries Blog, the European Technology and Innovation Platform and IEA Bioenergy Task 42 were investigated. However, data on commercial plants processing sewage sludge for biomaterials, bioplastics and bio-chemicals are limited. The identified biorefineries using sewage sludge for the production of bio-chemicals are depicted in Table 41. For the data collected with the following considerations were taken into account:

- The existence of commercial installations.
- The moisture content of wet sewage sludge was considered 60% w/w [243].
- The bio-oil yield of sewage sludge through pyrolysis was considered 17% [244].
- The yield of hydrothermal carbonization used in Terranova Energy GmbH was considered 85% [245].

Table 41: Biorefineries processing sewage sludge in EU-28; data from bio-refineries platforms

Name[1]	Country	Feedstock type	Feedstock quantity kt/yr[db]	Main product	Production kt/yr	Status
To-Syn-Fuel	Germany	Sewage sludge	0.003	Bio-oil	0.0005 kt/yr	Operational
TerraNova Energy GmbH	Germany	Sewage sludge	2.6	Bio-coal	2.2 kt/yr	N.A.
AquaGreen ApS	Denmark	Organic residues and waste streams	2	1. Clean syngas 2. Solid fuels 3. Other (Syngas and Biochar)	N.A.	Operational (2022)

[1] Data is retrieved from IEA Bioenergy Task 42, available at: http://webgis.brindisi.enea.it/bioenergy/maps.php and the European Technology and Innovation Platform, available at: https://www.etipbioenergy.eu/databases/production-facilities (accessed on 24 July 2023).

Due to the limited data, an investigation on the internet was also conducted. It seems that prospects for the valorisation of sewage sludge exist, and efforts have been made to assess treatment technologies on a demonstration scale. Some examples are the following:

Paques Biomaterials: The Paques Biomaterials team has developed its own biotechnology for the production of PHA polymers. In 2022 they started operation of their first demonstration plant for PHA biomass production in Dordrecht, Netherlands. This Demo plant is part of the project PHA2USE, involving a consortium between Paques Biomaterials, HVC, Aquaminerals, STOWA and 5 Dutch water authorities. This Demo facility can be used with different PHA biomass production approaches and use different circular feedstocks, brought in from various locations [246].

Ingelia: Ingelia has developed a process of hydrothermal carbonization (HTC) of biomass, which enables the recovery of the carbon contained in the organic waste streams regardless of the humidity and heterogeneity to obtain a solid carbon-based biomaterial (hydrochar). Ingelia has designed and built a Hydrothermal Carbonization Plant of Biomass located in Valencia Spain that shows the viability of industrial implementation. Ingelia is also developing HTC plants in different European and world countries, with the collaboration of local financial partners. Some of the developed and planned installations of Ingelia in the EU-28 are [247]:

- United Kingdom: Ingelia has set up a commercial-scale HTC plant in Immingham, England, with a capacity of 25 kt/yr of sewage sludge.
- Belgium: Ingelia has partnered with the Belgian company Eneco to build an HTC plant in Antwerp, Belgium, with a capacity of 40 kt/yr of sewage sludge.
- Germany: Ingelia has partnered with the German company EEW Energy from Waste to build an HTC plant in Helmstedt, Germany, with a capacity of 20,000 tons per year of sewage sludge.

RWE Power AG: The multi-fuel-conversion (MFC) pilot-plant was commissioned in Niederaußem, Germany. The installation is able of the gasification of sewage sludge producing clean syngas with subsequent phosphorus recovery [248, 249].
By adding the quantities in Table 41 (4,6 kt/yr in EU-27) with the capacity of the Ingelia plant in the UK (25 kt/yr), the total amount of sewage sludge destined to the bio-based industry is 29,6 kt/yr in EU-28.

4.3.5 Balancing of total Material Flows and Stocks

The final step in completing the MFA is the execution of the mass balances for each stage in order to balance the supply and uses of BFS. The objective of this step is to close the gap and illustrate the estimated quantities of materials that:

- Enter the system as flows of unreported sources.
- Exit the system either to conventional destinations, such as in landfill or incineration.
- Constitute losses.
- Are headed for other unreported/ unspecified uses.

All the retrieved and estimated quantities of the investigated value chain for the EU-27 flows are depicted in Table 42.

Table 42: Balance sheet of the URBAN sector MFA; EU-27 (data in kt^{db}/yr), average values of the most recent three years with available data (OFMSW: 2019-2021: generation and treatment except for incineration without en. recovery (2017-2019), 2018-2020: imports/exports; SS: generation and treatment: mainly 2018-2020, imports/exports: 2019-2021)

Input		Output	
OFMSW			
Generation	78,806	Exports	-
Imports	-	Composting	29,702
		Anaerobic digestion	12,729
		Biobased industry	1,681
Total	**78,806**	**Total**	**44,112**
		OFMSW for disposal/incineration	34,694
Sewage sludge			
Generation	8,356	Exports	257
Imports	315	Agricultural use	2728
		Compost and other applications	995
		Landfill	833
		Incineration	2316
		Other	768
		Biobased industry	4.6
Total	**8,671**	**Total**	**7,901**
		Unspecified	771

Accordingly, the balance sheet of the URBAN sector for the EU-28 is illustrated in Table 43.

Table 43: Balance sheet of the URBAN sector MFA; EU-28 (data in kt^{db}/yr), average values of the most recent three years with available data (OFMSW: 2019-2021: generation and treatment except for incineration without en. recovery (2017-2019), 2018-2020: imports/exports; SS: generation and treatment: mainly 2018-2020, imports/exports: 2019-2021)

Input		Output	
OFMSW			
Generation	89,203	Exports	-
Imports	-	Composting	33,267
		Anaerobic digestion	14,257
		Biobased industry	1,681
Total	**89,203**	**Total**	**49,205**
		OFMSW for disposal/incineration	39,998
Sewage sludge			
Generation	9,795	Exports	257
Imports	315	Agricultural use	3709
		Compost and other applications	995
		Landfill	840
		Incineration	2561
		Other	769
		Biobased industry	29.5
Total	**10,110**	**Total**	**9,159**
		Unspecified	951

By conducting the mass balance, the quantity of the OFMSW landfilled and incinerated (with or without energy recovery) is 34,694 kt/yr for the EU-27 and 39,998 kt/yr for the EU-28. In the same manner by conducting the mass balance, a quantity of sewage sludge has an unspecified destination (771 kt/yr for the EU-27 and 951 kt/yr for the EU-28).

4.3.6 Presentation of the results

The balance sheet of section 4.3.5 was applied to formulate the Sankey diagrams of the MFAs for the OFMSW and Sewage Sludge.

4.3.6.1 OFMSW

As depicted in Figure 13 and Figure 14, approximately half of the generated OFMSW is subjected to conventional treatment, i.e., incineration (with and without energy recovery) and landfill. The most popular recovery routes are composting and anaerobic digestion, which consist of the other half of municipal bio-waste treatment. Only ~2% of this type of BFS is destined to the bio-based industry.

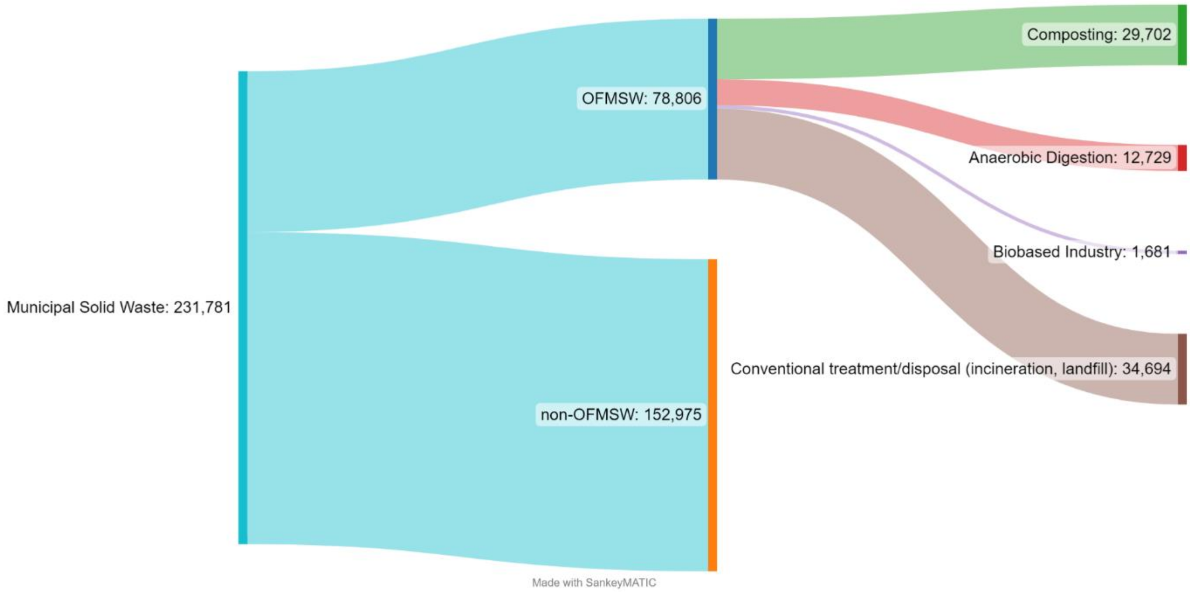

Figure 13: MFA Sankey diagram for OFMSW (EU-27); Quantities in kt/yr[db], average values of the most recent three years with available data (2019-2021: generation and treatment except for incineration without en. recovery (2017-2019), 2018-2020: imports/exports)

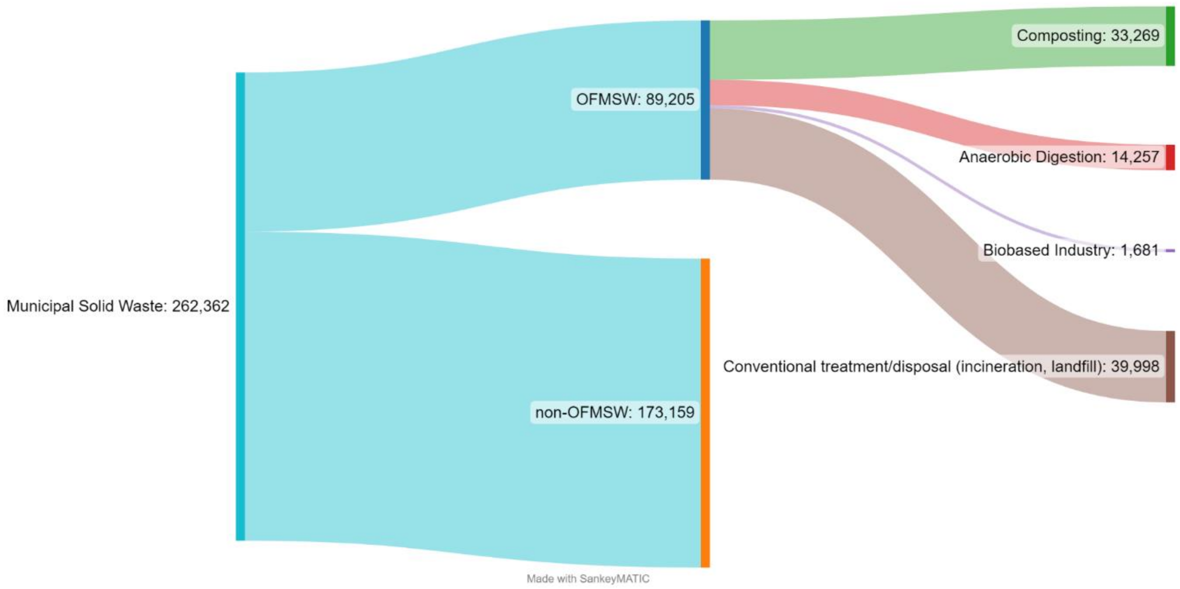

Figure 14: MFA Sankey diagram for OFMSW (EU-28); Quantities in kt/yr[db], average values of the most recent three years with available data (2019-2021: generation and treatment except for incineration without en. recovery (2017-2019), 2018-2020: imports/exports)

4.3.6.2 Sewage sludge

By the investigation of the Sankey diagrams in Figure 15 and Figure 16 it can be concluded that a significant fraction of the available sewage sludge (~ 37%) is valorised in agriculture, while ~10% is used for compost and other applications. Incineration is also an important management option for sewage sludge (~25%), while landfilling is not preferred in the EU-28 (~8%). The amount of destined to the bio-based industry still remains low (0.3%) with many prospects of development since many technologies are headed for commercialization. It should be noted that the management of sewage sludge is not well defined since the destination of ~17% is unknown (other and unspecified uses).

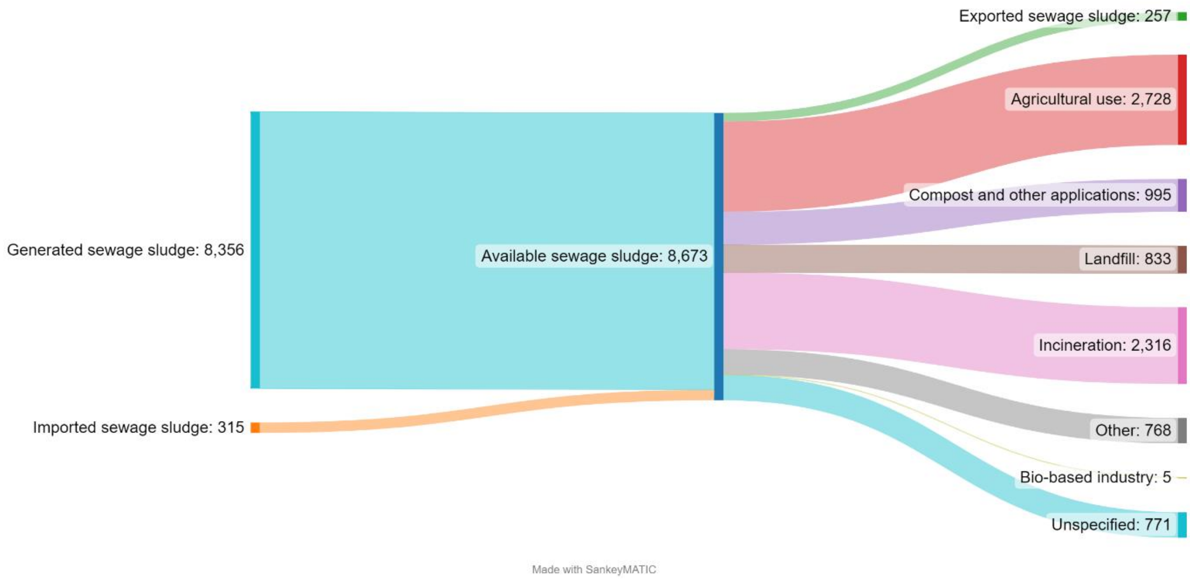

Figure 15: MFA Sankey diagram for sewage sludge (EU-27); Quantities in kt/yr^{db}, average values of the most recent three years with available data (generation and treatment: mainly 2018-2020, imports/exports: 2019-2021)

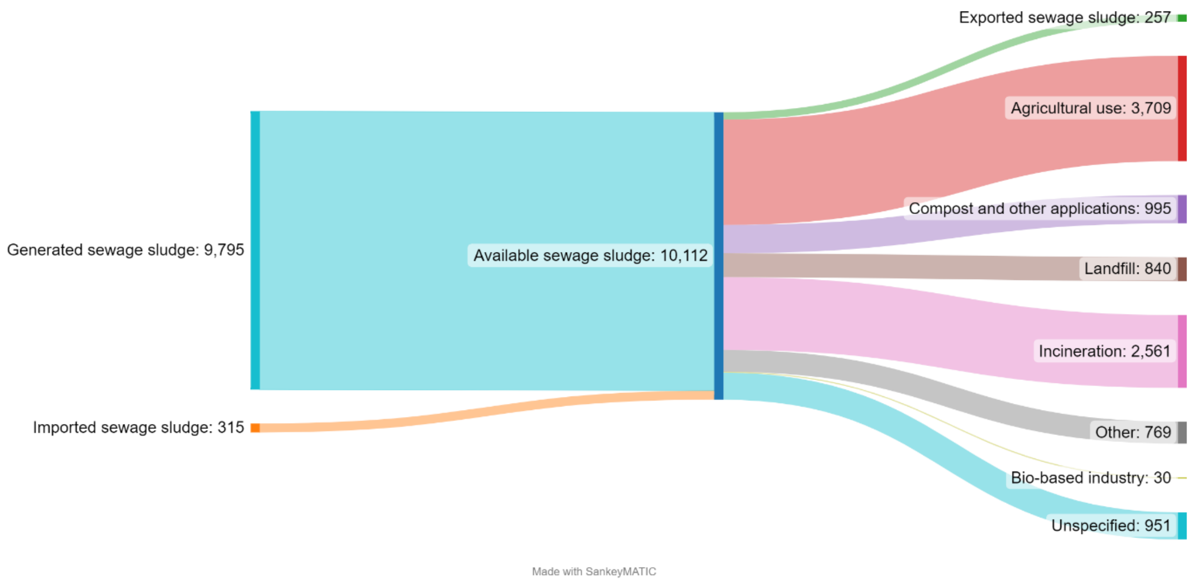

Figure 16: MFA Sankey diagram for sewage sludge (EU-28); Quantities in kt/yr^{db}, average values of the most recent three years with available data (generation and treatment: mainly 2018-2020, imports/exports: 2019-2021)

4.4 Case Study 3: Agricultural sector

In Section 4.4 a complete analysis is conducted for the most important secondary biomass flows that are generated through agricultural practices as well as processing of significant agricultural commodities.

4.4.1 Goal and scope definition

Agriculture is an essential pillar for the European bioeconomy. The sector supplies bio-based industries with primary as well as secondary products. Secondary products, namely straw, stems and prunings are predominantly discarded or treated conventionally for the generation of energy and feed, despite their remarkable potential for valorisation through the production of bio-based products. Also, industrial processing of agricultural products contributes to the generation of side streams, such as pomace and kernels, which are a cheap resource, rich in bioactive compounds such as peptides, carotenoids, and phenolic compounds, constituting excellent raw materials for product formulation as well (Section 2.4.2) [250]. Therefore, to successfully integrate this abundant resource in the bio-based value chain, it is important to identify the precise quantities and examine their allocation in the different routes, by executing a complete MFA that illustrates the current management status.

4.4.2 System boundaries definition and assumptions

To define the specific system boundaries applied to CS3, the outline of the value chain of the agriculture's secondary feedstocks depicted in Figure 17 has been taken into account. The value chain illustrates the course of materials and the interlinks that occur among the major stages of their current management conditions. The flows of materials are analyzed from the primary stage of their generation/extraction, covering their conventional and bio-based paths of utilization. The emphasis is placed on the allocation and quantification of the available biomass to the bio-based applications. The spatial system boundaries include EU-28, while with regard to temporal boundaries, the analysis is conducted on an annual basis. In most of the cases, data was extracted for the last three years, and the mean value was calculated so as to eliminate time dependent variations.

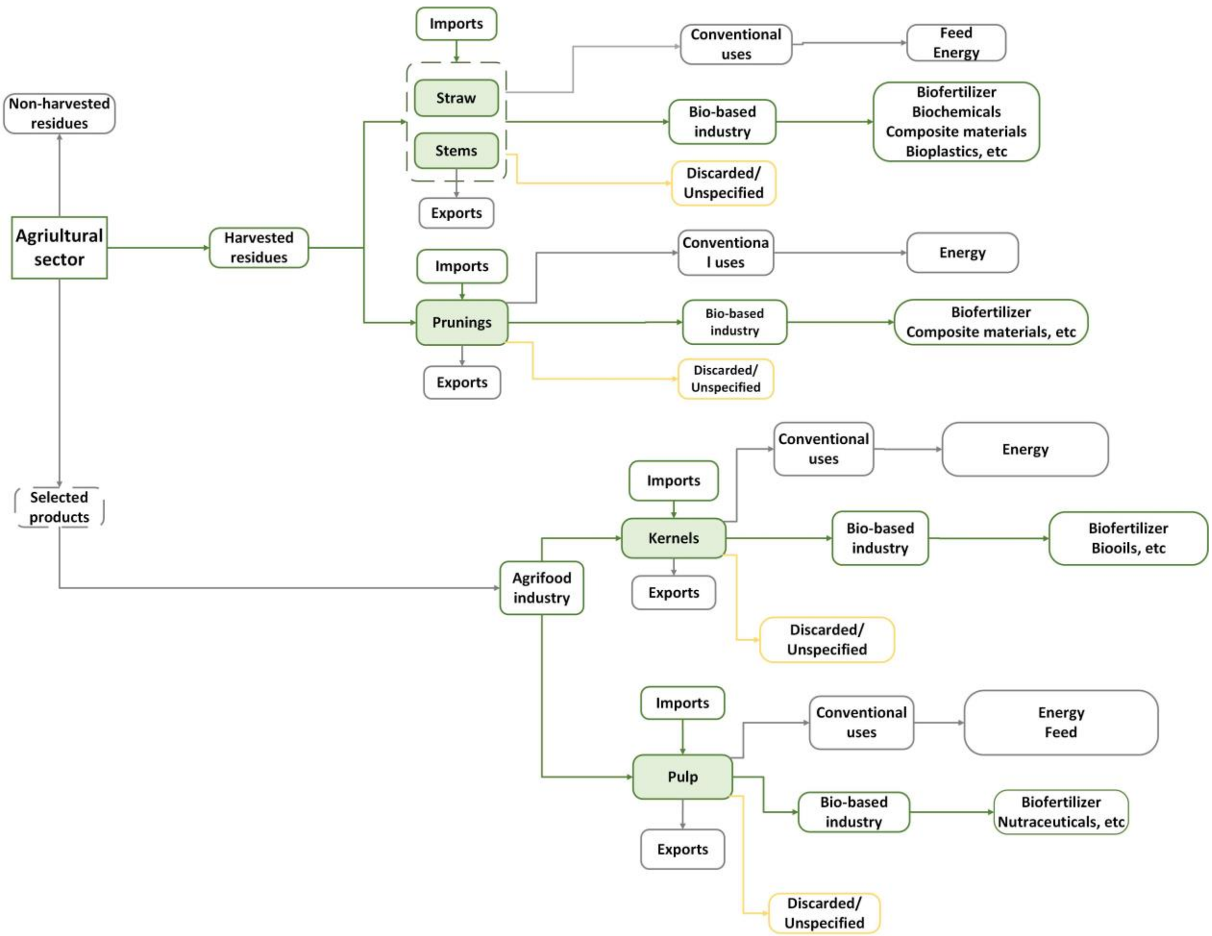

Figure 17: Outline of agricultural sector's investigated value chain

4.4.3 Identification of relevant Flows, Stocks and Concentrations

In the agricultural sector, the examined flows of residual biomass originate from agricultural practices (straw, stems and pruning) as well as from food industry by-products (kernels and pomace). The selection of the cultivations from which the agricultural biomass will be derived and subsequently analysed prioritizes the most significant commodities in the EU-28 as reflected in the cultivated areas dedicated to each crop. To achieve a successful and purposeful feedstock selection, the statistical data of the cultivated areas for the selected crops in the geographical area of EU-28 were retrieved from the FAOSTAT database and are presented in Table 44 and Table 45. In the scope of the study, the emphasis was placed on cereal, oil, industrial and arboreal crops since these crops occupy larger cultivation areas and produce considerable amounts of residual biomass. Also, both stems and stalks are taken into account in residual biomass calculation.

Table 44: Harvested area of basic crops cultivated in EU-28 (FAOSTAT database)

Cultivation	Harvested area (ha)	Type of residue
Wheat	25,819,070	Straw
Barley	11,418,430	Straw
Maize	9,247,050	Stems/ Stalks
Rapeseed	5,631,960	Stems/ Stalks
Sunflower	4,368,740	Stems/ Stalks
Oats	2,753,510	Straw
Triticale	2,670,113	Straw
Rye	1,971,328	Straw
Soya beans	939,620	Straw
Rice	408,470	Straw

Table 45: Harvested area of basic arboreal crops cultivated in EU-28 (FAOSTAT database)

Cultivation	Harvested area (ha)	Type of residue
Olives	4,999,900	Prunings
Grapes	3,119,896	Prunings
Almonds	881,340	Prunings
Apples	507,269	Prunings
Oranges	274,820	Prunings
Peaches and nectarines	194,050	Prunings
Cherries	125,249	Prunings
Pears	108,430	Prunings

The selected crops, as is evident from Table 44 and Table 45 data, are extensively cultivated in Europe. Regarding the cereal and oil crops, the selection was based on the cultivated land in conjunction with each plant's potential in residue generation in terms of quantity (assessed based on RPR indicators) and properties that favour their valorisation (see Section 2.4.2). Similarly, the selection of the arboreal cultivations was based on the cultivated area and especially the trees occupying land surface larger than 100,000 ha.

4.4.4 Determination of Mass Flows, Stocks, and Concentrations

In the following subsections, the data mining process for the identification of the relevant feedstocks and their utilization is described.

4.4.4.1 Quantification of the identified feedstock flows

First, it is necessary to quantify the agricultural feedstocks that are generated domestically in EU-28, either from agricultural practices or agrifood industry.

Straw and stems: Straw and stems constitute major by-products of the agricultural sector and are generated during harvesting practices. Despite the massive volumes generated on an annual basis, it is reported that there are not any systematic statistics that accumulate data for agricultural residue production. Normally, this kind of information is extracted from estimations based on the primary products of agriculture by the implementation of empirical models [4, 61]. The calculation of agricultural residues is executed based on Equation 1 [251-253].

$$\text{Residue\_Production} = \text{Crop\_Production} \times \text{RPR} \times \text{Availabiltiy} \quad (1)$$

Where RPR is the Residue-to-Product Ratio that expresses the amount of residue that corresponds to the main grain produced (ton/ton). The availability factor delineates the percentage of collectable residues to the total amount of residues produced, taking into account mechanical difficulties in collection and conventional uses such as the indispensable disposal on field for soil enhancement, animal feed and bedding applications as well as other well-established uses. The RPR indicators are characteristic for each crop and their values are obtained from scientific literature. The RPR indicators of the analysed crops are gathered on Table 46.

Table 46: Literature review of RPR indicators and adopted values for each crop

Cultivation	[254]	[252]	[251]	RPR values adopted in the study
Wheat	1.2	1.28	0.5 - 1.75	1.20

Cultivation	[254]	[252]	[251]	RPR values adopted in the study
Barley	1.7	1.19	1.08 - 1.36	1.37
Maize	1.5	1.00 - 1.17	1.50 - 2.25	1.49
Rapeseed	2.75		1.60 - 1.80	2.23
Sunflower	2.62	2.20	0.70 - 3.50	2.31
Oats	2	1.36 - 1.60	0.34 - 0.39	1.28
Triticale	1.5			1.50
Rye	2	1.71 - 3.10	0.99	1.80
Soybeans	2.5		0.76 - 3.50	2.32
Rice	1.5	1.70	0.45 - 1.75	1.43

Subsequently, it is essential to identify the availability factor to quantify the **actual percentage** of residues that are collected. To reflect the existing status, instead of adopting a generic availability factor derived from literature, the percentage of collected residues is calculated based on JRC's study "Biomass production, supply, uses and flows in the European Union" [61]. More specifically, the ratio of non-harvested to the total residue production is equal to (336,629/430,965) x 100% = 78.11%, as reported in [61]. Therefore, 21.89% of the calculated residues are actually collected from the field and enter the value chain. In the present analysis the same availability factor is adopted, however applied in the novel, updated quantities calculated.

The agricultural residual biomass quantities are analytically presented on Table 47 and Table 48. The necessary data concerning the crop production quantities are obtained from the FAOSTAT database. More specifically, the mean values of the reported data for the time period 2019-2021 (most recent available data) are extracted, for the countries of EU-28. Additionally, the total amount of generated residues is calculated, while in the last column the provided information refers to the fraction of biomass that is practically obtained.

Table 47: Crop production, available and obtained straw residues in EU-28 (FAOSTAT database); mean values for 2019-2021

Cultivation	Type of residue	Crop production (kt/yr)	Available residues (kt/yr)	Obtained residues (kt/yr)
Wheat	Straw	146,831	176,197	38,570
Barley	Straw	61,018	84,705	18,542
Oats	Straw	8,652	11,183	2,448
Triticale	Straw	11,183	16,774	3,672
Rye	Straw	8,353	15,363	3,363
Soybeans	Straw	2,813	6,528	1,429

Cultivation	Type of residue	Crop production (kt/yr)	Available residues (kt/yr)	Obtained residues (kt/yr)
Rice	Straw	2,858	3,974	870
Total	**Straw**		**314,724**	**68,893**

Table 48: Crop production, available and obtained stems residues for EU-28; mean values for 2019-2021

Cultivation	Type of residue	Crop production (kt/yr)	Available residues (kt/yr)	Obtained residues (kt/yr)
Maize	Stems	68,850	102,586	24,237
Rapeseed	Stems	18,889	42,123	8,555
Sunflower	Stems	10,016	23,136	5,004
Total	**Stems**		**167,845**	**37,796**

Prunings: A similar approach is applied in the case of arboreal crops and the generated prunings. The essential difference in pruning quantification lies in the introduction of RSR (Residue-to-Surface) indicator that expresses the amount of prunings that correspond to a specific area of cultivation [254]. Primarily, the RSR indicators [254] are detected for each tree crop analysed, followed by the quantities of main products as retrieved from the FAOSTAT database, for the years 2019-2021, in the EU-28. Subsequently, by applying the availability factor that has been identified for the agricultural residues, the collected pruning quantities are estimated. The information that relates to the quantities of pruning residues is accumulated on Table 49.

Table 49: Crop production, available and obtained prunings deriving from the most important arboreal crops in EU-28; mean values for 2019-2021

Cultivation	Cultivated area (ha)	RSR (ton/ha) [254]	Available prunings (kt/yr)	Obtained prunings (kt/yr)
Olives	4,999,900	2.82	14,100	3123
Grapes	3,119,896	5.97	18,626	4104
Almonds	881,340	2.95	2,599	548
Apples	507,269	4.51	2,288	498
Oranges	274,820	3.75	103	225
Peaches and nectarines	194,050	4.25	825	186
Cherries	125,249	4.01	502	111
Pears	108,430	5.40	59	130
Total	**9,865,823**		**39,101**	**8,924**

Orange pomace: The solid residue obtained from the process of juice extraction is defined as orange pulp and contains peel (60–65%), internal tissues (30–35%) and seeds (0–10%). The solid residue corresponds to 50% of the fresh fruit [83]. Every year, a substantial amount of oranges is destined to the food processing industry, mainly for the production of orange juice. The officially recorded by European Commission [255] quantities of fresh oranges destined for processing industry along with the estimated orange pomace production is demonstrated on Table 50.

Table 50: Amount of processed oranges and produced pulp in orange processing industry in EU

Market year	Oranges for processing (in kt of fresh equivalent)	Produced pomace (in kt)
2021/2022	1,110.0	555
2020/2021	996.0	498
2019/2020	848.0	424
2018/2019	1,309.0	654.5
Mean value	**984.7**	**492.3**

Apple pomace: Apple pomace is the solid residue of apple pressing and represents approximately 30% of the original fruit [77]. The total amount of apples that are destined for the processing industry, as reported by the "EU fruit and vegetables market observatory"[256] is presented in Table 51, along with the calculated apple pulp produced.

Table 51: Amount of processed apples and produced pulp from apple processing industry in EU

Year	Apples for processing (in kt)	Produced pomace (in kt)
2021	2,920	876
2020	2,500	750
2019	2,007	602.1
Mean value	**2,476**	**742.8**

Peach pomace: Peach pomace is a significant by-product of the peach process industry and amounts to 15-28% of the transformed raw material [74]. For the MFA calculations the mean value is adopted, assuming that 21.5% of the processed quantities of peaches results as pomace. Additionally, it can be deduced that fruit stones represent approximately 7% of the fruit weight, as mentioned in [69] and in accordance with [66] that consider peach kernels as 5-10% of the total fruit weight. The peaches and nectarines quantities for processing is retrieved in [257] and is shown on Table 52 along with the estimated pomace and kernels produced.

Table 52: Amount of processed peaches & nectarines, produced pomace and kernels generated from peach processing industry in EU

Year	Peaches and nectarines for processing (in kt) [257]	Produced pomace (in kt)	Produced kernels (in kt)
2019/2020	710.79	152.8	49.76
2018/2019	707.86	152.2	49.55
2017/2018	734.32	157.9	51.40
Mean value 2018-2020	**717.66**	**154.3**	**50.24**

Grape pomace: According to Beres et al., 1 kg of grapes is required to produce 0.75 L of red wine. Furthermore, the wine-making industry produces pomace as a by-product which represents 20-30% of the original grape weight (assumed as 25% in the study) [258]. The aforementioned data applied on the wine official European Commission production statistics [259] derived for EU and the resulting pomace quantities are presented on Table 53.

Table 53: Amount of processed grapes and produced pomace from winemaking industry in EU

Marketing year	Wine production (in 1000 hectoliters)	Produced pomace (in kt)
2022/2023	165,691	5,523.0
2021/2022	158,683	5,289.4
2020/2021	157,177	5,239.2
2019/2020	144,033	4,801.1
Mean value 2020-2022	**160,517**	**5,350.5**

Olive pomace: By adopting the mass balance proposed by Romero-García et al. [73], that is depicted on Figure 18, it is feasible to calculate the olive-related residual biomass streams.

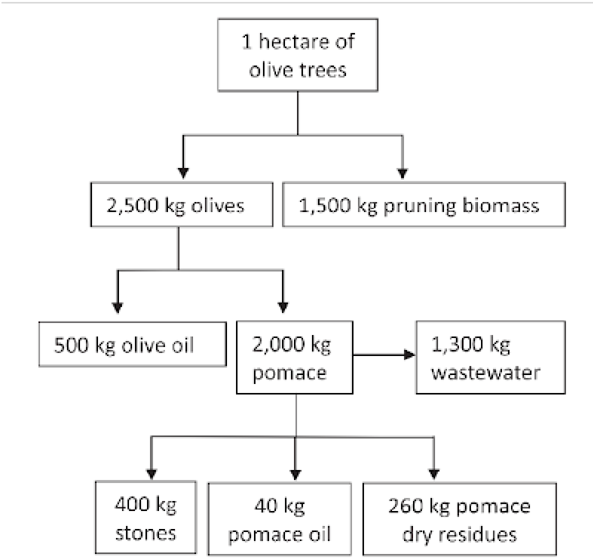

Figure 18: Mass balance of olive vale chain [73]

The quantity of olive oil produced in EU-28 as reported in the FAOSTAT database, along with the calculated olive stones and pomace dry residues are gathered on Table 54. The conversion of dry residual pomace to the fresh pomace generated is based on the consideration of moisture content equal to 27.5%, as the mean value for 25-30% [72].

Table 54: Amount of olive oil production, pomace and kernels derived from olive oil industry

Year	Olive oil production (in kt)	Pomace dry residue (in kt)	Pomace (in kt)	Olive stones (in kt)
2020	2,116.0	1,100.3	1,517.7	1,692.8
2019	1,924.4	1,000.7	1,380.3	1,539.5
2018	2,533.4	1,317.4	1,817.1	2,026.8
Mean value 2018-2020	**2,191.3**	**1,139.5**	**1,571.7**	**1,753.0**

4.4.4.2 Traded biological feedstocks

The quantities of the traded commodities in the EU are retrieved from the WITS database. After a thorough screening of the database, the product codes that align with the investigated flows of the agrifood sector are cited on Table 55.

Table 55: HS codes and description of traded secondary agricultural feedstocks (as reported in WITS)

HS code	Product description	Information
121300	Cereal straw and husks; unprepared, whether or not chopped, ground, pressed or in the form of pellets	There is available information about the imports and exports for each EU-28 country, focusing on years 2019-2021
121230	Apricot, peach or plum stones and kernels; of a kind used primarily for human consumption	No imported or exported quantities are reported in EU countries

Focusing on cereal straw, (Harmonized System Code (HS) 121300) traded flows, there is available data provided for every country within the defined system boundaries. The Harmonized System is a standardized numerical method of classifying traded products. On Table 56, the imported and exported quantities between the EU-28 countries and the rest of the world are depicted (excluding the trade quantities reported among EU-28 countries). Substantial fluctuations are observed between the different years, and thus a mean value from 2018-2021 is considered (the quantities reported for 2019 are not available).

Table 56: Imports and exports of cereal straw and husks (HS 121300) for EU-28 (WITS, 2023)

	2018	2020	2021	Mean value (excluding 2019)
EU-28 imports (in t)	11,414	7,741	4,024	7,726
EU-28 exports (in t)	529,042	642,327	712,797	628,055

With regard to "Apricot, peach or plum stones and kernels" (HS 121230) category, it is noted that there are not any trade volumes reported entering or exiting EU-28.

4.4.4.3 Quantification of the destinations of biological feedstocks

4.4.4.3.1 Conventional uses

Feed: A very prevalent use of agricultural residues is their incorporation in animal nutrition. According to [61] and [4], it is estimated that 33% of the harvested residues are used for feed in the EU. The remaining quantities are either lost and discarded or utilized in bioenergy and biomaterials fields. In JRC's "Biomass production, supply, uses and flows in the European Union" [61] it is highlighted that due to large data gaps it is impossible to estimate and allocate precisely the quantities of agricultural residues to each valorisation pathway. By applying this ratio on the estimated residual quantities, the agricultural residues that are destined for feed applications are projected at 35,563 kt annually.

Energy: Another potential conventional use of agricultural residues is the generation of energy. In general, agricultural residues are a very attractive source of bioenergy generation since their production does not exacerbate the "land-use" conflict and therefore there is extensive research on the topic of residual biomass energy potential. In this context, a study conducted by Monforti et al. [260], deduced that the optimal sustainable collection of agricultural residues in the EU achieving soil carbon stock preservation, could correspond to 146,000 kt/year. Additionally, they estimate that this quantity could lead to energy generation equal to 55 Mtoe [260, 261].

In parallel, focusing on the current status of bioenergy in EU-28, a synopsis of the main key facts is presented, providing information concerning the biomass supply and the corresponding share to bioenergy mix [262]:

- Direct supply of woody biomass from forests and other wooded land contributed 32.5% (44 Mtoe). This category includes fellings, residues from fellings (tops, branches, bark, stumps) or landscape management residues (woody biomass from parks, gardens, tree rows, bushes).
- Indirect supply of wood contributed another 28.2% (38 Mtoe). This category comprises of residues from sawmilling, woodworking, furniture industry (bark, sawdust), by-products of the pulp and paper industry (black liquor, tall oil) or processed fuelwood, post-consumer recycled wood (recycled wood for energy generation, household waste wood).
- 27% (36 Mtoe) originated from agricultural biomass (equally from agricultural crops and agricultural by-products).
- Waste (municipal, industrial, etc.) make up the remaining 12.4% (17 Mtoe).

Therefore, by concluding that 18 Mtoe of bioenergy consumed in the EU derives from agricultural by-products, it is feasible to correlate the energy quantity to the quantity of agricultural by-products employed for its production by adopting the results described by Monforti et al. [260]. Proportionally, 18 Mtoe of agricultural by-products derived energy correspond to 18 x (146,000/55) = 47,782 kt of agricultural by-products per year destined to energy generation.

Despite the fact that agri-food-related by-products contain valuable compounds and present substantial potential for higher value applications, they are predominantly used in lower value destinations. More analytically, orange, apple, peach, grape and olive pulp are majorly used for animal feed [63]. Alternatively, the by-products are normally disposed in landfills, burned, or used in steam production [65]. In this vein, it is reported that 3% of the generated grape pomace is reused as animal feed [258]. This percentage is applied to the other sources of pomace as well. This assumption translates to the generation of an additional 230.19 kt of animal feed.

Similarly, the by-products from the agri-food industry are widely used for energy generation as a solid biofuel, especially for the covering of the unit's energy needs. The olive stones exhibit great potential as solid biofuel for combustion due to their favorable lower and higher heating values compared to other lignocellulosic materials. Consequently, olive kernels are massively utilized as biofuels, and more specifically it is documented that 99% of the generated olive kernels are currently used as solid biofuel for thermal power generation [263]. Also, it is assumed that 20% of peach kernels are headed for energy applications, since this utilization is not as widely established for this kind of by-product due to the necessity of introducing structural changes to adapt the stone burning furnaces [66]. The olive and peach kernels contribute to an additional 360.6 kt of biofuel feedstock.

4.4.4.3.2 Bio-based industry

The agricultural residues are currently used in bio-based industry applications, however on a small scale. The most significant products generated from this feedstock are biofertilizers, cosmeceuticals, biosurfactants and bio-solvents.

Biofertilizers: Agricultural by-products are an excellent basis to produce bio-based fertilizers. Regarding the official classification of fertilizers, the interest is placed on the bio-based category of fertilizers named "Animal or vegetable fertilizers, whether or not mixed together or chemically treated; fertilizers produced by the mixing or chemical treatment of animal or vegetable products" (HS code: 310100). The reported produced quantity in EU-27 for 2019 is 7.96 million tons [264]. It is noted that this category of fertilizers is the most relevant to the report, since the other categories (31.02-31.05) refer to mineral or chemical fertilizers (nitrogenous, phosphatic, potassic or mixed).

Biochemicals: The production volumes of bio-based chemicals are retrieved from the BioMAT database as presented in [61, 143]. The precise market quantities that correspond to the most significant bio-based chemicals are presented on Section 2.5.

Biorefinery database: To overcome the obstacle of data insufficiency, the "Chemical and material driven biorefineries in the EU" database is utilized as a foundation for estimations [201]. In this context, there is a distinct category in the database identifying the biorefineries that use agricultural secondary biomass as feedstock. The most important information regarding these facilities is briefly presented.

- Total number of biorefineries: 298 (TRL higher than 8)
- 223 biorefineries use agriculture as feedstock (90.7% primary biomass and 9.3% of secondary biomass)

Filter applied: Feedstock origin (residues from agriculture)

Number of facilities: 26 (some biorefineries produce multiple products and therefore are double counted). On Table 57, the number of facilities per product category is presented, as extracted from the database. Consequently, it is feasible to draw the share of facilities operating with agricultural residues to the total number of refineries that produce a specific product.

Table 57: Number of biorefinery facilities operating with agricultural residues and the share that they occupy for general product categories [201]

Product general category	Number of facilities operating with agricultural residues as feedstock	Number of total facilities (all possible feedstocks included)	% of facilities operating with agricultural residues
Chemicals	19	195	9.74
Others	12	138	8.70
Composites and fibers	4	95	4.21
Liquid biofuels	2	26	7.69

The products in more detail are displayed in Table 58 [201].

Table 58: Number of biorefinery facilities operating with agricultural residues and the share that they occupy for detailed product categories [201]

Product detailed	Number of facilities operating with agricultural residues as feedstock	Number of total facilities (all possible feedstocks included)	% of facilities operating with agricultural residues
Polymers	11	76	14.47
Building blocks	7	95	7.37
Cosmeceuticals	6	28	21.43

Product detailed	Number of facilities operating with agricultural residues as feedstock	Number of total facilities (all possible feedstocks included)	% of facilities operating with agricultural residues
Nutraceuticals	4	38	10.52
Pharmaceuticals	4	39	10.26
Composites	3	50	6.00
Fibers	2	72	2.78
Flavors and fragrances	2	19	10.53
Fuels	2	26	7.69
Organic fertilizers	2	8	25.00
Paints and coatings	2	23	8.70
Agrochemicals	1	10	10.00
Food	1	34	2.94
Heat	1	19	5.26
Lubricants	1	11	9.09
Power	1	22	4.55
Resins	1	21	4.76
Solvents	1	5	20.00
Surfactants	1	31	3.23

The product categories "Fuels", "Food", "Heat" and "Power" are excluded from the analysis as they do not align with the Project's objectives. The next step involves the data collection regarding the bio-based production volumes for the bio-products of interest in the EU. The volumes of the bio-based products are retrieved from the BioMAT disseminated data and official European Commission's and well-established Institutions' Reports [61, 264], in order to ensure the data credibility. Subsequently, the calculated percentages that describe the share of bio-based industry operating with agricultural residues are applied to each product category. Finally, since the estimated quantities refer to the bio-based industry's products, it is necessary to proceed to the conversion of the product to the industry's feedstock. To accomplish this, a conversion factor of 80% is applied. It is a reasonable value, adopted in similar research (such as [265]) that describes a typical efficiency in the context of an industrial plant. This estimation sufficiently delivers the scope of the current study. The final estimated quantities of agricultural residues as feedstocks for bio-based industry are presented on Table 59.

Table 59: Estimated quantities of agricultural residues used in bio-based industry

Product detailed	Bio-based production volume (in kt/y)	% of facilities operating with agricultural residues	Agricultural residues as feedstocks (kt/yr)
Polymers for plastics	780	14.47	141
Building blocks	230	7.37	21
Cosmeceuticals	2,199	21.43	589
Pharmaceuticals	695	10.26	89
Composites	410	6.00	31
Fibers	647	2.78	22
Flavors and fragrances	174	10.53	23
Organic fertilizers	7,960	25.00	2,488
Paints and coatings	724	8.70	79
Lubricants	291	9.09	33
Resins	432	4.76	26
Solvents	418	20.00	105
Surfactants	4,691	3.23	189

4.4.5 Balancing of total Material Flows and Stocks

The final step in completing the MFA is the execution of the mass balances for each stage so as to balance the supply and use of goods. The objective of this step is to close the gap and illustrate the estimated quantities of materials that either exit or enter the system without being reported. All the retrieved and estimated data about the quantities of the investigated value chain's flows are gathered in the Balance Sheet (Table 60), given in kt.

Table 60: Balance sheet of agricultural sector MFA (EU-28); Quantities in kt/yr^{db}, average values of the most recent three years with available data (cereals by-products generation: 2019-2021, imports/exports: 2018, 2020, 2021, fruit processing by-products generation: between 2018-2023)

Input			Output		
Harvested straw		**68,893**	**Feed**		35,793
	Wheat	38,570	**Energy**		48,143
	Barley	18,542	**Exports**		628
	Oats	2,448	**Bio-based industry**		3,836
	Triticale	3,672		Polymers for plastics	141
	Rye	3,363		Building blocks	21
	Soybeans	1,429		Cosmeceuticals	589
	Rice	870		Pharmaceuticals	89

Input			Output		
Harvested stems		**36,796**		Composites	31
	Maize	24,237		Fibers	22
	Sunflower	5,004		Flavors and fragrances	23
	Rapeseed	8,555		Organic fertilizers	2,488
Harvested prunings		**8,924**		Paints and coatings	79
	Olives	3123		Lubricants	33
	Grapes	4104		Resins	26
	Almonds	548		Solvents	105
	Apples	498		Surfactants	189
	Oranges	225			
	Peaches and nectarines	186			
	Cherries	111			
	Pears	130			
Recovered kernels		**1,803**			
	Peach	50			
	Olive	1,753			
Recovered pomace		**8,312**			
	Orange	492			
	Apple	743			
	Peach	154			
	Grape	5,350			
	Olive	1,572			
Imports		**8**			
Non-harvested residues		**374,072**			
Total biomass input		**125,736**	**Total biomass output**		**88,400**
Discarded biomass and unreported uses 37,336					

4.4.6 Presentation of the results

All the quantified flows are illustrated schematically on a Sankey diagram (Figure 19) that provides a detailed overview of the agriculture's secondary biomass value chain. The diagram enables the monitoring of biomass utilization and depicts the most important destinations.

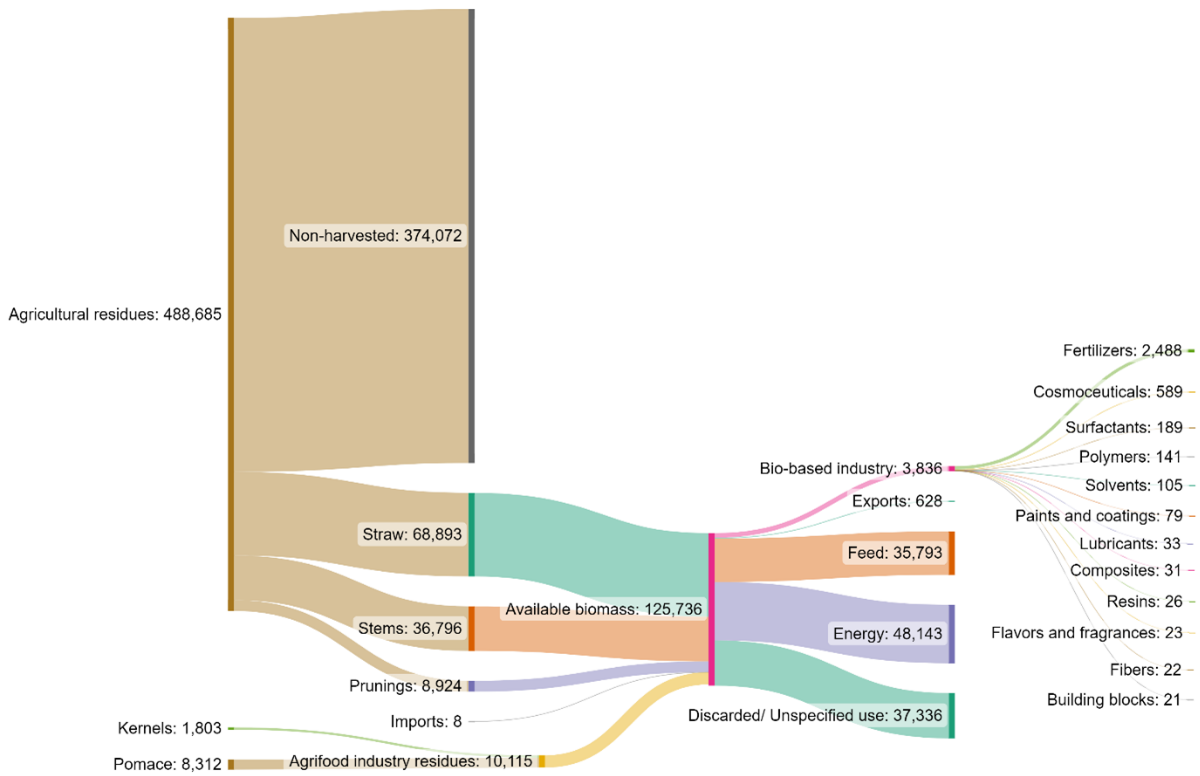

Figure 19: MFA Sankey diagram for agricultural biomass (EU-28); Quantities in kt/yr^{db}, average values of the most recent three years with available data (cereals by-products generation: 2019-2021, imports/exports: 2018, 2020, 2021, fruit processing by-products generation: between 2018-2023)

From the developed Sankey diagram for agriculture case study, it can be concluded that a small fraction of agriculture and food processing industry by-products are actually used in the bio-based sector for the formulation of high-value products. The vast majority of the residual biomass has an established market for feed and energy applications.

4.5 Case Study 4: Forestry sector

Forestry contributes substantially to European biomass resources. The analysis of the flows that describe woody biomass usage necessitates a thorough examination of the various value chains that connect the biomass generation sources to the conventional and bio-based applications. In the following Sections the system and methodology that has been applied for the quantification of the flows are analysed.

4.5.1 Goal and scope definition

Forestry industry is a crucial part of the EU's production and economy. More specifically, forestry-based industries can support the achievement of the objectives of EU industrial policy, by contributing to different strategic areas, such as increasing energy efficiency, utilizing renewable sources, bioeconomy, circular economy and natural carbon sinks [266]. To boost the circularity of the sector, it is important to monitor and measure the generated by-products and their current uses so as to identify gaps and opportunities. The by-products that will be analysed in CS4 are wood chips, sawdust, bark, fiber sludge and black liquor since they are generated in abundance and exhibit potential for valorisation. Currently, the aforementioned by-products are used mainly for energy production, while substantial recycling in the material industry also takes place.

4.5.2 System boundaries definition and assumptions

Forestry MFA focuses on the solid by-products generated from wood-processing industry and the liquid side streams of fiber sludge and black liquor that derive from pulp and paper mills. The quantification of flows is conducted in the boundaries of EU-28 on an annual basis. To define the specific system boundaries applied to CS4, the outline of the forestry value chain will be examined as illustrated in Figure 20.

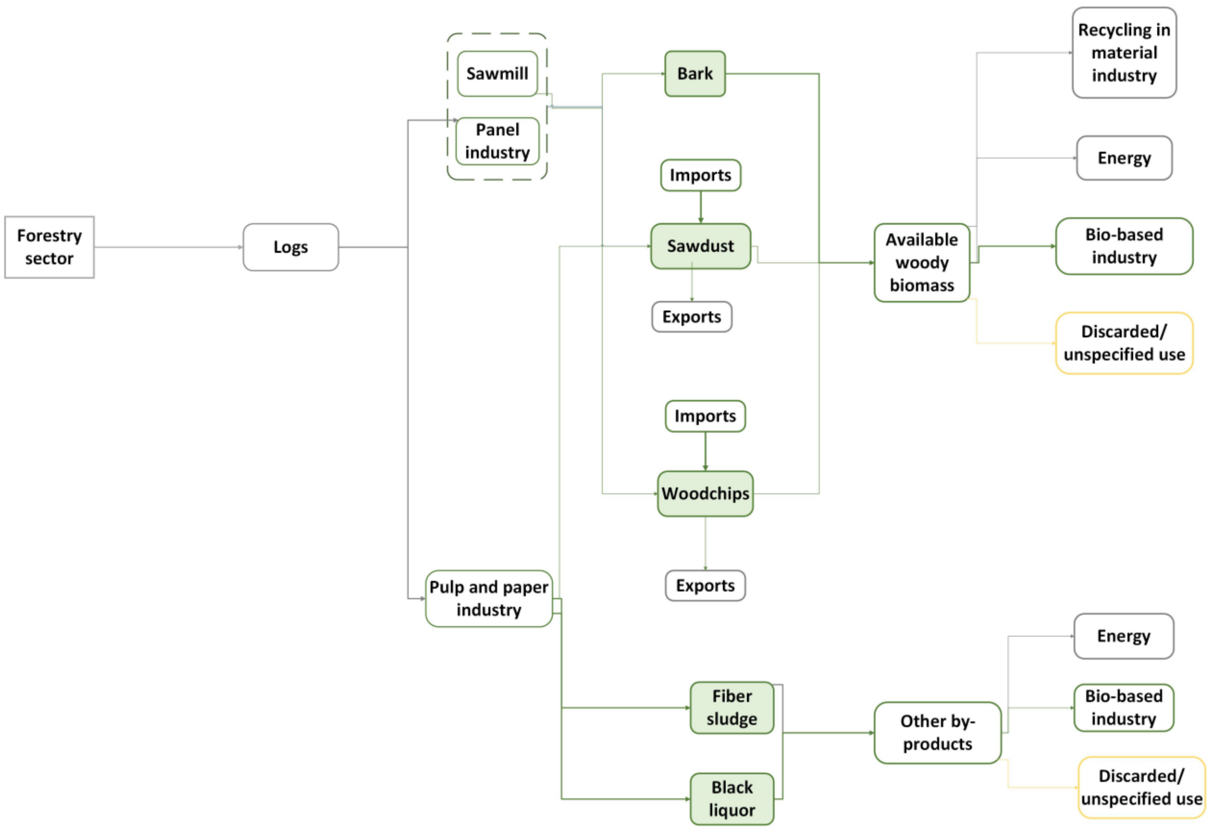

Figure 20: Outline of forestry case study value chain

4.5.3 Identification of relevant Flows, Stocks and Concentrations

The forest-based economy is quite complex since there are numerous interconnections, synergies and competition between the different sub-sectors. Wood constitutes a resource that is vastly reused, there is established utilization of the by-products and significant quantities of post-consumer wood are recovered, jointly achieving multiple re-integrations of wood fibers in the value chain. The emphasis of the current analysis is placed on secondary woody biomass, which comprises all the woody biomass resulting from a previous processing in at least one industry. It includes solid by-products, like wood chips and particles, sawdust bark and other by-products, like black liquor and fiber sludge.

In this sense, it is purposeful to display some characteristic paradigms of the reutilization of secondary biomass in the context of wood-based industry. Secondary woody biomass is widely used in the manufacturing of wood-based commodities and energy generation. Sawmilling is an illustrative example, as it produces by-products that are collected and utilized as raw material for wood pulp and wood-based panels manufacturing as well as for energy production. Also, side streams from chemical pulping are destined to the chemical industry and for energy production as well [198].

4.5.4 Determination of Mass Flows, Stocks, and Concentrations

The quantification of the flows of interest is analytically described in the following Subsections. First, the feedstock flows are determined based on data mining of established databases and combination of the acquired data. With regard to biomass fate, the main destination that aligns with BioReCer's scope is the bio-based industry. However, further insight is given on energy uses and by-product recycling in the material industry.

4.5.4.1 Quantification of the identified feedstock flows

To begin with, it is important to mention and briefly analyse the main data sources for the forestry sector.

The **FAOSTAT database** provides information retrieved from the Joint Questionnaire of Forest Sector (JFSQ), which is the collaborative initiative of FAO, Eurostat, International Tropical Timber Organization (ITTO) and the United Nations Economic Commission for Europe (UNECE), under the coordination of the inter-secretariat Working Group on Forest Sector Statistics. The research aims at the collection of data regarding the world timber status, reporting specific quantities about removals, production and trade of forestry-related products. In this context, it is worth mentioning that Eurostat is responsible for the compilation of information of EU countries. In all JFSQ releases, the dataset includes data obtained from sources beyond the official replies to questionnaires and estimates made by official agencies.

The **Wood Resource Balance (WRB) sheets** have been developed by JRC so as to provide an overview of sources and uses of woody biomass while it also highlights data gaps and inconsistencies. This insightful research includes balance tables for woody biomass for all the EU28 countries for the years from 2009 to 2017 [267]. The analysis is based on information retrieved from JFSQ for the primary woody biomass sources and the production of wood-based commodities. As for energy-related uses of woody biomass, data is sourced mainly from the Joint Wood Energy Enquiry (JWEE) which is an international survey collecting national statistics on wood energy sources and uses in UNECE countries [198]. Complementarily, information about energy uses is collected from National Renewable Energy Action Plans (NREAP) progress reports submitted by each member country.

Additionally, the indispensable conversion factors and input/output coefficients for the processing of the retrieved data are sourced from the recently updated study "Forest Product Conversion Factors" conducted by FAO, ITTO and UNECE [268]. The conversion factors provided include a broad spectrum of ratios used in the wood-based forest, manufacturing, and energy sectors. Also, the report includes coefficients and resource balances that provide insight on the input and output quantities of the wood-processing industries [268].

Another important aspect is the homogenization of the flows' units. The various sources report data in different units and therefore it is imperative to convert this information to a uniform unit. It is decided to utilize "ton of dry matter" as the unit of the analysis, especially since the MFA includes by-products that are normally liquid (e.g., fiber sludge and black liquor).

The FAOSTAT database provides quantitative information regarding by-products of the wood-processing industry. The items that fall in this category are [269]:

- **Wood chips and particles:** Wood, which has been deliberately reduced to chips (flat, rigid and roughly squared), particles (thin and flexible), flakes, etc. from wood in the rough, processing residues or recovered wood products and has not been agglomerated. Wood chips and particles are used for producing cellulose pulp by mechanical means, by chemical means or by combining mechanical and chemical means, for the manufacture of fiberboard or particle board, for energy or for other purposes. The specification of the chips and particles may vary in respect to dimensions and quality according to location and end-use. The pieces are in forms ranging from flat, rigid, and roughly squared chips down to small, thin flexible particles.

- **Wood residues**: Other wood processing co-products that have not been reduced to chips or particles and have not been agglomerated. These residues may often serve as raw material for the manufacture of certain forest products, notably pulp, particle board and fiberboard and may always be used as a source of energy. The category of wood residues includes solid wood processing residues, sawdust, shavings, and bark removed under processing.

The quantities of the aforementioned categories are displayed on Table 61, as retrieved from the FAOSTAT database.

Table 61: Quantities of wood chips and particles and wood residues produced in EU-28 (FAOSTAT database)

	2019	2020	2021	Mean value
Wood chips and particles (m^3)	68,469,524	65,560,231	71,599,146	68,542,967
Wood residues (m^3)	48,489,692	47,921,313	51,695,062	49,368,689

According to the "Wood residues" definition, bark and sawdust are the main constituents of this category. It is of great interest to define the exact quantities of each separate material.

A conversion factor proposed by FAO, ITTO & UNECE study to estimate bark volume is that the industrially recovered bark amounts to 80 kg (with moisture) per 1 m^3 of roundwood measured underbark (i.e., excluding bark). FAO statistics provide roundwood underbark volumes [268]. In 2019-2021, the reported industrial roundwood (mean value) in EU28 amounted to 389,416,531 m^3. By applying the conversion factor, the bark produced is estimated at 31,153,322 m^3. Subsequently, the aforementioned study provides an additional conversion factor, in the context of a material balance applied in the wood processing industry. More specifically, it is suggested that sawdust and sanding correspond to 10% of roundwood that is supplied to sawmill plants. According to FAOSTAT, 228,936,321 m^3 of sawlogs are supplied to sawmills in EU-28 for 2019-2021 (mean value).

Therefore, sawdust estimated quantity is 22,893,632 m^3. The aforementioned data, along with their conversion to dry mass units is displayed on Table 62.

Table 62: Estimated quantities of wood chips, sawdust and bark produced in EU-28; Reference years: 2019-2021

Flow	Quantity in m^3	Quantity in kt/yr^{db}
Wood chips	68,542,967	26,046
Sawdust	22,893,632	4,808
Bark	31,153,322	14,736

The density of wood chips is equal to 380 kg/m^3, as a reported average value for 0% moisture content [270]. Additionally, bark density for over dried biomass is 473 kg/m^3 [271]. With regard to sawdust, a typical density value is 210 kg/m^3 [272].

Additionally, some other residual streams are detected in the pulp and paper industry. Apart from the wood residues (wood chips, sawdust, and bark) that derive from wood-processing stages, the mill sludge is an organic residual stream generated from wastewater treatments of the pulp and paper mills [111]. It is highlighted that the amount of wood residues related to pulp and paper mills is included in the categories "Wood chips and particles" and "Wood residues" that have been analyzed and presented above.

Focusing on fiber sludge, it is estimated that 4.3-40 kg (dry weight) of sludge can be generated for every ton of board and paper produced [113]. For the MFA calculations, the mean value of 22.15 kg (db) of sludge per ton of board and paper produced will be adopted. The data concerning the productivity of the pulp and paper industry is derived from the FAOSTAT database. The retrieved and calculated quantities of paper, board and fiber sludge are presented on Table 63.

Table 63: Production of paper, board and mill sludge in EU; FAOSTAT database

	2019	2020	2021	Mean value
Paper and board in EU-28 (in kt)	89,945	85,938	90,910	88,932
Sludge production from pulp and paper mills (in kt^{db})	1,970			

Also, black liquor is an important side stream of a pulp and paper mill. More specifically, a pulp mill that produces bleached kraft pulp generates 1.7-1.8 tons of black liquor (measured as dry content) per tonne of pulp [273, 274]. Currently, the Kraft process is the predominant method for producing pulp, implemented in approximately 90% of all pulp mills, as it exhibits advantages over other pulping methods [275]. The black liquor quantity is calculated for the mills that apply Kraft processing. The pulp production data is derived from the Confederation of European Paper Industries (CEPI). CEPI is the pan-European association representing the forest fiber and paper industry. CEPI disseminates reports that cover European pulp and paper production, consumption, and trade, as well as data on raw materials use and industry structure. It is worth noting that CEPI represents 91% of the European pulp and paper industry in terms of production. The chemical wood pulp production and estimated black liquor generated are shown on Table 64.

Table 64: Production of pulp and black liquor in EU-28; FAOSTAT database

	2020	2021	2022	Mean value
Chemical wood pulp production (in kt)	27,335	27,008	28,281	27,541
Black liquor production from pulp and paper mills (in kt^{db})	48,197			

4.5.4.2 Quantification of traded flows

The quantities of the traded flows are retrieved from the WITS database. The product codes that are relevant to the investigated feedstocks, along with their reported imports and exports are demonstrated on Table 65 and Table 66 respectively.

Table 65: Imported quantities of forestry flows in EU (WITS database)

	Imported quantities (in kt)			
Product	2019	2020	2021	Mean value
Wood; in chips or particles, coniferous (HS 440121)	5,146	5,126	3,941	4,738
Wood; in chips or particles, non-coniferous (HS 440122)	2,399	1,642	2,310	2,117
Wood; sawdust, waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms (HS 440130)		7,105	7,700	7,402

Table 66: Exported quantities of forestry flows in EU (WITS database)

Product	Exported quantities (in kt)			
	2019	2020	2021	Mean value
Wood; in chips or particles, coniferous (HS 440121)	424	328	375	376
Wood; in chips or particles, non-coniferous (HS 440122)	122	130	125	126
Wood; sawdust, waste and scrap, whether or not agglomerated in logs, briquettes, pellets or similar forms (HS 440130)		2,932	1,661	2,296

4.5.4.3 Quantification of the destinations of biological feedstocks

4.5.4.3.1 Conventional uses

Energy: Biomass derived from the forestry sector is the main pillar of bioenergy in the EU. Noteworthily, forestry accounts for more than 60% of all EU domestic biomass supplied for energy purposes. In 2016, direct supply of woody biomass from forests and other wooded land contributed 32.5% (providing 44 Mtoe), and indirect supply of wood contributed another 28.2% (38 Mtoe) [262].

The "Wood Resource Balances of European Union" study conducted by JRC is used as a basis for information retrieval regarding the allocation of wood resources in the energy generation field. WRB offers credible data derived from official sources and applied to EU28, shedding light on the percentage of direct and indirect wood resources in material and energy sectors. This piece of information is demonstrated on Table 67, for the most recent years available, namely 2015-2017. The specific shares of direct, indirect and unreported wood consumption in energy production based on JRC's WRB can be accessed at European Commission Bioeconomy Knowledge Centre web portal: https://knowledge4policy.ec.europa.eu/publication/wood-resource-balances.

To elaborate on the data provided, the following definitions are provided [199]:

- **Direct wood** is defined as: "any wood fibre entering energy production without any further treatment or conversion. It comprises removals from forests and outside".
- **Indirect wood** is defined as: "Processed and unprocessed byproducts (residues) from the wood processing, solid (sawdust, chips, slabs, etc.) or liquid from the pulp industry (black liquor or tall oil). Processed wood fuels with improved energy content per bulk volume (compressed), such as wood pellets, briquettes but also

wood charcoal are also mainly included under indirect supply. Moreover, it includes post-consumer wood".

Table 67: Share of direct, indirect, and unreported wood consumption in energy generation for EU-28

	2015	2016	2017	Mean value
Direct wood (%)	42.2	42	42.9	42.37
Indirect wood (%)	50.4	50.6	49.6	50.20
Unreported wood (%)	7.4	7.4	7.6	7.47

It is worth mentioning that the fluctuations in the percentages reported over the years are negligible (ranging from -2.0 to 2.6%). Thus, it is acceptable to extract the mean value of the WBR data and use it for the current analysis.

The extracted percentages of Table 67 are applied to the most recent data provided by the FAOSTAT database. In this sense, it is necessary to provide thorough clarifications for the definition of the items. According to FAO's publication "Classification of Forest Products", **wood fuel** (including wood for charcoal) is defined as "Roundwood that will be used as fuel for purposes such as cooking, heating or power production. It includes wood harvested from main stems, branches, and other parts of trees (where these are harvested for fuel), round or split, and wood that will be used for the production of charcoal (e.g., in pit kilns or portable ovens), wood pellets and other agglomerates. It also includes wood chips to be used for fuel that are made directly (i.e., in the forest) from roundwood" [269].

Therefore, it can be deduced that wood fuel as described by FAO corresponds fully to WRB's definition of direct wood. On the other hand, indirect wood includes various products. To eliminate the quantity of indirect wood to the feedstocks of interest (wood chips and residual wood), it is important to quantify the other streams, namely wood pellets, briquettes, wood charcoal, black liquor, and post-consumer wood. The results of data collection from the FAOSTAT database for wood fuel, wood briquettes and other agglomerates, wood pellets and wood charcoal production quantities in EU-28 are reported on Table 68.

Table 68: Statistical data about the generated quantities of wood fuel, wood briquettes, wood pellets, wood charcoal and post-consumer wood (FAOSTAT database)

	2019	2020	2021	Mean value	Conversion to (kt), where applicable
Wood fuel (m^3)	124,182,364	122,280,215	126,472,171	124,311,583	87,018
Wood briquettes and other Agglomerates (kt)	2,123	1,595	2,170	1,963	
Wood pellets (kt)	19,298	19,393	20,020	19,570	
Wood charcoal (kt)	278	342	364	328	
Post-consumer wood (kt)	28,004	29,074	29,732	28,937	

Consequently, given that 42.37% of wood consumption for energy generation derives from direct wood (Table 67) and by considering that 87,018 kt of direct wood (wood fuel) is consumed (conversion to mass based on wood fuel density equal to 0.7 t/m^3 oven dried) [276] it can be deduced that: 87,018/0.4237 = 205,377 kt of wood is totally destined to energy generation. Therefore, based on Table 67, the indirect wood quantities (50.20% of the total wood) are equal to 103,100 kt.

Additionally, the reported quantities of the recorded streams cited in WRB's definition of indirect wood (namely wood briquettes, pellets, charcoal, post-consumer wood and black liquor) are summed resulting in 79,707 kt of wood dry mass. For this calculation, it was assumed that 50% of the recovered post-consumer wood and 90% of the generated black liquor are used for energy generation (reasonable ratio since black liquor is predominantly used for energy production and especially for combustion [275]). Therefore, according to "Indirect wood" definition, the remaining 103,100-79,707=23,393 kt derive from the utilization of wood industry by-products.

4.5.4.3.2 Recycling in material industry

The MFA study is a means to reflect and measure the circularity of a system. Therefore, it is critical, in the frame of the analysis, to include the streams of residual biomass that are recycled in the traditional material industry. According to JRC value chain study [61] and the definitions about wood residues and wood chips provided by FAO [268], the most notable and appropriate destinations for the use of wood by-products are the manufacturing of particle boards and paper pulp and thus, these streams need to be quantified.

Recycling in panel industry: To maximize the precision of information, the publications of the European Panel Federation (EPF) are explored. The EPF has 30 European countries as members and acts as a contact point for all producers of particleboard and other products and constitutes an information hub that provides information about the wood-panel industry through detailed reports. In this context, it is reported that the raw wood consumption by the European wood-based panel industry (specifically, particleboards, medium density panels (MDF), Oriented strand board (OSB), hard and soft boards) derives from [277]:

- 48% roundwood
- 31% industrial by-products
- 21% recovered roundwood

In addition, the data reporting the quantities of panels produced in EU-28 is demonstrated on Table 69.

Table 69: Particleboard production in EU28 (FAOSTAT database)

	2019	2020	2021	Mean value
Particleboard production[1] (m^3)	62,760,141	60,830,162	65,307,502	62,965,935
Conversion to kt[2]	41,171	39,905	42,842	41,306

[1] Particleboard includes: Plywood, Particle board, OSB, Hardboard, MDF/HDF, other fibreboard, [2] density equal to 0.656 t/m^3 [268]

Therefore, it is calculated that 12,804 kt of wood by-products are supplied to the panel industry yearly, by taking into account the fact that 31% of wood feedstock is supplied by by-products [277].

Recycling in pulp and paper industry: Pulp and paper industry constitutes another important pillar for the forestry sector. To elucidate the related value chains and flow quantities, the research focus was oriented to CEPI. According to CEPI's key statistics report updated for 2022 [278], wood chips occupied 22% of the total wood feedstock in pulp and paper industry, while the remaining 78% is provided by roundwood. Also, CEPI provides precise information regarding the wood chips that are supplied as feedstock to the pulp and paper industry. For 2022, the supply of wood chips to the pulp and paper industry amounted to 34,801,000 m^3. This amount equates to 13,224 kt^{db} of wood chips that are supplied to the pulp and paper industry yearly.

4.5.4.3.3 Bio-based industry

The problem of data scarcity concerning the bio-based industry is encountered in the forestry sector as well. The extensive report "Biomass production, supply, uses and flows in the European Union" conducted by JRC, mentions that statistical data on production quantities of innovative wood-based products in the EU are limited and scattered [61]. With regard to the wood-based by-products market, wood-based composites and bioplastics can be produced from wood-industry by-products. As for wood-based composites, it is reported that in Europe there are roughly 30 major producers in nine different countries. In 2018-2020, the annual production of wood-based composites was estimated at 470 kt. Wood-based composites can be made from wood flour, particles, chips, or solid wood mixed or coated with an adhesive, then recombined to create the desired product. Depending on the application of the composite product, the share of woody biomass can range from 50% to 75%. Wood-based bioplastics production amounted to 500 kt in Europe. [61].

To complement additional data, the Biorefineries database [262] is utilized for the forestry sector. It serves as a basis to draw representative and realistic estimations about the share of feedstocks in the bio-based industry. In this database, it is feasible to categorize the facilities according to the type of feedstock and the generated products. To elaborate, the number of biorefineries that produce a specific biobased product is identified and subsequently, a filter is applied limiting the number of biorefineries, counting only those that produce the target product from a specific raw material of interest (e.g., secondary forestry biomass). Then, the percentage of the biorefineries that use the feedstock of interest and produce a specific product to the total number of biorefineries that generate this product is calculated. This percentage is subsequently applied to the total amount of each bio-product category to calculate the exact quantities of products.

In this case, the biomass feedstock of interest is the forestry residues (secondary forestry biomass). For this specific category, the following information can be extracted:

- Total number of biorefineries: 298 (TRL higher than 8)

- 223 biorefineries use forestry as feedstock (57.1% primary biomass and 42.9% of secondary biomass)

Filter applied: Feedstock origin (residues from forestry)
Number of facilities: 39 (some biorefineries produce multiple products and therefore are double counted)

In Table 70, the number of facilities per product category is presented, as extracted from the database. Therefore, the share of facilities operating with forestry residues to the total number of refineries that produce a specific product is identified.

Table 70: Number of biorefinery facilities operating with forestry residues and the share that they occupy for general product categories [201]

Product general category	Number of facilities operating with forestry residues as feedstock	Number of total facilities (all possible feedstocks included)	% of facilities operating with forestry residues
Chemicals	29	195	14.87
Others	21	138	15.21
Composites and fibers	17	95	17.89
Liquid biofuels	5	26	19.23

More meticulous data is provided on Table 71.

Table 71: Number of biorefinery facilities operating with forestry residues and the share that they occupy for detailed product categories [201]

Product detailed	Number of facilities operating with forestry residues as feedstock	Number of total facilities (all possible feedstocks included)	% of facilities operating with forestry residues
Polymers	17	76	22.37
Building blocks	12	95	12.63
Cosmeceuticals	2	28	7.14
Nutraceuticals	3	38	7.89
Pharmaceuticals	6	39	15.38
Composites	9	50	18.00
Fibers	13	72	18.06
Flavors and fragrances	4	19	21.05
Fuels	5	26	19.23
Paints and coatings	5	23	21.74

Product detailed	Number of facilities operating with forestry residues as feedstock	Number of total facilities (all possible feedstocks included)	% of facilities operating with forestry residues
Agrochemicals	3	10	30.00
Food	2	34	5.88
Heat	7	19	36.84
Power	7	22	31.82
Resins	6	21	28.57
Surfactants	2	31	6.45

The product categories "Fuels", "Food", "Heat" and "Power" are excluded from the analysis since these types of products are out of the scope of the BioReCer Project. To estimate the quantities of forestry residues that are supplied for the production of the bio-based products, the percentages of Table 71 are applied to the production volume of each bio-based product in the EU. The bio-based production volumes in the EU are analysed in Section 2.5. Then, the conversion factor of 80% is considered as a typical value for processing of lignocellulosic biomass, and is implemented to calculate the raw material that is utilized to produce each bio-based product [265]. The final results are presented on Table 72. It is noted that for bio-composites and bioplastics, specific data tailored for forestry residues has been retrieved and thus these quantities will be used in the Balance Sheet (Table 73) [61].

Table 72: Estimated quantities of agricultural residues used in bio-based industry

Product detailed	Bio-based production volume (in kt/yr)	% of facilities operating with forestry residues	Forestry residues as feedstocks (kt/yr)
Building blocks	230	12.63	36.3
Cosmeceuticals	2,199	7.14	196.3
Pharmaceuticals	695	15.38	133.6
Fibers	647	18.06	146.1
Flavors and fragrances	174	21.05	45.8
Paints and coatings	724	21.74	196.8
Agrochemicals	7,747	30.00	2,905.1
Resins	432	28.57	154.3
Surfactants	4,691	6.45	378.2

It is noted that the "Forestry residues as feedstocks" on Table 72 are given on fresh matter. To convert these amounts to dry matter, a moisture content of 45% was assumed for the feedstocks [279].

4.5.5 Balancing of total Material Flows and Stocks

The focus is placed on the illustration of the status of the bio-based uses that are currently employed in the EU. In this sense, it is purposeful to quantify the conventional uses as well (e.g., energy), however not in detail. Finally, the mass balances are executed for each major stage of the value chain to estimate the quantities that are subject to unreported uses or are simply discarded. All the indispensable information required for the construction of the Sankey diagram is accumulated on the Balance Sheet illustrated on Table 73. All the data is converted to kt^{db}.

Table 73: Balance sheet of forestry sector MFA (EU-28); Quantities in kt/yr^{db}, average values of the most recent three years with available data (2019-2021, except for the production of pulp liquor (2020-2022) and the quantity destined to energy purposes (2015-2017))

Input			Output		
Available woody biomass		**52,738**	**Recycling to panel industry**		**12,804**
	Bark	14,736	**Recycling to pulp and paper industry**		**13,224**
	Wood chips	26,046	**Energy**		**66,771**
	Sawdust	4,808		Woody biomass	23,393
	Sawdust imports	4,071		Pulp and paper other streams	43,377
	Wood chips imports	3,770	**Wood chips exports**		**276**
Pulp and paper other streams		**50,167**	**Sawdust exports**		**1,263**
	Fiber sludge	1,970	**Bio-based industry**		**2,839**
	Black liquor	48,197		Composites	259
				Plastics	275
				Cosmeceuticals	108
				Pharmaceuticals	73
				Fibers	80
				Flavors and fragrances	25
				Paints and coatings	108

Input		Output		
			Agrochemicals	1,598
			Resins	85
			Surfactants	208
			Building blocks	20
Total inputs	**102,905**	**Total outputs**		**97,176**
Discarded biomass and unreported uses				
5,729				

4.5.6 Presentation of the results

The most efficient visualization of the results is achieved by constructing the Sankey diagrams that are tailored for the value chains of the agricultural sector. The forestry case study Sankey diagram is depicted on Figure 21.

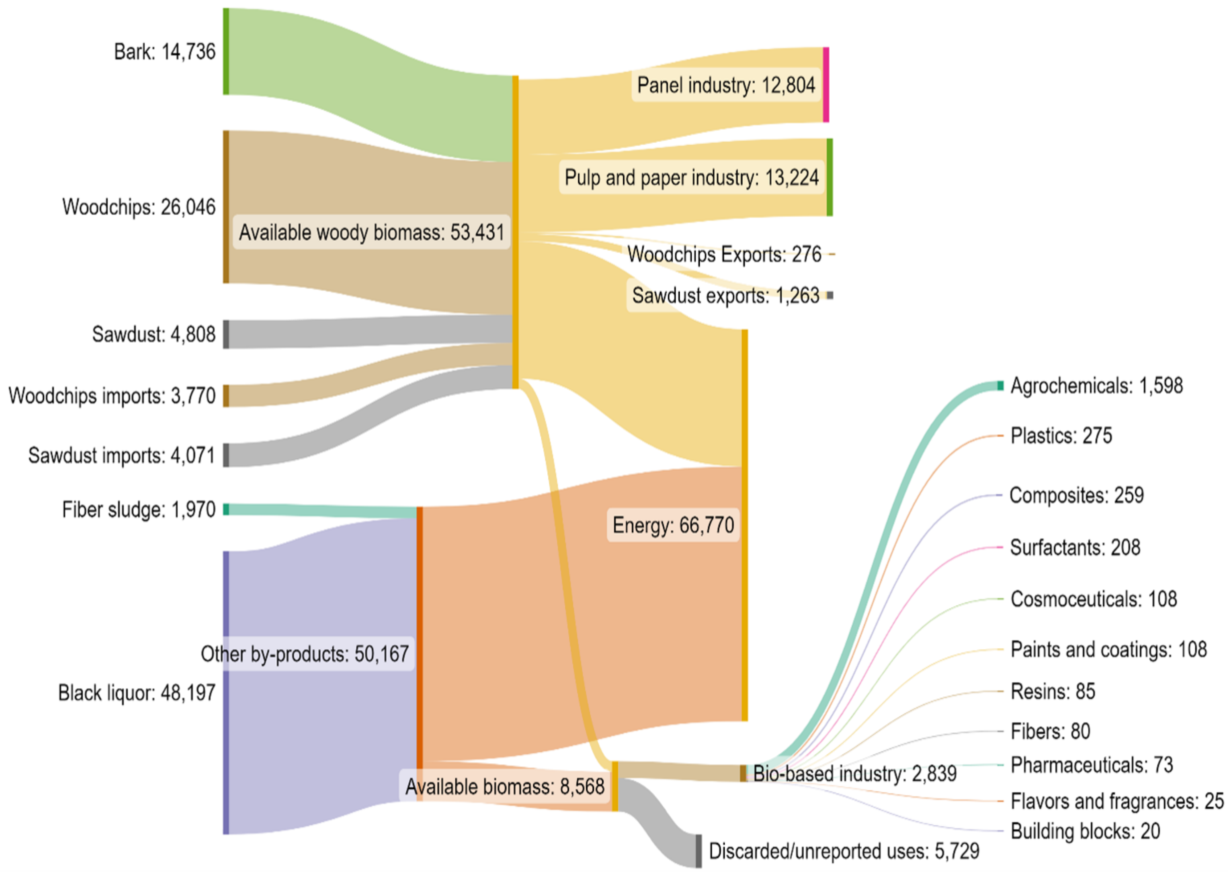

Figure 21: MFA Sankey diagram for forestry biomass (EU-28); Quantities in kt/yr^{db}, average values of the most recent three years with available data (2019-2021, except for the production of pulp liquor (2020-2022) and the quantity destined to energy purposes (2015-2017))

From the assessment of the forestry case study Sankey diagram, it is evident that forestry-related biomass is majorly used for energy generation. Also, substantial quantities are destined for recycling in the panel and pulp and paper industry. The amount of forestry by-products that is supplied to bio-based industry is relatively small compared to other conventional uses. However, there is considerable potential in the expansion of the forest bio-based industry since forestry by-products are generated in large amounts from specific industries and exhibit many beneficial compounds and properties that favour their valorisation.

5 Conclusions

The transition to a bio-based economy, i.e., the sustainable use of renewable biological feedstocks in place of the fossil-based feedstocks, is expected to deliver significant benefits for the economic growth, environmental protection and social development in Europe. There are challenges to solve in order to make more biobased feedstock available for new industry. The situation is different for different types of biological material. BFS, even though rich in valuable compounds, are characterized by high spatial distribution of available resources, seasonal production, variability on critical physicochemical properties, short storing time etc. Therefore, the development of sustainable value chains of biological feedstocks is a challenging prerequisite for the transition to a circular, sustainable bio-based economy.

Towards this goal, Material Flow Analysis was developed, for mapping the current European (EU-27 and/or EU-28) biological feedstocks by identifying their source, their trade, and their fate. MFA is a methodological approach to quantify flows and stocks of materials or substances in a system, which can be an industrial plant, a sector, or a region. MFA can be used to track the sources, uses, and destinations of materials or substances, and to identify potential improvements in resource efficiency, waste reduction, or circular economy. In D2.1 a general comprehensive methodology for carrying out a MFA of the main biological feedstocks that can be used by bio-based value chains was presented.

This methodology was implemented for the estimation of biological feedstock flows of four Case Studies, i.e., the by-products originating from the (i) fisheries, (ii) waste from urban/industrial activities, (iii) agricultural as well as (iv) forestry sectors. MFA was performed to the main primary biomass resources and biological secondary raw materials flow in the bio-based value chains to identify their source (e.g., imports or domestic production), their trade flows, geographic distributions, and fate (e.g., stocks, waste, and processed output). MFA was based on data and databases concerning primary sector activities and reliable estimations and assumptions where necessary. Sankey diagrams were developed enabling the visualization of the results.

First of all, an abundance of data was available concerning the generation of primary biomass in official European or international databases. In some cases, reliable conversion factors were used in order to determine the quantities of the produced secondary biomass. Furthermore, adequate data could be retrieved for the conventional uses of the investigated BFS. However, a lack of sufficient and consistent data was observed concerning the bio-based industry, especially with reference to residual biomass as feedstock. The current databases do not systematically cover this industrial domain. However, the recording of this data is a crucial step towards the monitoring and assessment of the bio-based industry's status and potential.

The MFA of the investigated bio-based sectors sheds light on the mapping and current status of utilization of secondary biomass feedstocks in the EU. It is a useful tool that contributes to the assessment of the circularity of the bio-based secondary resources. The analysis offers an illustration of the gaps, tendencies and opportunities detected in the bio-based sector so as to support its expansion and robustness.

Fisheries production has been increasing in recent years. The production of waste in the fishing industry amounts to ~24% of the available fisheries biomass, while ~20% of the total fisheries is used for the production fishmeal and fish oil, while the amount of fishmeal and fish oil originating from FB is constantly increasing. Fishmeal and fish oil are mainly used in aquaculture and animal husbandry and are directly used for human consumption. Only a small fraction (~6%) is destined to other/unspecified uses. These destinations may be pet feed, nutraceuticals, and carrier for pesticides, in paints and in leather production. Fisheries waste is mainly treated conventionally through disposal and anaerobic digestion, while ~24% is valorised in composting. Even though fisheries waste consists of valuable compounds, such as proteins, lipids, collagen and fat-soluble vitamins, inadequate data exist on their valorisation in the bio-based industry. Many prospects have been indicated in the literature, but it seems that they have not yet reached commercialization or small initiatives exist, which have not been reported yet.

Concerning the waste from urban/industrial activities the OFMSW and sewage sludge were investigated. The OFMSW comprises 34% of the total MSW and it is mainly produced domestically in the EU, while 32% of the potentially generated bio-waste is separately collected in order to be managed sustainably. Currently ~54% of the generated OFMSW is treated with composting and anaerobic digestion, while ~44% is landfilled or incinerated (with or without energy recovery). It should be stressed that even though the management of MSW and bio-waste is well defined by the EU legislation, the valorisation of the OFMSW is considered limited, since only ~2% is destined to the bio-based sector. This may be attributed to limited reporting of the specific data or to the fact that these prospects have not reached commercialization yet. Consequently, even though the collected OFMSW are usually used for compost and energy recovery, there are prospects for the production of

products with greater value and it is believed that there is room for these applications, since a great amount of OFMSW is treated conventionally, as demonstrated by the MFA.
Sewage sludge is a BFS with high organic load and nutrient content. This is why a significant fraction of the available sewage sludge (~ 37%) is valorised in agriculture, while ~10% is used for compost and other applications. Incineration is also an important management option for sewage sludge (~25%), while landfilling is not preferred in the EU-28 (~8%). The amount destined to the bio-based industry still remains low (0.3%) with many prospects of development since many technologies are headed for commercialization. It should be noted that the management of sewage sludge is not well defined since the destination of ~17% is unknown (other and unspecified uses).

Agriculture and agro-industry are significant contributors to the available secondary biomass generated in the EU. The most prolific by-products are the agricultural residues generated during harvesting, namely straw, stems and stalks. It is estimated though that only ~22% of the total generated quantity is collected since this kind of residue is highly beneficial for soil enhancement purposes. Considerable quantities of waste are generated during food processing as well. The current study focused on the processing of important fruits and the relevant by-products. Agricultural residues in total are majorly used as animal feed (approximately 33% of the obtained quantities). Energy generation is also an important destination, with a slightly larger volume of by-products headed in this direction. The bio-based industry based on agricultural by-products is still relatively small compared to the bioprocessing of primary agricultural products. The most important bio-based products are organic fertilizers, cosmeceuticals, and surfactants. Constraints that hinder further development of higher-value valorisation practices were also recognized. Indicatively the spatial distribution renders logistics management complicated and high costs are incurred. The seasonality in residue production is an additional point of concern, while the large volumes and difficulties in storage deter the systematic valorisation of this feedstock.

With regard to the forestry sector and the wood industry, it is evident that annually substantial amounts of by-products are generated. The most important woody by-product is wood chips, followed by bark and sawdust. These residues correspond approximately to 39% of the total amount of industrial roundwood supplied to the wood industry. There is also an established market of wood by-product trade. Europe is a net importer of woody by-products which constitute approximately 25% of the available sawdust and wood chips available. The value of wood is widely recognized as reflected in the established pathways for its utilization and the substantial quantities of recovered post-consumer wood. According to the current study's estimations, 38% of available woody by-products are destined for energy generation, while approximately 50% is recycled as material for traditional wood industry (approximately 24% is used as raw material for panel production and 25% for pulp and paper industry). In the context of the pulp and paper industry, several other waste streams are produced, such as fiber sludge and black liquor which is generated in notably large quantities. Currently, it is reported that black liquor is mainly used for energy generation. Today only a small portion of the available forestry by-products proceeds for further valorisation in bio-based industries, corresponding to less than 3% of the totally generated by-products. The most important bio-products in terms of quantities are agrochemicals (including bio-fertilizers), bioplastics and biocomposites.

From an overall assessment of the present study, it can be deduced that the systematic management and valorisation of secondary biomass is still poorly developed in the EU. It is a common remark for all case studies that the integration of the residual biomass flows to higher value applications is proportionately low. A substantial volume of residues is reused, however in lower value applications, such as energy and soil enhancement/compost. A relatively larger amount of residual biomass re-enters the value chain in the case of forestry sector (compared to the other case studies) and mainly it is sent to traditional wood-processing industries (such as panel production and pulp and paper mills) with lower amounts being sent to biorefineries. Undoubtedly, there is room for expansion of residual biomass supply to the bio-based industry. There are still huge amounts that are discarded from the system or are majorly underutilized. The upcycling of residual biomass is an essentially beneficial practice since limited, conventional resources are substituted with biomass that does not exacerbate land conflict and in parallel waste disposal problems are alleviated.

Overall, D2.1 provides an overview of important biological feedstocks at a European and country level that will help illuminate the current status of biomass utilization. Throughout the course of the Project, further development and enrichment of the MFAs will be performed, tailored to the value chains and specific regions of BioReCer's case studies. In this regard, detailed information and additional date on the biomass flows of the case studies will be collected based (among other) to locally produced biomass data based on specific references from local stakeholders. These data will serve as a foundation for the description of BioReCer value chains and the detection of the extent of material utilization and the conversion factors, among other key outcomes. This piece of information is crucial for the analysis of the case studies and the demonstration of BIORECER tools at the four case studies. They will be also potentially highly interesting for involved stakeholders, actors of similar value chains (biomass producers, bio-based industries, consumers) and certification schemes owners. *These data will be presented in the following Deliverable D2.4 (due on M30), which is an update of the present D2.1, and which focuses on more detail on the detailed local (regional) MFA across the four BIORECER case studies.*

6 List of abbreviations

AD	Anaerobic Digestion
BAS	Biosolids Assurance Scheme
BFS	Biological Feedstocks
BIT	BioReCer ICT tool
BRSP	BioResources Stakeholders Platform
CAP	Common Agricultural Policy
CEPI	Confederation of European Paper Industries
CFP	Common Fisheries Policy
CS	Case Study
COD	Chemical Oxygen Demand
Dx.x	Deliverable x.x
DB	Dry basis
EFTA	European Free Trade Association
EPF	European Panel Federation
EU	European Union
EU-27	27 European Union countries
EU-28	28 European Union countries
EurEau	European federation of national associations of water services
FAO	Food and Agriculture Organization
FB	Fish By-products
FSC	Forest Stewardship Council
GHG	Greenhouse Gasses
GHS	Globally Harmonised System
HS	Harmonized System
HTC	Hydrothermal Carbonisation
HVO	Hydrotreated Vegetable Oils
ICT	Information and Communications Technology
ISCC	International Sustainability & Carbon Certification

ISO	International Organization for Standardization
ITTO	International Tropical Timber Organization
JFSQ	Joint Questionnaire of Forest Sector
JRC	Joint Research Centre
JWEE	Joint Wood Energy Enquiry
LCA	Life Cycle Analysis
LWE	Live Weight Equivalent
MDF	Medium density Panels
MFA	Material Flow Analysis
MFC	Multi-Fuel-Conversion
MSW	Municipal Solid Waste
NADH	Nicotinamide Adenine Dinucleotide
NIST	National Institute of Standards and Technology
NQAO	National Quality Assurance Organisations
NREAP	National Renewable Energy Action Plans
OECD	Organisation for Economic Co-operation and Development
OFMSW	Organic Fraction of Municipal Solid Waste
OSB	Oriented Strand Board
PAH	Polycyclic Aromatic Hydrocarbons
PCB	Polychlorinated Biphenyls
PEFC	Programme for the Endorsement of Forest Certification
PHA	Polyhydroxyalkanoates
PUFA	Polyunsaturated Fatty Acids
R&D	Research and Development
RDF	Refuse Derived Fuel
RPR	Residue-to-Product Ratio
RSB	Roundtable on Sustainable Biomaterials
RSR	Residue-to-Surface Ratio
SWE	Solid Wood Equivalent
TRL	Technology Readiness Levels

Tx.x	Task x.x
UNECE	United Nations Economic Commission for Europe
USA	United States of America
VFA	Volatile Fatty Acids
WITS	World Integrated Trade Solution
WP	Work Package
WRB	Wood Resource Balance
WS	Wheat Straw/Stems
WWTP	Wastewater Treatment Plants
ω-3	Omega-3

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Annex A: Information about the crops from which straw and stems are derived

Annex A includes information specializing on the crops from which straws and stems are derived (apart from wheat and maize which are described at Section 2.4.1.1).

Barley: Barley (*Hordeum vulgare L.*) is the fourth most widespread cereal in the world, with a total acreage of about 50 million hectares and a total grain production amounting to 150 million tons. Barley is one of the most versatile cereals, cultivated in different conditions ranging from high latitudes, dry temperature, or severe temperature fluctuations while it presents remarkable genetic evolution to drought. Barley grain's principal uses include animal feed and malt and beer industry, which is a field particularly significant from an economic point of view. On the contrary, only 2% of the grains are destined for human consumption [280, 281]. Barley straw (the leftover stems after the barley grains are harvested) is an abundant biomass in the regions producing barley for malting, feeds, and fuel ethanol. The by-products of barley grain processing are used as feed: brewer's grains, brewer's yeast, malt culms (barley sprouts and rootlets), barley distillers and soluble, hulls, bran, and barley feed (the by-product of pearl barley production).

Rice: Rice (*Oryza sativa L.*) is a staple for the nutrition of billions of people and its cultivation is particularly prevalent in Asia where 90% of the total rice quantity is produced, occupying 140 million hectares of land. The total amount of rice produced in 2019 amounted to 756 million tons. Rice can be cultivated in tropical, semitropical, and temperate regions and it is a characteristic water intensive crop. In Europe, rice cultivation is present in few counties and virtually all production volume derives from Italy, Spain, Greece, and Portugal. Rice straw (or paddy straw) is an abundant by-product cut at grain harvest or after. It is normally disposed on soil, utilized as mulch on fields to retain nitrogen content or incinerated in situ [282].

Oats: Oats (*Avena spp.*) belong to the grass family Poaceae and are mostly cultivated in cool climate. The world production of oats reached over 22 million tons in 2014. Oats have been commonly used as livestock feed. They are suitable as feed for dairy and beef cattle, horses, and sheep. They have also been gaining importance as human foods in light of the abovementioned bioactive components and health effects [283]. Oat straw is the green, unripe part of the plant, both leaves and stems, and is sold as Avena sativa, green oats or wild oat extract. It is accessible in health food stores and on the Internet as a powder, juice, tincture or as a tea. The nutritive properties of oats and oat straw are not very different, except that oat straw is lower in calories and higher in Vitamin A (carotenes) and Vitamin C, than the grain alone. Oat straw is one of the best anti-osteoporosis herbs – the others are alfalfa, horsetail, nettles, and red clover blossoms. Oats is rich in calcium and vitamins needed for building bones. Consistent use of oats and oat straw in the diet reduces cholesterol and improves circulatory function, helps to stabilize blood sugar levels, brings about noticeable improvement in coordination, bone density, balance, memory, sensitivity to pleasant stimuli, clarity of thinking and overall calmness and centeredness.

Rye: Rye (Secale cereale L.) is a winter-hardy annual or biennial grass. It is mostly grown for its grain, particularly in Europe and North America, in areas where climate and soil are unfavourable for other cereals, or as a winter crop where temperatures are too low for winter wheat. Rye is the only cereal grain other than wheat to have the necessary properties for bread making. In its main areas of production, such as Poland, rye grain is also used for feed, and more than 40% of the world production was used for animal feeding in 2016. Non-food part of rye is agro-waste which is about 15–20% of rye [284]. Due to its low soil and fertilization requirements and its good overwintering capacity, it can be cultivated in areas, which are not suited for other cereals. More than 90% of the world's rye is grown in the northern, central, and eastern parts of Europe. The use of especially wholemeal rye flour is of great interest because of its high dietary fibre and lysine (Lys) contents. Still, the rye world production in 2015/2016 was only about 12 million tons, which is about 0.5% of the total world cereal production. One reason is that the bread-making performance of refined rye flour is inferior to that of refined wheat flour [285].

Triticale: Triticale (*Triticosecale Wittmack*) is a hybrid crop developed by crossing wheat (Triticum sp.) and rye (Secale sp.). The global production of triticale amounted to 15.36 million tons in 2020 (FAO). Triticale cultivation requires lower amounts of water and fertilizers, presents better eco-physiological components of biomass in water stress, and a significantly higher yield of grain and protein compared to wheat and maize [286]. Although triticale is an excellent candidate for animal feed due to high protein, amino acid, polysaccharide, and B vitamin content, it has yet to be well-recognized for human food applications. Triticale harvesting is accompanied by a high production of straw, which is of direct interest to livestock farmers. This is likely because of the higher fibre content and lower energy content and protein. Furthermore, the uptake of nutrients by triticale is more efficient compared to nutrient uptake of wheat and other cereals, triticale is thus suited to cultivate on marginal lands. The grain protein content of triticale is, in general, similar compared to the grain protein content of wheat, rendering it a valuable alternative grain for inclusion in feed [287].

Rapessed: Rapeseed (Brassica napus) is grown on more than 3 million hectares in Europe, occupying more than 60% of the total area dedicated to oilseeds and rendering Europe a world leader in its cultivation, followed by Canada and China. Rapeseed is a significant source of oil and fat. Rapeseed oil production reached 24.5 million tons in 2019 (FAO). The extracted rapeseed oil is supplied to numerous sectors and especially in food and cosmetic industry due to its high vitamin and unsaturated fatty acid content, good flavour, and health benefits. Additionally, rapeseed oil is utilized as an independent fuel or as a diesel fuel additive [288, 289]. An important by-product of the manufacture of vegetable oils is pomace, or "oil cake" which corresponds to 60% of the weight of input seeds and is destined mainly for animal feed [289]. Rapeseed straw is generated after seed harvesting and is an abundant and inexpensive resource, potentially useful as a raw material for biofuels production.

Sunflower: Sunflower (Helianthus annuus) is an oilseed crop, widely cultivated for oil extraction and it is reported that 90% of sunflower seeds are headed for this purpose, representing the fourth source of oil in the world. Sunflower seed production reached 51.5 million tons in 2019, while sunflower oil production amounted to 18.4 million tons (FAO). However, the residues produced during harvesting such as heads, stalks and leaves remain unutilized and usually are incinerated. The utilization of sunflower residues is prevailingly linked to bioethanol production. However, sunflower residues could be also used as precursors for the extraction of cellulose based materials [290].

Annex B: Composition of secondary biomass related to the agrifood sector

In the following tables detailed compositional data of the secondary biomass related to the agrifood sector are presented.

Table B-1: Indicative composition of straw; range (mean value)

Parameter	Wheat	Barley	Oat	Rye	Soy bean	Rice	Ref.
Moisture (% wt)^{ar}	0.0-17 (9.3)	3.8-12 (9.2)	8.2	8.97	12 (stalks)	6.6-12 (8.3)	[85] Rye: [86] Soya: [87]
Ash (%wt)^{db}	1.3-22 (9.0)	2.2-11 (8.6)	2.6-7.8 (5.9)	1.2-10 (4.1)	6	12-22 (18.5)	[85]
Structural compounds							
Cellulose (%wt)^{db}	28-52 (6.3)	33-46 (41.2)	37	28-5 (36.9)	38-41 (39.5)	28-41 (35.7)	[85]
Hemicellulose (%wt)^{db}	11-39 (5.2)	22-26 (23.6)	24.9	11-28 (22.5)	16	22-27 (23.7)	[85]
Lignin (%wt)^{db}	8.0-30 (5.2)	15-23 (18)	15.4	2.0-20 (11.40)	16	9.9-21.6 (14.0)	[85]
Crude protein (%wt)^{db}	3.6-4.2 (3.9)	3.8	3.6	2.5-6.7 (4.1)	5.5 (just protein)	2.4-6.8 (4.2)	[88] Soya: [85]
Starch (%wt)^{db}	0.1-2.6 (1.0)	0.0-2.4 (1.2)	-	-	-	-	[88]
Total sugars (%wt)^{db}	0.3-5.7 (1.2)	-	-	-	-	-	[88]
Elemental analyses							
Carbon (%wt)^{db}	39-48 (42.6)	37-40 (41.6)	46-48 (47.0)	49-50 (49.2)	-	45-60 (49.8)	[85]

Parameter	Wheat	Barley	Oat	Rye	Soy bean	Rice	Ref.
Oxygen (%wt)^{db}	36-43 (40.4)	37-46 (41.5)	39-44 (41.1)	5.5-6.4 (6.1)	-	4.6-7.7 (6.0)	[85]
Hydrogen (%wt)^{db}	5.1-5.9 (5.5)	5.5-5.7 (5.6)	4.9-5.8 (5.35)	44-45 (44.1)	-	31-65 (45.6)	[85]
Nitrogen (%wt)^{db}	0.4-1.1 (0.7)	0.56-0.6 (0.58)	0.5-0.7 (0.63)	0.25-1.5 (0.6)	0.9	0.8-1.7	[85]
Sulfur (%wt)^{db}	0.1-0.3 (0.2)	0.01-0.08 (0.05)	0.08-0.11 (0.1)	0.04-0.12 (0.1)	-	0.08-0.23 (0.16)	[85]
Nutrients, minerals and metals							
Phosphorus (g/kg)^{db}	0.1-1.0 (0.6)	0.65-1.9 (1.17)	0.2-2.4 (1.2)	1.3	-	0.5-1.7 (0.9)	[88]
Potassium (g/kg)^{db}	9.8-22 (14.9)	12-14 (13.3)	10.4-18 (14.7)	12.2	-	11-25 (18.0)	[88]
Calcium (g/kg)^{db}	1.8-8.2 (4.7)	1.9-4.6 (3.2)	1-3.3 (2.5)	4.1	-	1.7-4.4 (2.9)	[88]
Magnesium (g/kg)^{db}	0.4-3.4 (1.5)	0.77-1.7 (1.23)	0.7-1.5 (1.1)	1.4	-	1.0-3.0 (1.9)	[88]
Manganese (mg/kg)^{db}	16-100 (42.5)	28-30 (29.1)	22-48 (33.0)	18.0	-	155-924 (454)	[88]
Zinc (mg/kg)^{db}	8.5-34 (19.1)	15.0	15-27 (20.0)	12.0	-	20-56 (34.0)	[88]
Copper (mg/kg)^{db}	2.4-5.7 (3.9)	10-14 (12.0)	3.0-7.0 (5.0)	3.0	-	2.0-12.0 (6.0)	[88]
Iron (mg/kg)^{db}	64-219 (155.7)	70-2,829 (1025)	99.0	54.0	-	120-765 (335)	[88]

Parameter	Wheat	Barley	Oat	Rye	Soy bean	Rice	Ref.
Nickel (mg/kg)^{db}	0.8	-	-	-	-	-	[85]
Silicon (g/kg)^{db}	9.0-84.8 (23.8)	2.9-4.6 (1.2)	-	-	-	84.8	[85]
Bioactive compounds							
Policosanols[1] (mg/kg)^{db}	137-3,000 (1,137)	-	-	-	-	-	[291]
Phytosterols[2] (mg/kg)^{db}	834-1,206 (1,080)	-	-	-	-	-	[291]
Phenolic compounds[3] (mg/kg)^{db}	1,350-2,130 (2,240)	-	-	-	-	-	[292]
Triterpenoids (mg/kg)^{db}	Traces	-	-	-	-	-	[292]
Tannins (e.g. tannic acid) (g/kg)^{db}	2.5	3.6	-	-	-	0.1	[88]
Tannins condensed (e.g. catechin) (g/kg)^{db}	0.2	0.2	-	-	-	0	[88]

[1] Eicosanol, Heneicosanol, Docosanol, Tricosanol, Tetracosanol, Hexacosanol, Heptacosanol, Octacosanol, Triacontanol, [2] Stigmasterol, β-sitosterol, stigmastanol, [3] p-Coumaric acid, Ferulic acid

Table B-2: Indicative composition of stalks; range (mean value)

Parameter	Corn stalks	Sunflower stalks	Ref.
Moisture (% wt)^{ar}	8.02	9.2	[85]
Ash (%wt)^{db}	3.0-7.0 (5.5)	4.6	[85]

Parameter	Corn stalks	Sunflower stalks	Ref.
Structural compounds			
Cellulose (%wt)^{db}	38	35.0-38.5 (36.8)	[85]
Hemicellulose (%wt)^{db}	26	33.5	[85]
Lignin (%wt)^{db}	11	17.5	[85]
Crude protein (%wt)^{db}	1.8-11.5 (3.9) (for dry maize stover)	1.8-11.2 (7.3)	[88]
Starch (%wt)^{db}	10.9-11.9 (11.4) (for dry maize stover)	-	[88]
Elemental analyses			
Carbon (%wt)^{db}	46.9-48.2 (47.5)	42.0 (for sunflower stems)	[85] Sunflower: [86]
Oxygen (%wt)^{db}	44.9-46.2 (45.6)	40.0 (for sunflower stems)	[85] Sunflower: [86]
Hydrogen (%wt)^{db}	5.8-6.2 (6.0)	5.2 (for sunflower stems)	[85] Sunflower: [86]
Nitrogen (%wt)^{db}	0.9-1.4 (1.1)	1.4 (for sunflower stems)	[85] Sunflower: [86]
Sulfur (%wt)^{db}	0.1-0.2 (0.1)	0.2 (for sunflower stems)	[85] Sunflower: [86]
Nutrients, minerals and metals			
Phosphorus (g/kg)^{db}	0.2-2.6 (0.8) (for dry maize stover)	2.6-2.7 (2.6)	[88]
Potassium (g/kg)^{db}	5.4-28.0 (14.0) (for dry maize stover)	38.0-38.7 (38.4)	[88]
Calcium (g/kg)^{db}	1.6-11.7 (3.2) (for dry maize stover)	7.7-8.9 (8.3)	[88]

Parameter	Corn stalks	Sunflower stalks	Ref.
Magnesium (g/kg)^{db}	1.7-3.0 (2.3) (for dry maize stover)	7.8-10.5 (9.2)	[88]
Manganese (mg/kg)^{db}	16-242 (107) (for dry maize stover)	-	[88]
Zinc (mg/kg)^{db}	9-37 (17) (for dry maize stover)	-	[88]
Copper (mg/kg)^{db}	2-6 (4) (for dry maize stover)	-	[88]
Iron (mg/kg)^{db}	975	-	[88]
Nickel (mg/kg)^{db}	-	-	[85]
Silicon (g/kg)^{db}	-	-	[85]
Bioactive compounds			
Ferulic Acid (g/kg)^{db}	5.24-7.53 (6.8)	-	Corn stalks:[293, 294]
p-Coumaric Acid (g/kg)^{db}	10.5-29.1 (18)	-	Corn stalks: [293, 294]

Table B-3: Indicative composition of representative prunings; range (mean value)

Parameter	Grape	Olive tree	Almond tree	Apple tree	Orange tree	Cherry tree	Ref.
Moisture (% wt)^{ar}	43.7[1]	4.6-14 (8.4)	11.4	5.1	31.1	26[3]	[85] Grape: [88]
Ash (%wt)^{db}	2.2-3.0 (2.6)	13.3	1.63	-	4.4 (at 815°C)	1.3[3]	[85]
Structural compounds							
Cellulose (%wt)^{db}	-	30.3	-	36.2	40.5	42.0[3]	[85] Orange: [89]
Hemicellulose (%wt)^{db}	-	17.9	-	25.1	29.3	34.0[3]	[85] Orange: [89]

Parameter	Grape	Olive tree	Almond tree	Apple tree	Orange tree	Cherry tree	Ref.
Lignin (%wt)^{db}	10-25 (17.1)[1]	21 (acid insoluble) 3.1 (acid soluble)	-	11.9	20.8	24.0[3]	[85] Grape: [88] Orange: [90]
Crude protein (%wt)^{db}	3.0-6.7 (4.6)[1]	4.1-11 (7.8)[2]	-	-	2.7 (proteins)	-	[88]
Elemental analyses							
Carbon (%wt)^{db}	47.6-49 (48.6)	47-52 (49.2)	50-52 (51.1)	46.4	50.0	-	[85]
Oxygen (%wt)^{db}	5.9-6.0 (6.0)	6.0-6.6 (6.3)	5.4-6.0 (5.7)	5.3	5.9-6.0 (5.9)	-	[85]
Hydrogen (%wt)^{db}	43-45 (44.0)	44.6-47 (46.2)	41.6-43 (42.4)	42.8	43.6-44 (43.9)	-	[85]
Nitrogen (%wt)^{db}	0.8-0.9 (0.8)	0.6-1.1 (0.8)	0.6-0.7 (0.6)	1.0	0.3	-	[85]
Sulfur (%wt)^{db}	0.01-0.07 (0.03)	0.08-0.1 (0.09)	0.01	0.09	0.02	-	[85]
Nutrients, minerals and metals							
Phosphorus (g/kg)^{db}	0.8-3.3 (1.5)[1]	1.1[2]	-	-	-	-	[88]
Potassium (g/kg)^{db}	2.1-7.6 (3.1)[1]	4.7	-	2.5	-	-	[88] Apple and olive: [295]
Calcium (g/kg)^{db}	4-15.6 (7.0)[1]	24.0[2]	-	-	-	-	[88]
Magnesium (g/kg)^{db}	1.3-2.3 (1.7)[1]	-	-	-	-	-	[88]

Parameter	Grape	Olive tree	Almond tree	Apple tree	Orange tree	Cherry tree	Ref.
Manganese (mg/kg)^{db}	32[1]	86.2	-	102	-	-	[88] Apple and olive: [295]
Zinc (mg/kg)^{db}	26-43 (37)[1]	9.5	4.6	20.6	-	-	[88] Apple and olive: [295] Almond: [296]
Copper (mg/kg)^{db}	5-16 (10)[1]	4.0	4.9	-	-	-	[88] Olive and almond: [296]
Iron (mg/kg)^{db}	36-148 (65)[1]	-	-	-	-	-	[88]
Nickel (mg/kg)^{db}	-	3.4	-	4.7	-	-	Apple and olive: [295]
Bioactive compounds							
Tannins, condensed, eq. catechin (g/kg) ^{db}	27.0-56.5 (41.8)[1]	7.0[2]	-	-	-	-	[88]

[1]Grape branches and leaves, fresh, [2]olive leaves and branches, dry, [3]cherry wood

Table B-4: Indicative composition of peach and olive pits; range (mean value)

Parameter	Peach pits	Olive pits	Ref.
Moisture (% wt)^{ar}	20.0[1]	6.1-12.1 (8.7)	[85] Peach: [68]
Ash (%wt)^{db}	1.0-1.1 (1.1)	0.4-3.2 (2.3)	[85]
Structural compounds			
Cellulose (%wt)^{db}	-	28.1	[85]
Hemicellulose (%wt)^{db}	-	37.1	[85]

Parameter	Peach pits	Olive pits	Ref.
Lignin (%wt)^{db}	-	25.3-31.2 (28.2)	[85]
Crude protein (%wt)^{db}	26.7[1]	31.0-33.0 (32.0)[3]	[88] Peach: [93]
Carbohydrates (%wt)^{db}	16.0 [1] 12.9[2]	-	Peach: 1. [93] 2. [65]
Reducing sugars (%wt)^{db}	7.1[1]	-	Peach: [93]
Elemental analyses			
Carbon (%wt)^{db}	49.7-53.6 (51.6)	46.6-53.7 (50.0)	[85]
Oxygen (%wt)^{db}	39.5-43.4 (41.5)	38.9-47.4 (43.7)	[85]
Hydrogen (%wt)^{db}	6.0-6.4 (6.2)	5.3-6.8 (6.2)	[85]
Nitrogen (%wt)^{db}	0.3-0.5 (0.4)	0.4-2.4 (0.8)	[85]
Sulfur (%wt)^{db}	0.02-0.05 (0.04)	0.0-0.2 (0.1)	[85]
Nutrients, minerals and metals			
Phosphorus (g/kg)^{db}	0.02	0.53	[85]
Potassium (g/kg)^{db}	0.1-2.3	6.6	[85]
Calcium (g/kg)^{db}	0.05-0.4	5.1	[85]
Magnesium (g/kg)^{db}	0.03-0.1	0.38-1.17 (0.78)	[85]
Manganese (mg/kg)^{db}	29[1]	10.3	[85] Peach: [93]
Zinc (mg/kg)^{db}	9.0[1]	9.7	[85] Peach: [93]
Copper (mg/kg)^{db}	10.0[1]	8.5	[85] Peach: [93]
Iron (mg/kg)^{db}	14.0[1]	352	[85] Peach: [93]
Nickel (mg/kg)^{db}	2.0[1]	20.0	[85] Peach: [93]

Parameter	Peach pits	Olive pits	Ref.
Bioactive compounds			
Total phenolic content	8.1 g/100g [1]	61.4% [1]	Peach: [66] Olive: [72]

[1] kernels, [2] peach seeds, [3] olive kernels, exhausted.

Table B-5: Indicative composition of olive cake and apple, peach, grape and orange pomace; range (mean value)

Parameter	Olive cake	Apple pomace	Peach pomace	Grape pomace[5]	Orange pomace	Ref.
Moisture (% wt)[ar]	6.4	5.7[2]	94.1	60.3	82.5[6]	[85] Peach: [94] Grape and Citrus: [88]
Ash (%wt)[db]	10.9	2.8[2]	2.1	4.2-9.5	3-9.2 (4.4)[6]	[85] Peach: [65] Citrus: [88]
Structural compounds						
Cellulose (%wt)[db]	28.4	-	-	-	19.7[7]	[85] Orange bagasse: [83]
Hemicellulose (%wt)[db]	20.3	-	-	-	6.3[7]	[85] Orange bagasse: [83]
Lignin (%wt)[db]	28.1	6.4-23.2 (15.7)[3]	4.7[2]	20-50 (34.7)	4.2[7]	[88] Peach: [96] Orange bagasse: [83]
Crude protein (%wt)[db]	7-12 (9.5) [1]	4.4-16.0 (6.8)[3]	7.4	8.3-16.4 (11.8)	4.1-9.1 (6.5)[6]	[88] Peach pomace: [94]

Parameter	Olive cake	Apple pomace	Peach pomace	Grape pomace[5]	Orange pomace	Ref.
Carbohydrate (%wt)[db]	-	48-85	25.9 *(water soluble)*	1.6 (starch)	4.4 (starch)[6]	Apple: [76] Peach: [94]
Total sugars (%wt)[db]	-	6.2[3]	-	3.9-31.8 (18.5)	25.8[6]	[88]
Elemental analyses						
Carbon (%wt)[db]	58.4	51.0	-	57-58 (57.9)	38.9[8]	[85] Orange peel: [95]
Oxygen (%wt)[db]	33.0	40.0	-	6.1-6.5 (6.3)	53.6[8]	[85] Orange peel: [95]
Hydrogen (%wt)[db]	7.8	8.7	-	33.6-34.2 (33.9)	6.2[8]	[85] Orange peel: [95]
Nitrogen (%wt)[db]	1.8	1.0	-	2.0-2.2 (2.1)	1.1[8]	[85] Orange peel: [95]
Sulfur (%wt)[db]	0.2	0.05	-	0.03-0.22 (0.1)	0.11[8]	[85] Orange peel: [95]
Nutrients, minerals and metals						
Phosphorus (g/kg)[db]	0.9-1.6 (1.3)[1]	0.1-1.6 (1.1)[3]	2.2[2]	2-3 (2.5)	0.3-2.0 (1.5)[6]	[88] Peach pulp: [96]
Potassium (g/kg)[db]	6.7-14.2 (10.5)[1]	6.0-7.4 (6.8)[3]	0.4[2]	-	5.1[6]	[88] Peach pulp: [97]
Calcium (g/kg)[db]	6.0-18.9 (12.5)[1]	0.9-2.4 (1.7)[3]	-	4.7-9.2 (7.2)	6.1-9.4 (7.8)[6]	[88]
Magnesium (g/kg)[db]	0.7[1]	0.4-1.0 (0.7)[3]	-	-	0.7[6]	[88]

Parameter	Olive cake	Apple pomace	Peach pomace	Grape pomace[5]	Orange pomace	Ref.
Manganese (mg/kg)^{db}	-	2[3]	-	-	8.0[6]	[88]
Zinc (mg/kg)^{db}	-	2[3]	6.9[2]	-	14.0[6]	[88] Peach pulp: [97]
Copper (mg/kg)^{db}	-	2[3]	1.2[2]	78	5.0[6]	[88] Peach pulp: [97]
Iron (mg/kg)^{db}	1200[1]	67[3]	13.5[2]	-	80.0[6]	[88] Peach pulp: [97]
Bioactive compounds						
Total extractable polyphenols (g GAE/kg) ^{db}	13.9	-	-	-	-	Olive Cake: [98]
Total extractable tannins (g/kg) ^{db}	5.0-24.0	-	-	-	-	Olive Cake: [98]
pectin (g/kg)^{db}	-	35-153	-	-	-	Apple: [76]
Phenolic acids (mg/kg)^{db}	-	523–1542		-	560[9]	Apple and orange: [99]
Phenolic compounds (mg GAE/g) ^{db}	-	-	2.0[4]	30.7-48.8	-	Peach pomace: [100] Grape pomace: [101]
Flavonoids (mg/kg)^{db}	-	2153–3734	320 QE[4]	-	55 Flavones[9]	Apple and orange: [99]

Parameter	Olive cake	Apple pomace	Peach pomace	Grape pomace[5]	Orange pomace	Ref.
					22,298 Flavanones[9]	Peach pomace: [100]

[1]Olive oil cake, crude, without stones, [2]pulp, [3]fresh apple pomace, [4]frozen peach pomace, [5]fresh grape pomace, [6]fresh citrus pulp, [7]orange bagasse, [8]orange peel, [9]orange peel and pulp.

Annex C: Detailed data related to CS1: Fishery sector

In the following tables the detailed data, retrieved for the fishery sector, are depicted.

Table C-1: Available fisheries biomass per source of origin (mean values for years 2014-2016); DataM platform

Region	Imports, kt^{db}	Aquaculture, kt^{db}	Cupture, kt^{db}	Unknown, kt^{db}	Exports, kt^{db}	TOTAL, kt^{db}
EU-27	1531	267	1168	617	0	3582
Austria	35.9	0.9	0.1	0.1	0.0	37
Belgium	69.2	0.0	6.5	2.4	0.0	78
Bulgaria	9.0	3.4	2.2	7.8	0.0	22
Croatia	0.1	3.7	19.0	17.5	16.9	23
Cyprus	7.0	1.4	0.4	0.1	0.0	9
Czechia	23.3	5.1	0.9	2.6	0.0	32
Denmark	0.0	8.9	190.4	433.7	271.5	362
Estonia	0.0	0.2	18.2	26.9	28.3	17
Finland	21.1	3.6	46.6	3.0	0.0	74
France	406.6	43.7	136.4	41.6	0.0	628
Germany	201.9	8.1	64.6	56.5	0.0	331
Greece	104.6	28.0	16.9	5.9	0.0	155
Hungary	11.0	4.1	1.5	0.7	0.0	17
Ireland	0.0	9.3	69.2	48.6	66.1	61
Italy	412.3	37.9	48.4	15.0	0.0	514
Latvia	0.0	0.2	26.3	41.7	33.2	35
Lithuania	0.8	1.1	28.5	43.8	29.4	45
Luxembourg	5.0	0.0	0.0	0.0	0.0	5
Malta	8.3	1.4	0.7	0.1	0.0	11
Netherlands	26.4	15.7	93.8	232.3	229.2	139
Poland	69.9	9.6	51.3	16.2	0.0	147
Portugal	97.8	2.6	46.7	15.3	0.0	162
Romania	34.7	2.9	2.4	3.1	0.0	43
Slovakia	11.7	0.4	0.5	0.1	0.0	13
Slovenia	5.7	0.4	0.1	1.1	0.0	7
Spain	229.0	71.3	246.7	148.4	0.0	695
Sweden	45.5	3.4	49.9	39.3	0.0	138

Table C-2: Destinations of fisheries biomass (mean values for years 2014-2016); DataM platform

Region	Available Fishmeal and Fish oil, kt ^{db}	Available, aquatic-based food, kt^{db}
EU-27	664	2358
Austria	6	29
Belgium	6	66
Bulgaria	9	12
Croatia	0	17
Cyprus	2	7
Czechia	7	23
Denmark	280	27
Estonia	8	2
Finland	16	43
France	49	503
Germany	43	243
Greece	99	47
Hungary	3	14
Ireland	19	11
Italy	59	416
Latvia	17	9
Lithuania	16	17
Luxembourg	0	5
Malta	6	3
Netherlands	21	87
Poland	27	83
Portugal	10	126
Romania	7	33
Slovakia	0	12
Slovenia	1	6
Spain	125	451
Sweden	44	78

Table C-3: Fisheries waste streams per source of origin (mean values for years 2014-2016); DataM platform

Region	Waste from Aquatic based food , kt^{db}	Waste from biomass supply , kt^{db}	Waste streams from Aquaculture and capture fisheries, kt^{db}	Total , kt^{db}
EU-27	312	262	299	873
Austria	3.9	1.1	0.1	5.1
Belgium	8.7	4.7	1.6	14.9

Region	Waste from Aquatic based food , kt^{db}	Waste from biomass supply , kt^{db}	Waste streams from Aquaculture and capture fisheries, kt^{db}	Total , kt^{db}
Bulgaria	1.5	0.9	0.8	3.2
Croatia	2.2	1.7	4.8	8.7
Cyprus	0.9	0.2	0.2	1.3
Czechia	3.0	1.1	0.6	4.7
Denmark	3.6	7.7	46.3	57.6
Estonia	0.2	2.6	4.4	7.2
Finland	5.7	3.4	11.4	20.6
France	61.6	40.4	35.8	137.8
Germany	32.4	29.1	16.1	77.5
Greece	6.3	2.7	6.0	14.9
Hungary	1.8	0.5	0.7	3.0
Ireland	1.5	14.3	17.3	33.1
Italy	52.0	25.1	14.3	91.4
Latvia	1.2	2.9	6.3	10.4
Lithuania	2.3	4.9	6.9	14.0
Luxembourg	0.6	0.2	0.0	0.8
Malta	0.5	0.1	0.3	0.9
Netherlands	11.5	7.5	23.6	42.6
Poland	11.0	23.9	13.0	47.8
Portugal	16.7	14.8	11.4	42.9
Romania	4.4	2.2	0.8	7.3
Slovakia	1.6	0.4	0.1	2.1
Slovenia	0.7	0.2	0.0	1.0
Spain	56.8	56.1	64.2	177.0
Sweden	10.3	4.1	12.2	26.6

Table C-4: Destinations of fisheries waste streams (mean values for years 2014-2016); DataM platform

Region	Disposal and AD , kt^{db}	Composting , kt^{db}	Total , kt^{db}
EU-27	664	209	873
Austria	4.1	1.0	5.1
Belgium	11.7	3.2	14.9
Bulgaria	2.5	0.7	3.2
Croatia	6.5	2.2	8.7
Cyprus	1.0	0.3	1.3
Czechia	3.7	1.0	4.7
Denmark	41.9	15.7	57.6
Estonia	5.2	2.0	7.2

Region	Disposal and AD , kt^{db}	Composting , kt^{db}	Total , kt^{db}
Finland	15.5	5.1	20.6
France	106.2	31.6	137.8
Germany	59.5	18.0	77.5
Greece	11.5	3.5	14.9
Hungary	2.3	0.6	3.0
Ireland	24.0	9.1	33.1
Italy	71.7	19.7	91.4
Latvia	7.6	2.8	10.4
Lithuania	10.4	3.7	14.0
Luxembourg	0.7	0.2	0.8
Malta	0.7	0.2	0.9
Netherlands	32.0	10.6	42.6
Poland	35.7	12.2	47.8
Portugal	32.8	10.1	42.9
Romania	5.7	1.5	7.3
Slovakia	1.7	0.4	2.1
Slovenia	0.8	0.2	1.0
Spain	133.9	43.1	177.0
Sweden	20.3	6.3	26.6

Annex D: Detailed data related to CS2: Urban/industrial sector

The waste related activities, as defined in the EU Waste Framework Directive 2008/98, are the following:

Recovery Operations

R1*: Use principally as a fuel or other means to generate energy

R2: Solvent reclamation/regeneration

R3: Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)

R4: Recycling/reclamation of metals and metal compounds

R5: Recycling/reclamation of other inorganic materials

R6: Regeneration of acids or bases

R7: Recovery of components used for pollution abatement

R8: Recovery of components from catalysts

R9: Oil re-refining or other reuses of oil

R10: Land treatment resulting in benefit to agriculture or ecological improvement

R11: Use of wastes obtained from any of the operations numbered R1 to R10

R12*: Exchange of wastes for submission to any of the operations numbered R1 to R11

R13*: Storage of wastes pending any of the operations numbered R1 to R12 (excluding temporary storage, pending collection, on the site where it is produced)

* not considered recovery to a final product

Disposal Operations

D1: Deposit into or onto land, e.g., landfill

D2: Land treatment, e.g., biodegradation of liquid or sludgy discards in soils

D3: Deep injection, e.g., injection of pumpable discards into wells, salt domes or naturally occurring repositories

D4: Surface impoundment, e.g., placement of liquid or sludgy discards into pits, ponds or lagoons

D5: Specially engineered landfill, e.g., placement into lined discrete cells which are capped and isolated from one another and the environment

D6: Release into a water body, except seas/oceans

D7: Release into seas/oceans, including seabed insertion

D8: Biological treatment resulting in final compounds or mixtures which are discarded by any of the operations numbered D1 to D12

D9: Physico-chemical treatment resulting in final compounds or mixtures which are discarded by any of the operations numbered D1 to D12, e.g., evaporation, drying, calcination

D10: Incineration on land

D11: Incineration at sea

D12: Permanent storage, e.g., emplacement of containers in a mine

D13: Blending or mixing prior to submission to any of the operations numbered D1 to D12

D14: Repackaging prior to submission to any of the operations numbered D1 to D13

D15: Storage pending any of the operations numbered D1 to D14 (excluding temporary storage, pending collection, on the site where it is produced)

In the following tables the detailed data, retrieved for the Urban/industrial sector, are depicted.

Table D-1: Generated MSW, OFMSW and non-OFMSW; data collected from Eurostat [ENV_WASMUN]

	MSW		OFMSW	Non OFMSW
Region	**Reference years**	**kt**	**kt**	**kt**
EU-27	2019-2021 Eurostat estimation	231,781	78,806	152,975
EU-28	sum of available data	262,362	89,203	173,159
Austria	2018-2020	5,926	2,015	3,911
Belgium	2019-2021	7,327	2,491	4,836
Bulgaria	2018-2020	2,924	994	1,930
Croatia	2019-2021	1,757	597	1,160
Cyprus	2019-2021	561	191	370
Czechia	2019-2021	5,714	1,943	3,771
Denmark	2019-2021	4,751	1,615	3,135
Estonia	2019-2021	508	173	335
Finland	2019-2021	3,290	1,118	2,171
France	2019-2021	37,263	12,670	24,594
Germany	2019-2021	52,561	17,871	34,690
Greece	2017-2019	5,517	1,876	3,641
Hungary	2019-2021	3,918	1,332	2,586
Ireland	2018-2020	3,069	1,044	2,026
Italy	2018-2020	29,711	10,102	19,609
Latvia	2019-2021	873	297	576
Lithuania	2019-2021	1,338	455	883
Luxembourg	2019-2021	499	170	329
Malta	2019-2021	333	113	220

	MSW		OFMSW	Non OFMSW
Region	Reference years	kt	kt	kt
Netherlands	2019-2021	9,048	3,076	5,972
Poland	2019-2021	13,181	4,482	8,700
Portugal	2019-2021	5,290	1,799	3,492
Romania	2019-2021	5,595	1,902	3,693
Slovakia	2019-2021	2,538	863	1,675
Slovenia	2019-2021	1,051	357	694
Spain	2019-2021	22,208	7,551	14,658
Sweden	2019-2021	4,474	1,521	2,953
United Kingdom	2016-2018	31,136	10,586	20,550

Table D-2: OFMSW exports to EU, EFTA and OECD (non-EFTA) countries for 2018; data from Eurostat [226]

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8822267	1,301	0.147	Germany	EU-27	R3	200108	kitchen waste
Austria	EU-27	8822267	433	0.049	Germany	EU-27	R3	200108	bio-waste
Belgium	EU-27	11398589	4,822	0.423	Netherlands	EU-27	R3	200108	200108
Ireland	EU-27	4830392	7,391	1.530	United Kingdom	OECD (non-EFTA)	Mix	200108	biodegradable Food Waste
Ireland	EU-27	4830392	5,522	1.143	United Kingdom	OECD (non-EFTA)	Mix	200108	bio-degradable food waste
Norway	EFTA	5295619	175	0.033	Sweden	EU-27	R3	200108	
Norway	EFTA	5295619	343	0.065	Sweden	EU-27	R3	200108	
Norway	EFTA	5295619	172	0.033	Sweden	EU-27	R3	200108	
Norway	EFTA	5295619	9,772	1.845	Sweden	EU-27	R3	200108	
Norway	EFTA	5295619	2,622	0.495	Denmark	EU-27	R3	200108	
Norway	EFTA	5295619	597	0.113	Denmark	EU-27	R1	200108	
Slovenia	EU-27	2066880	20	0.010	Austria	EU-27	R3	200108	biodegradable kitchen waste
Sweden	EU-27	10120242	78	0.008	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
Liechtenstein	EFTA	38114	48	1.267	Austria	EU-27	R3	200125	speiseöle und -fette, ohne diejenigen, die aus öffentlichen

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									Sammelstellen stammen
Finland	EU-27	5513130	195	0.035	Sweden	EU-27	R12	200138	unclassified - 90% av trämaterial
Norway	EFTA	5295619	15,574	2.941	Sweden	EU-27	R1	200138	
Norway	EFTA	5295619	594	0.112	Sweden	EU-27	R1	200138	
Norway	EFTA	5295619	2,225	0.420	Sweden	EU-27	R1	200138	
Austria	EU-27	8822267	17	0.002	Germany	EU-27	R3	200201	separate collected biodegradable waste
Germany	EU-27	82792351	17	0.000	Netherlands	EU-27	D14	200201	garden and park waste
Germany	EU-27	82792351	12,281	0.148	France	EU-27	R3	200201	garden and park waste
Netherlands	EU-27	17181084	3,106	0.181	Germany	EU-27	R12	200201	other waste
Ireland	EU-27	4830392	2,450	0.507	United Kingdom	OECD (non-EFTA)	R3	Mix	biodegradable kitchen, canteen and garden Waste
Ireland	EU-27	4830392	23,156	4.794	United Kingdom	OECD (non-EFTA)	R3	Mix	biodegradable kitchen & canteen waste

Table D-3: OFMSW imports from EU, EFTA and OECD (non-EFTA) countries for 2018; data from Eurostat [226]

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8822267	20	0.002	Slovenia	EU-27	R3	200108	separate collected biowaste
Denmark	EU-27	5781190	2,980	0.515	Norway	EFTA	Mix	200108	
Denmark	EU-27	5781190	3,599	0.623	Norway	EFTA	Mix	200108	
France	EU-27	66926166	3,308	0.049	Italy	EU-27	R3	200108	
Germany	EU-27	82792351	1,934	0.023	Austria	EU-27	R3	200108	biodegradable kitchen and canteen waste
Netherlands	EU-27	17181084	3,811	0.222	Belgium	EU-27	R3	200108	other waste
Norway	EFTA	5295619	75	0.014	Sweden	EU-27	R3	200108	
Sweden	EU-27	10120242	9,919	0.980	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
Sweden	EU-27	10120242	351	0.035	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
United Kingdom	OECD (non-EFTA)	66273576	7,178	0.108	Ireland	EU-27	Mix	200108	segregated food waste
United Kingdom	OECD (non-EFTA)	66273576	5,091	0.077	Ireland	EU-27	Mix	200108	food waste

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Sweden	EU-27	10120242	7,213	0.713	Norway	EFTA	R1	200138	wood other than that mentioned in 20 01 37
Sweden	EU-27	10120242	4,344	0.429	Norway	EFTA	R1	200138	wood other than that mentioned in 20 01 37
Germany	EU-27	82792351	3,706	0.045	Netherlands	EU-27	R12	200201	garden and park waste
Italy	EU-27	60483973	2,268	0.037	Switzerland	EFTA	R3	200201	
United Kingdom	OECD (non-EFTA)	66273576	28,009	0.423	Ireland	EU-27	R3	Mix	biodegradable kitchen, canteen and garden waste
United Kingdom	OECD (non-EFTA)	66273576	2,475	0.037	Ireland	EU-27	R3	Mix	Biodegradable kitchen, cateen and Garden Waste
Austria	EU-27	8822267	5,803	0.658	Germany	EU-27	R3	200399	biowaste
Spain	EU-27	46658447	856	0.018	Andorra	Non-OECD	R3	Mix	BIODEGRADABLE WASTE

Table D-4: Waste exports to EU, EFTA and OECD (non-EFTA) countries for 2019; data from Eurostat (Eurostat, 2023)

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8858775	1,886	0.213	Germany	EU-27	R3	200108	kitchen waste
Ireland	EU-27	4904226	783	0.160	United Kingdom	OECD (non-EFTA)	R3	200108	Canteen & Biodegradable Food Waste
Ireland	EU-27	4904226	166	0.034	United Kingdom	OECD (non-EFTA)	R3	200108	Food waste classified as biodegradable kitchen and canteen waste 20 01 08
Ireland	EU-27	4904226	5,524	1.126	United Kingdom	OECD (non-EFTA)	Mix	200108	Bio-degradable food waste
Ireland	EU-27	4904226	122	0.025	United Kingdom	OECD (non-EFTA)	Mix	200108	Biodegradable Kitchen And Canteen Waste
Ireland	EU-27	4904226	12,348	2.518	United Kingdom	OECD (non-EFTA)	Mix	200108	mixture of catering waste and former food stuffs (solid)
Ireland	EU-27	4904226	52	0.011	United Kingdom	OECD (non-EFTA)	Mix	200108	Segregated biodegradable food waste.
Italy	EU-27	60359546	1,280	0.021	Croatia	EU-27	R3	200108	

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Norway	EFTA	5328212	1,042	0.196	Sweden	EU-27	R3	200108	200108
Norway	EFTA	5328212	4,203	0.789	Sweden	EU-27	R3	200108	200108
Norway	EFTA	5328212	1,799	0.338	Sweden	EU-27	R3	200108	200108
Norway	EFTA	5328212	2,244	0.421	Sweden	EU-27	R1	200108	200108
Norway	EFTA	5328212	1,347	0.253	Denmark	EU-27	R3	200108	200108
Norway	EFTA	5328212	2,552	0.479	Denmark	EU-27	R1	200108	200108
Sweden	EU-27	10230185	200	0.020	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
Liechtenstein	EFTA	38378	57	1.496	Austria	EU-27	R3	200125	[ak] Speiseöle- und -fette, ohne diejenigen, die aus öffentlichen Sammelstellen stammen
Croatia	EU-27	4076246	97	0.024	Hungary	EU-27	R3	200138	AC170
Croatia	EU-27	4076246	1,064	0.261	Austria	EU-27	R3	200138	AC170
Finland	EU-27	5517919	215	0.039	Sweden	EU-27	R12	200138	Unclassified - 90% av trämaterial
Germany	EU-27	83019213	1,142	0.014	Austria	EU-27	R3	200138	Wood waste (treated with paint, glue etc.)
Norway	EFTA	5328212	2,843	0.534	Sweden	EU-27	R1	200138	200138
Norway	EFTA	5328212	3,930	0.738	Sweden	EU-27	R1	200138	200138
Norway	EFTA	5328212	10,051	1.886	Sweden	EU-27	R1	200138	200138

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Slovenia	EU-27	2080908	707	0.340	Austria	EU-27	R3	200138	Wastes collected from households
Germany	EU-27	83019213	7,320	0.088	France	EU-27	R3	200201	Garden and park waste
Netherlands	EU-27	17282163	5,510	0.319	Germany	EU-27	R3	200201	other waste

Table D-5: Waste imports to EU, EFTA and OECD (non-EFTA) countries for 2019; data from Eurostat [226]

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Croatia	EU-27	4076246	1,280	0.314	Italy	EU-27	R3	200108	
Denmark	EU-27	5806081	4,025	0.693	Norway	EFTA	Mix	200108	
Denmark	EU-27	5806081	1,426	0.246	Norway	EFTA	R3	200108	
Germany	EU-27	83019213	2,413	0.029	Austria	EU-27	R3	200108	biodegradable kitchen and canteen waste
Norway	EFTA	5328212	199	0.037	Sweden	EU-27	R3	200108	200108
Sweden	EU-27	10230185	1,042	0.102	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
Sweden	EU-27	10230185	21,389	2.091	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Sweden	EU-27	10230185	2,189	0.214	Norway	EFTA	R1	200108	biodegradable kitchen and canteen waste
Romania	EU-27	19401658	1,605	0.083	France	EU-27	R3	200138	waste wood
Sweden	EU-27	10230185	215	0.021	Finland	EU-27	R12	200138	wood other than that mentioned in 20 01 37
Sweden	EU-27	10230185	2,842	0.278	Norway	EFTA	R1	200138	wood other than that mentioned in 20 01 37
Germany	EU-27	83019213	487	0.006	Netherlands	EU-27	R12	200201	garden and park waste
Germany	EU-27	83019213	5,429	0.065	Netherlands	EU-27	R3	200201	garden and park waste
Italy	EU-27	60359546	2,217	0.037	Switzerland	EFTA	R3	200201	
Austria	EU-27	8858775	4,282	0.483	Germany	EU-27	R3	200399	mixed waste for composting
Spain	EU-27	46934632	920	0.020	Andorra	Non-OECD	R3	Mix	biodegradable waste - biodegradable waste from kitchens and restaurants

Table D-6: Waste exports from EU, EFTA and OECD (non-EFTA) countries for 2020; data from Eurostat [226]

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Germany	EU-27	83166711	4,860	0.058	Austria	EU-27	R3	200108	Biodegradable kitchen and canteen waste
Ireland	EU-27	4964440	258	0.052	United Kingdom	OECD (non-EFTA)	R3	200108	Food waste classified as biodegradable kitchen and canteen waste 20 01 08
Ireland	EU-27	4964440	64	0.013	United Kingdom	OECD (non-EFTA)	Mix	200108	Biodegradable Kitchen And Canteen Waste
Italy	EU-27	59641488	3,181	0.053	Croatia	EU-27	R3	200108	
Norway	EFTA	5367580	1,213	0.226	Denmark	EU-27	R3	200108	1111
Norway	EFTA	5367580	836	0.156	Sweden	EU-27	R3	200108	200108
Norway	EFTA	5367580	3,308	0.616	Sweden	EU-27	R3	200108	200108
Norway	EFTA	5367580	21	0.004	Sweden	EU-27	R3	200108	1111
Norway	EFTA	5367580	4,587	0.854	Sweden	EU-27	R1	200108	200108
Sweden	EU-27	10327589	177	0.017	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
Ireland	EU-27	4964440	3,446	0.694	United Kingdom	OECD (non-EFTA)	R3	Mix	Biodegradable Kitchen, Canteen and

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									Garden Waste.
Liechtenstein	EFTA	38747	39	1.002	Austria	EU-27	R3	200125	[ak] Speiseöle- und -fette, ohne diejenigen, die aus öffentlichen Sammelstellen stammen
Germany	EU-27	83166711	874	0.011	Austria	EU-27	R3	200138	
Norway	EFTA	5367580	3,020	0.563	Sweden	EU-27	R1	200138	1141
Slovenia	EU-27	2095861	54	0.026	Austria	EU-27	R3	200138	treated wood collected from households
Netherlands	EU-27	17407585	10,958	0.629	Germany	EU-27	R3	200201	other waste

Table D-7: Waste imports to EU, EFTA and OECD (non-EFTA) countries for 2020; data from Eurostat [226]

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Croatia	EU-27	4058165	3,180	0.784	Italy	EU-27	R3	200108	mixed waste
Denmark	EU-27	5822763	1,692	0.291	Norway	EFTA	R3	200108	200108
Germany	EU-27	83166711	375	0.005	Austria	EU-27	R1	200108	biodegradable kitchen and canteen waste
Norway	EFTA	5367580	199	0.037	Sweden	EU-27	R3	200108	200108

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Sweden	EU-27	10327589	4,669	0.452	Norway	EFTA	R1	200108	biodegradable kitchen and canteen waste
Sweden	EU-27	10327589	774	0.075	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
Sweden	EU-27	10327589	3,494	0.338	Norway	EFTA	R3	200108	biodegradable kitchen and canteen waste
United Kingdom	OECD (non-EFTA)	67025542	64	0.001	Ireland	EU-27	Mix	200108	other - Biodegradeable Kitchen Waste
Spain	EU-27	47332614	650	0.014	Andorra	Non-OECD	R3	Mix	biodegradable kitchen and restaurant waste and biodegradable waste
United Kingdom	OECD (non-EFTA)	67025542	3,507	0.052	Ireland	EU-27	R3	Mix	other - Biodegradable kitchen,canteen and garden waste
Sweden	EU-27	10327589	3,713	0.360	Norway	EFTA	R1	200138	wood other than that mentioned in 20 01 37

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Sweden	EU-27	10327589	389	0.038	Finland	EU-27	R12	200138	wood other than that mentioned in 20 01 37
Sweden	EU-27	10327589	1,682	0.163	Denmark	EU-27	R1	200138	wood other than that mentioned in 20 01 37
Germany	EU-27	83166711	14,740	0.177	Netherlands	EU-27	R3	200201	garden and park waste
Italy	EU-27	59641488	979	0.016	Switzerland	EFTA	R3	200201	

Table D-8: Treatment operations of MSW; data collected from Eurostat [ENV_WASMUN] last updated: 4/4/2023

	RECYCLING - COMPOSTING AND DIGESTION		RECYCLING - MATERIAL		R1: INCINERATION ENERGY RECOVERY		PREPARING FOR REUSE		D10 (INCINERATION WITHOUT EN. RECOVERY)		D1-D7, D12: LANDFILL AND OTHER	
Region	**kt/yr**	**Reference years**	**kt/yr**	**Reference years**	**kt/yr**	**Reference years**	**kt/yr**	**Reference years**	**kt/yr**	**Reference years**	**kt/yr**	**Reference years**
EU-27	42,431	2019-2021	68,618	2019-2021	59,981	2019-2021	976	sum of available data	1,172	2017-2019	54,296	2019-2021
EU-28	47,524	sum of available data	77,157	sum of available data	71,112	sum of available data	0	sum of available data	1,916	sum of available data	60,277	sum of available data
Austria	1,640	2018-2020	1,890	2018-2020	2,214	2018-2020	33	2,020	2	2018-2020	119	2018-2020

Region	RECYCLING - COMPOSTING AND DIGESTION		RECYCLING - MATERIAL		R1: INCINERATION ENERGY RECOVERY		PREPARING FOR REUSE		D10 (INCINERATION WITHOUT EN. RECOVERY)		D1-D7, D12: LANDFILL AND OTHER	
	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years
Belgium	1,487	2019-2021	2,364	2019-2021	3,464	2019-2021	34	2020-2021	9	2019-2021	39	2019-2021
Bulgaria	126	2018-2020	861	2018-2020	147	2018-2020	0	2,020	0	2018-2020	1,692	2018-2020
Croatia	80	2019-2021	454	2019-2021	3	2019-2021	0	not available	0	2019-2021	1,042	2019-2021
Cyprus	7	2019-2021	82	2019-2021	9	2019-2021	2	2019-2021	0	2019-2021	366	2019-2021
Czechia	705	2019-2021	1,538	2019-2021	774	2019-2021	0	2019-2021	4	2019-2021	2,670	2019-2021
Denmark	949	2019-2021	1,132	2019-2021	2,675	2019-2021	0	not available	0	2019-2021	30	2019-2021
Estonia	15	2019-2021	138	2019-2021	231	2019-2021	0	not available	0	2019-2021	88	2019-2021
Finland	435	2019-2021	908	2019-2021	1,923	2019-2021	0	2,020	3	2019-2021	20	2019-2021
France	6,950	2019-2021	8,763	2019-2021	11,631	2019-2021	174	2019-2021	53	2019-2021	9,472	2019-2021
Germany	11,265	2019-2021	24,750	2019-2021	15,713	2019-2021	698	2020-2021	495	2019-2021	338	2019-2021
Greece	263	2017-2019	842	2017-2019	72	2017-2019	0	2017-2019	0	2017-2019	4,341	2017-2019
Hungary	373	2019-2021	969	2019-2021	494	2019-2021	0	2019-2021	2	2019-2021	2,034	2019-2021
Ireland	297	2018-2020	886	2018-2020	1,336	2018-2020	12	2,020	0	2018-2020	469	2018-2020
Italy	6,530	2018-2020	8,576	2018-2020	5,581	2018-2020	0	not available	172	2018-2020	6,195	2018-2020
Latvia	59	2019-2021	303	2019-2021	27	2019-2021	1	2,020	0	2019-2021	473	2019-2021
Lithuania	271	2019-2021	349	2019-2021	339	2019-2021	1	2019-2021	0	2019-2021	237	2019-2021
Luxembourg	113	2019-2021	148	2019-2021	217	2019-2021	0	not available	0	2019-2021	20	2019-2021
Malta	0	2019-2021	37	2019-2021	4	2019-2021	0	2019-2021	0	2019-2021	288	2019-2021
Netherlands	2,661	2019-2021	2,515	2019-2021	3,660	2019-2021	0	not	88	2019-2021	125	2019-2021

Region	RECYCLING - COMPOSTING AND DIGESTION		RECYCLING - MATERIAL		R1: INCINERATION ENERGY RECOVERY		PREPARING FOR REUSE		D10 (INCINERATION WITHOUT EN. RECOVERY)		D1-D7, D12: LANDFILL AND OTHER	
	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years
								available				
Poland	1,518	2019-2021	3,457	2019-2021	2,700	2019-2021	0	not available	172	2019-2021	5,334	2019-2021
Portugal	839	2019-2021	681	2019-2021	1,121	2019-2021	0	2020-2021	0	2019-2021	2,777	2019-2021
Romania	287	2019-2021	359	2019-2021	295	2019-2021	0	2020-2021	0	2019-2021	4,197	2019-2021
Slovakia	348	2019-2021	776	2019-2021	179	2019-2021	18	2,020	28	2019-2021	1,162	2019-2021
Slovenia	158	2019-2021	467	2019-2021	115	2019-2021	1	2019-2021	14	2019-2021	81	2019-2021
Spain	4,145	2019-2021	4,377	2019-2021	2,410	2019-2021	0	not available	0	2019-2021	11,276	2019-2021
Sweden	771	2019-2021	1,087	2019-2021	2,569	2019-2021	2	2020-2021	0	2019-2021	27	2019-2021
United Kingdom	5,232	2016-2018	8,450	2016-2018	11,208	2016-2018	0	not available	873	2016-2018	5,367	2016-2018

[1] Calculated from the mass balance

Table D-9: Generated sewage sludge; data collected from Eurostat [ENV_WW_SPD]; Last updated: 12/8/2022

Region	Reference years	kt[db]
EU-27	sum of available data	8,356.4
EU-28	sum of available data	9,795.2
Austria	2018-2020	232.0
Belgium	2018-2020	165.6
Bulgaria	2017-2019	55.4
Croatia	2018-2020	20.8
Cyprus	2016-2018	7.7
Czechia	2018-2020	222.8
Denmark	2010	141.0
Estonia	2018-2020	21.3
Finland	2017-2019	156.0
France	2015-2017	1,139.3
Germany	2017-2019	1,765.7
Greece	2017-2019	103.3
Hungary	2017-2019	242.8
Ireland	2018-2020	57.4
Italy	2010	1,102.7
Latvia	2018-2020	24.0
Lithuania	2018-2020	41.7
Luxembourg	2018-2020	9.1
Malta	2018-2020	9.4
Netherlands	2016, 18, 20	347.7
Poland	2018-2020	575.5
Portugal	2012-14-16	181.3
Romania	2018-2020	244.2
Slovakia	2018-2020	55.4
Slovenia	2018-2020	34.6
Spain	2016-2018	1,192.3
Sweden	2017-2019	207.2
United Kingdom	2009, 10, 12	1,438.8

[db] dry basis

FILTERED DATA OF WASTE SHIPMENTS FOR SEWAGE SLUDGE

Table D-10: Sewage sludge exports from EU, EFTA and OECD (non-EFTA) countries for 2019; data from Eurostat [226]; Last updated: 12/7/2023

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8858775	4,647	0.52	Germany	EU-27	R5	190805	sewer sludge
Austria	EU-27	8858775	26	0.00	Slovakia	EU-27	R3	190805	sewer sludge
Austria	EU-27	8858775	7,329	0.83	Switzerland	EFTA	R1	190805	sewer sludge
Austria	EU-27	8858775	9,410	1.06	Hungary	EU-27	R3	190805	sewer sludge
Austria	EU-27	8858775	10,971	1.24	Germany	EU-27	D10	190805	sewer sludge
Austria	EU-27	8858775	138	0.02	Germany	EU-27	R1	190805	sewer sludge
Belgium	EU-27	11467923	1,281	0.11	Luxembourg	EU-27	R1	190805	
Belgium	EU-27	11467923	734	0.06	France	EU-27	R10	190805	
Belgium	EU-27	11467923	10,211	0.89	France	EU-27	R3	190805	
Belgium	EU-27	11467923	2,647	0.23	Germany	EU-27	R1	190805	
Belgium	EU-27	11467923	21,518	1.88	Germany	EU-27	D10	190805	
Croatia	EU-27	4076246	59,646	14.63	Hungary	EU-27	R10	190805	AC270
Germany	EU-27	83019213	42,921	0.52	Netherlands	EU-27	R12	190805	Sludges from treatment of urban waste

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									water
Germany	EU-27	83019213	3,761	0.05	Switzerland	EFTA	R1	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	1,892	0.02	Switzerland	EFTA	R1	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	3,770	0.05	Switzerland	EFTA	R12	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	250	0.00	Switzerland	EFTA	R12	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	5,856	0.07	Austria	EU-27	R1	190805	Sludges from treatment

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									of urban waste water
Germany	EU-27	83019213	351	0.00	Belgium	EU-27	R1	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	922	0.01	Denmark	EU-27	R10	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	919	0.01	Denmark	EU-27	R3	190805	Sludges from treatment of urban waste water
Germany	EU-27	83019213	28,535	0.34	France	EU-27	R3	190805	Sludges from treatment of urban waste water
Italy	EU-27	60359546	1,213	0.02	Germany	EU-27	R1	190805	

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Italy	EU-27	60359546	38,801	0.64	Hungary	EU-27	R10	190805	
Italy	EU-27	60359546	6,423	0.11	Spain	EU-27	R3	190805	
Italy	EU-27	60359546	13,361	0.22	Switzerland	EFTA	D10	190805	
Italy	EU-27	60359546	3,700	0.06	Switzerland	EFTA	R1	190805	
Italy	EU-27	60359546	2,632	0.04	Hungary	EU-27	R12	190805	
Italy	EU-27	60359546	19,945	0.33	Hungary	EU-27	R3	190805	
Italy	EU-27	60359546	142	0.00	Croatia	EU-27	R1	190805	
Italy	EU-27	60359546	987	0.02	Austria	EU-27	R3	190805	
Italy	EU-27	60359546	468	0.01	Austria	EU-27	R1	190805	
Italy	EU-27	60359546	201	0.00	Germany	EU-27	D10	190805	
Italy	EU-27	60359546	24	0.00	France	EU-27	R3	190805	
Luxembourg	EU-27	613894	366	0.60	Germany	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	613894	802	1.31	Germany	EU-27	R13	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	613894	245	0.40	Germany	EU-27	D10	190805	boues provenant

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									du traitement des eaux usées urbaines
Luxembourg	EU-27	613894	4,610	7.51	France	EU-27	R3	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	613894	3,789	6.17	France	EU-27	R3	190805	boues provenant du traitement des eaux usées urbaines
Slovenia	EU-27	2080908	32,127	15.44	Hungary	EU-27	R10	190805	sludges from treatment of urban waste water
Slovenia	EU-27	2080908	32,589	15.66	Hungary	EU-27	R3	190805	sludges from treatment

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									of urban waste water
Slovenia	EU-27	2080908	4,358	2.09	Hungary	EU-27	Mix	190805	sludges from treatment of urban waste water
Sweden	EU-27	10230185	1,913	0.19	Finland	EU-27	R3	190805	sludges from treatment of urban waste water
Finland	EU-27	5517919	616	0.11	Sweden	EU-27	R3	Mix	Waste water treatment sludge

Table D-11: Sewage sludge imports to EU, EFTA and OECD (non-EFTA) countries for 2019; data from Eurostat [226] Last updated: 12/7/2023

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8858775	991	0.11	Italy	EU-27	R3	190805	sewer sludge

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8858775	467	0.05	Italy	EU-27	R1	190805	sewer sludge
Belgium	EU-27	11467923	1,771	0.15	France	EU-27	D10	190805	
Belgium	EU-27	11467923	14,398	1.26	Netherlands	EU-27	R1	190805	
Belgium	EU-27	11467923	44,913	3.92	Netherlands	EU-27	D10	190805	
Belgium	EU-27	11467923	47	0.00	Netherlands	EU-27	R12	190805	
Belgium	EU-27	11467923	720	0.06	France	EU-27	R5	190805	
Belgium	EU-27	11467923	1,142	0.10	France	EU-27	R10	190805	
Belgium	EU-27	11467923	9	0.00	France	EU-27	R1	190805	
Belgium	EU-27	11467923	678	0.06	Germany	EU-27	R5	190805	
Croatia	EU-27	4076246	142	0.03	Italy	EU-27	R1	190805	19 08 05
Denmark	EU-27	5806081	150	0.03	Germany	EU-27	R3	190805	
Denmark	EU-27	5806081	891	0.15	Germany	EU-27	R10	190805	
Finland	EU-27	5517919	1,913	0.35	Sweden	EU-27	R3	190805	Waste water treatment sludge
Germany	EU-27	83019213	2,663	0.03	Belgium	EU-27	R1	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	519	0.01	Belgium	EU-27	D10	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	20,726	0.25	Belgium	EU-27	D10	190805	sludges from treatment of urban waste

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
									water
Germany	EU-27	83019213	2,250	0.03	Austria	EU-27	R3	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	11,743	0.14	Austria	EU-27	D10	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	194	0.00	Austria	EU-27	R1	190805	Ssludges from treatment of urban waste water
Germany	EU-27	83019213	5,070	0.06	Austria	EU-27	R5	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	86	0.00	Italy	EU-27	D10	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	200	0.00	Italy	EU-27	D10	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	245	0.00	Luxembour g	EU-27	D10	190805	sludges from treatment of urban waste water

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Germany	EU-27	83019213	366	0.00	Luxembourg	EU-27	R1	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	1,133	0.01	Italy	EU-27	R1	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	1,158	0.01	France	EU-27	R1	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	997	0.01	Luxembourg	EU-27	R13	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	2,985	0.04	Netherlands	EU-27	R13	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	646	0.01	Luxembourg	EU-27	R5	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	44,289	0.53	Netherlands	EU-27	D10	190805	sludges from treatment of urban waste water
Germany	EU-27	83019213	23,267	0.28	Netherland	EU-27	R1	190805	sludges from

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
					s				treatment of urban waste water
Germany	EU-27	83019213	6,656	0.08	Netherlands	EU-27	R12	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	4,999	0.51	Italy	EU-27	R10	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	17,674	1.81	Italy	EU-27	R10	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	14,333	1.47	Italy	EU-27	R3	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	5,587	0.57	Italy	EU-27	R3	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	1,114	0.11	Serbia	Non-OECD	D8	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	9,405	0.96	Austria	EU-27	R3	190805	sludges from treatment of

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
									urban waste water
Hungary	EU-27	9772756	2,635	0.27	Italy	EU-27	Mix	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	61,280	6.27	Croatia	EU-27	R10	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	6,562	0.67	Italy	EU-27	Mix	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	4,288	0.44	Slovenia	EU-27	Mix	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	32,126	3.29	Slovenia	EU-27	R10	190805	sludges from treatment of urban waste water
Hungary	EU-27	9772756	32,505	3.33	Slovenia	EU-27	R3	190805	sludges from treatment of urban waste water
Luxembou rg	EU-27	613894	1,232	2.01	Belgium	EU-27	R5	190805	boues provenant du traitement des eaux usées

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
									urbaines
Luxembourg	EU-27	613894	1,191	1.94	France	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	613894	519	0.85	France	EU-27	R5	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	613894	559	0.91	Netherlands	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Spain	EU-27	46934632	26	0.00	Italy	EU-27	R3	190805	Llots de tractament d'aigues residuals urbanes
Spain	EU-27	46934632	1,602	0.03	Italy	EU-27	R3	190805	Llots de tractament d'aigües residuals urbanes
Spain	EU-27	46934632	5,122	0.11	Italy	EU-27	R3	190805	Llots del tractament d'aigües residuals urbanes

Table D-12: Sewage sludge exports from EU, EFTA and OECD (non-EFTA) countries for 2020; data from Eurostat [226] Last updated: 12/7/2023

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8901064	12,583	1.4137	Germany	EU-27	R5	190805	sewer sludge
Austria	EU-27	8901064	14,914	1.6755	Switzerland	EFTA	R1	190805	sewer sludge
Austria	EU-27	8901064	4,428	0.4975	Switzerland	EFTA	R12	190805	sewer sludge
Austria	EU-27	8901064	2,274	0.2555	Germany	EU-27	D10	190805	sewer sludge
Austria	EU-27	8901064	2,331	0.2619	Germany	EU-27	R1	190805	sewer sludge
Belgium	EU-27	11522440	1,479	0.1283	Luxembourg	EU-27	R1	190805	
Belgium	EU-27	11522440	491	0.0426	France	EU-27	R10	190805	
Belgium	EU-27	11522440	9,611	0.8341	France	EU-27	R3	190805	
Belgium	EU-27	11522440	2,087	0.1811	Germany	EU-27	R1	190805	
Belgium	EU-27	11522440	11,659	1.0119	Germany	EU-27	D10	190805	
Germany	EU-27	83166711	33,631	0.4044	Netherlands	EU-27	R12	190805	
Germany	EU-27	83166711	66	0.0008	Latvia	EU-27	R1	190805	
Germany	EU-27	83166711	842	0.0101	Denmark	EU-27	R10	190805	
Germany	EU-27	83166711	294	0.0035	Denmark	EU-27	R13	190805	
Germany	EU-27	83166711	6,516	0.0783	Denmark	EU-27	R3	190805	
Germany	EU-27	83166711	12,250	0.1473	France	EU-27	R3	190805	
Germany	EU-27	83166711	5,808	0.0698	Switzerland	EFTA	R1	190805	
Germany	EU-27	83166711	5,552	0.0668	Switzerland	EFTA	R12	190805	
Germany	EU-27	83166711	3,228	0.0388	Switzerland	EFTA	R12	190805	
Germany	EU-27	83166711	1,934	0.0233	Belgium	EU-27	R1	190805	
Germany	EU-27	83166711	290	0.0035	Austria	EU-27	R1	190805	
Greece	EU-27	10718565	8,321	0.7763	Cyprus	EU-27	R1	190805	sludges from treatment of urban waste water

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									(EWC 19 08 05)
Italy	EU-27	59641488	598	0.0100	France	EU-27	R3	190805	
Italy	EU-27	59641488	811	0.0136	Germany	EU-27	R1	190805	
Italy	EU-27	59641488	456	0.0076	Belgium	EU-27	R12	190805	
Italy	EU-27	59641488	1,379	0.0231	Austria	EU-27	R1	190805	
Italy	EU-27	59641488	1,604	0.0269	Croatia	EU-27	R1	190805	
Italy	EU-27	59641488	16,412	0.2752	Spain	EU-27	R3	190805	
Italy	EU-27	59641488	3,400	0.0570	Switzerland	EFTA	R1	190805	
Italy	EU-27	59641488	16,707	0.2801	Switzerland	EFTA	D10	190805	
Italy	EU-27	59641488	2,304	0.0386	Hungary	EU-27	R3	190805	
Luxembourg	EU-27	626108	1,699	2.7136	Germany	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	626108	587	0.9375	Germany	EU-27	R13	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	626108	1,146	1.8304	Belgium	EU-27	R5	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	626108	504	0.8050	Germany	EU-27	D10	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	626108	607	0.9695	France	EU-27	R3	190805	boues provenant du traitement des

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
									eaux usées urbaines
Luxembourg	EU-27	626108	941	1.5029	France	EU-27	R3	190805	boues provenant du traitement des eaux usées urbaines
Portugal	EU-27	10295909	3,005	0.2918	Spain	EU-27	R3	190805	Lamas do tratamento de águas residuais urbanas
Slovenia	EU-27	2095861	3,671	1.7518	Hungary	EU-27	R10	190805	sludges from treatment of urban waste water
Slovenia	EU-27	2095861	2,511	1.1979	Hungary	EU-27	R3	190805	sludges from treatment of urban waste water
Slovenia	EU-27	2095861	4,557	2.1743	Slovakia	EU-27	R3	190805	sludges from treatment of urban waste water
Slovenia	EU-27	2095861	916	0.4369	Croatia	EU-27	R1	190805	sludges from treatment of urban waste water
Slovenia	EU-27	2095861	4,530	2.1613	Austria	EU-27	R3	190805	sludges from treatment of urban waste water
Slovenia	EU-27	2095861	3,406	1.6249	Austria	EU-27	R1	190805	sludges from treatment of urban waste water

Country reporting	Country Category	Population	Quantity in tons	Quantity in kg per capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Slovenia	EU-27	2095861	5,791	2.7629	Austria	EU-27	Mix	190805	sludges from treatment of urban waste water
Sweden	EU-27	10327589	1,892	0.1832	Finland	EU-27	R3	190805	sludges from treatment of urban waste water
Finland	EU-27	5525292	351	0.0635	Sweden	EU-27	R3	Mix	Sewage sludge

Table D-13: Sewage sludge imports to EU, EFTA and OECD (non-EFTA) countries for 2020; data from Eurostat [226] Last updated: 12/7/2023

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8901064	1382	0.1553	Italy	EU-27	R1	190805	sewer sludge
Austria	EU-27	8901064	1890	0.2124	Slovenia	EU-27	R12	190805	sewer sludge
Austria	EU-27	8901064	3721	0.4181	Slovenia	EU-27	R13	190805	sewer sludge
Austria	EU-27	8901064	4535	0.5095	Slovenia	EU-27	R3	190805	sewer sludge
Austria	EU-27	8901064	3396	0.3815	Slovenia	EU-27	R1	190805	sewer sludge
Austria	EU-27	8901064	187	0.0210	Slovenia	EU-27	D15	190805	sewer sludge
Belgium	EU-27	11522440	35337	3.0668	Netherlands	EU-27	D10	190805	
Belgium	EU-27	11522440	16451	1.4277	Netherlands	EU-27	R1	190805	
Belgium	EU-27	11522440	543	0.0471	France	EU-27	R5	190805	
Belgium	EU-27	11522440	1819	0.1578	France	EU-27	D10	190805	
Belgium	EU-27	11522440	904	0.0784	France	EU-27	R10	190805	
Belgium	EU-27	11522440	1539	0.1336	Luxembourg	EU-27	R5	190805	
Belgium	EU-27	11522440	1907	0.1655	Germany	EU-27	R5	190805	
Belgium	EU-27	11522440	452	0.0393	Italy	EU-27	R1	190805	

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Croatia	EU-27	4058165	1602	0.3947	Italy	EU-27	R1	190805	19 08 05
Croatia	EU-27	4058165	916	0.2257	Slovenia	EU-27	R1	190805	19 08 05
Denmark	EU-27	5822763	5950	1.0219	Germany	EU-27	R3	190805	190805
Denmark	EU-27	5822763	304	0.0522	Germany	EU-27	R13	190805	190805
Denmark	EU-27	5822763	10356	1.7785	Germany	EU-27	R10	190805	190805
Finland	EU-27	5525292	1892	0.3424	Sweden	EU-27	R3	190805	Sewage sludge
Germany	EU-27	83166711	87779	1.0555	Netherlands	EU-27	D10	190805	
Germany	EU-27	83166711	22761	0.2737	Netherlands	EU-27	R1	190805	
Germany	EU-27	83166711	6383	0.0768	Netherlands	EU-27	R12	190805	
Germany	EU-27	83166711	829	0.0100	Italy	EU-27	R1	190805	
Germany	EU-27	83166711	1699	0.0204	Luxembourg	EU-27	R1	190805	
Germany	EU-27	83166711	983	0.0118	Luxembourg	EU-27	R13	190805	
Germany	EU-27	83166711	504	0.0061	Luxembourg	EU-27	D10	190805	
Germany	EU-27	83166711	2340	0.0281	Austria	EU-27	R3	190805	
Germany	EU-27	83166711	2274	0.0273	Austria	EU-27	D10	190805	
Germany	EU-27	83166711	14886	0.1790	Belgium	EU-27	D10	190805	
Germany	EU-27	83166711	10447	0.1256	Austria	EU-27	R5	190805	
Germany	EU-27	83166711	758	0.0091	Belgium	EU-27	R1	190805	
Germany	EU-27	83166711	372	0.0045	France	EU-27	R1	190805	
Hungary	EU-27	9769526	2303	0.2357	Italy	EU-27	R3	190805	sludges from treatment of urban waste water
Hungary	EU-27	9769526	3671	0.3758	Slovenia	EU-27	R10	190805	sludges from treatment of urban waste water
Hungary	EU-27	9769526	2511	0.2570	Slovenia	EU-27	R3	190805	sludges from treatment of urban

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
									waste water
Latvia	EU-27	1907675	66	0.0345	Germany	EU-27	R1	190805	sludges from treatment of urban waste water
Luxembourg	EU-27	626108	796	1.2713	France	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	626108	1417	2.2632	Belgium	EU-27	R5	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	626108	803	1.2825	Netherlands	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Slovakia	EU-27	5457873	4630	0.8483	Slovenia	EU-27	R3	190805	
Spain	EU-27	47332614	387	0.0082	Andorra	Non-OECD	R3	190805	Lodos del tratamiento de aguas residuales urbanas.
Spain	EU-27	47332614	3145	0.0664	Portugal	EU-27	R3	190805	
Spain	EU-27	47332614	921	0.0195	Italy	EU-27	R3	190805	Llots de tractament d'aigues residuals urbanes
Spain	EU-27	47332614	2971	0.0628	Italy	EU-27	R3	190805	Llots de tractament

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
									d'aigües residuals urbanes
Spain	EU-27	47332614	5408	0.1143	Italy	EU-27	R3	190805	Llots de tractament d'aigues residuals urbanes
Spain	EU-27	47332614	4740	0.1002	Italy	EU-27	R3	190805	Llots de tractament d'aigües residuals urbanes
Spain	EU-27	47332614	2298	0.0486	Italy	EU-27	R3	190805	Llots del tractament d'aigües residuals urbanes

Table D-14: Sewage sludge exports from EU, EFTA and OECD (non-EFTA) countries for 2021; data from Eurostat [226] Last updated: 12/7/2023

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8932664	9697	1.0856	Germany	EU-27	R5	190805	sewer sludge
Austria	EU-27	8932664	2436	0.2727	Hungary	EU-27	R10	190805	sewer sludge
Austria	EU-27	8932664	11486	1.2858	Switzerland	EFTA	R1	190805	sewer sludge
Austria	EU-27	8932664	968	0.1084	Switzerland	EFTA	R12	190805	sewer sludge
Austria	EU-27	8932664	7692	0.8611	Germany	EU-27	R12	190805	sewer sludge
Belgium	EU-27	11566041	74	0.0064	Luxembourg	EU-27	R1	190805	
Belgium	EU-27	11566041	325	0.0281	France	EU-27	R10	190805	

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Belgium	EU-27	11566041	649	0.0561	France	EU-27	R3	190805	
Belgium	EU-27	11566041	670	0.0579	Germany	EU-27	R1	190805	
Belgium	EU-27	11566041	7958	0.6881	Germany	EU-27	D10	190805	
Germany	EU-27	83155031	25339	0.3047	Netherlands	EU-27	R12	190805	
Germany	EU-27	83155031	4277	0.0514	Denmark	EU-27	R3	190805	
Germany	EU-27	83155031	6460	0.0777	Switzerland	EFTA	R1	190805	
Germany	EU-27	83155031	3349	0.0403	Switzerland	EFTA	R12	190805	
Germany	EU-27	83155031	5159	0.0620	Switzerland	EFTA	R12	190805	
Germany	EU-27	83155031	1868	0.0225	Belgium	EU-27	R1	190805	
Germany	EU-27	83155031	5055	0.0608	Austria	EU-27	R1	190805	
Greece	EU-27	10682547	14013	1.3118	Cyprus	EU-27	R1	190805	sludges from treatment of urban waste water (EWC 19 08 05)
Italy	EU-27	59257566	5141	0.0868	Germany	EU-27	R1	190805	
Italy	EU-27	59257566	333	0.0056	Austria	EU-27	R1	190805	
Italy	EU-27	59257566	1360	0.0230	Belgium	EU-27	R12	190805	
Italy	EU-27	59257566	384	0.0065	Belgium	EU-27	R1	190805	
Italy	EU-27	59257566	6563	0.1108	Croatia	EU-27	R1	190805	
Italy	EU-27	59257566	73	0.0012	Denmark	EU-27	R1	190805	
Italy	EU-27	59257566	25555	0.4312	Spain	EU-27	R3	190805	
Italy	EU-27	59257566	1174	0.0198	Switzerland	EFTA	D10	190805	
Italy	EU-27	59257566	2912	0.0491	Switzerland	EFTA	R1	190805	
Italy	EU-27	59257566	2119	0.0358	Netherlands	EU-27	D10	190805	
Luxembourg	EU-27	634730	914	1.4400	Germany	EU-27	R11	190805	boues provenant du traitement des eaux usées urbaines

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	To country	To country category	Disposal and recovery code	European List of Waste code	Notes
Luxembourg	EU-27	634730	2785	4.3877	Germany	EU-27	R1	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	634730	2689	4.2364	Germany	EU-27	R13	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	634730	4935	7.7750	Germany	EU-27	D10	190805	boues provenant du traitement des eaux usées urbaines
Luxembourg	EU-27	634730	193	0.3041	Belgium	EU-27	R5	190805	boues provenant du traitement des eaux usées urbaines
Portugal	EU-27	10298252	139	0.0135	Spain	EU-27	R3	190805	Lamas do tratamento de águas residuais urbanas
Finland	EU-27	5533793	364	0.0658	Sweden	EU-27	R3	Mix	Sewage sludge

Table D-15: Sewage sludge imports to EU, EFTA and OECD (non-EFTA) countries for 2021; data from Eurostat [226] Last updated: 12/7/2023

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Austria	EU-27	8932664	333	0.0372	Italy	EU-27	R1	190805	sewer sludge
Austria	EU-27	8932664	194	0.0217	Slovenia	EU-27	R13	190805	sewer sludge
Austria	EU-27	8932664	6254	0.7001	Slovenia	EU-27	R3	190805	sewer sludge
Austria	EU-27	8932664	8195	0.9174	Slovenia	EU-27	R1	190805	sewer sludge
Austria	EU-27	8932664	3857	0.4317	Slovenia	EU-27	R12	190805	sewer sludge
Austria	EU-27	8932664	110	0.0123	Slovenia	EU-27	D15	190805	sewer sludge
Austria	EU-27	8932664	600	0.0672	Bosnia and Herzegovina	Non-OECD	R1	190805	sewer sludge
Belgium	EU-27	11566041	200	0.0173	Netherlands	EU-27	R5	190805	
Belgium	EU-27	11566041	37236	3.2194	Netherlands	EU-27	D10	190805	
Belgium	EU-27	11566041	11306	0.9775	Netherlands	EU-27	D10	190805	
Belgium	EU-27	11566041	17605	1.5221	Netherlands	EU-27	R1	190805	
Belgium	EU-27	11566041	484	0.0419	France	EU-27	R5	190805	
Belgium	EU-27	11566041	1868	0.1615	Germany	EU-27	R1	190805	
Belgium	EU-27	11566041	1015	0.0878	France	EU-27	D10	190805	
Belgium	EU-27	11566041	2240	0.1936	France	EU-27	D10	190805	
Belgium	EU-27	11566041	529	0.0458	France	EU-27	R10	190805	
Belgium	EU-27	11566041	24	0.0021	France	EU-27	R1	190805	
Belgium	EU-27	11566041	195	0.0169	Luxembourg	EU-27	D10	190805	
Belgium	EU-27	11566041	1793	0.1551	Luxembourg	EU-27	R5	190805	
Belgium	EU-27	11566041	1745	0.1509	Italy	EU-27	R1	190805	
Croatia	EU-27	4036355	5522	1.3680	Italy	EU-27	R1	190805	19 08 05
Croatia	EU-27	4036355	1661	0.4116	Slovenia	EU-27	R1	190805	19 08 05
Denmark	EU-27	5840045	73	0.0125	Italy	EU-27	Mix	190805	AC270
Denmark	EU-27	5840045	3725	0.6378	Germany	EU-27	R3	190805	AC270

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
Finland	EU-27	5533793	2116	0.3823	Sweden	EU-27	R3	190805	Sewage sludge
Germany	EU-27	83155031	7913	0.0952	Belgium	EU-27	D10	190805	
Germany	EU-27	83155031	9682	0.1164	Austria	EU-27	R5	190805	
Germany	EU-27	83155031	670	0.0081	Belgium	EU-27	R1	190805	
Germany	EU-27	83155031	5836	0.0702	Luxembourg	EU-27	D10	190805	
Germany	EU-27	83155031	2824	0.0340	Luxembourg	EU-27	R1	190805	
Germany	EU-27	83155031	5020	0.0604	Italy	EU-27	R1	190805	
Germany	EU-27	83155031	2100	0.0252	Netherlands	EU-27	R12	190805	
Germany	EU-27	83155031	25259	0.3038	Netherlands	EU-27	R1	190805	
Germany	EU-27	83155031	3222	0.0388	Luxembourg	EU-27	R13	190805	
Germany	EU-27	83155031	56376	0.6780	Netherlands	EU-27	D10	190805	
Hungary	EU-27	9730772	2437	0.2504	Austria	EU-27	R10	190805	sludges from treatment of urban waste water
Hungary	EU-27	9730772	14006	1.4393	Slovenia	EU-27	R3	190805	sludges from treatment of urban waste water
Luxembourg	EU-27	634730	74	0.1166	Belgium	EU-27	R5	190805	boues provenant du traitement des eaux usées urbaines
Spain	EU-27	47394223	374	0.0079	Andorra	Non-OECD	R3	190805	Lodos de tratamiento de aguas residuales urbanas
Spain	EU-27	47394223	5775	0.1218	Italy	EU-27	R3	190805	Llots de tractament d'aigües residuals

Country reporting	Country Category	Population	Quantity, t	Quantity, kg/capita	From country	From country category	Disposal and recovery code	European List of Waste code	Notes
									urbanes
Spain	EU-27	47394223	2101	0.0443	Italy	EU-27	R3	190805	Llots de tractament d'aigües residuals urbanes
Spain	EU-27	47394223	13759	0.2903	Italy	EU-27	R3	190805	Llots de tractament d'aigües residuals urbanes
Spain	EU-27	47394223	139	0.0029	Portugal	EU-27	R3	190805	

Table D-16: Treatment operations of sewage sludge; data collected from Eurostat [ENV_WW_SPD] last updated: 12/8/2022

	Agricultural use		Compost and other applications		Landfill		Incineration		Other		Unspecified1
Region	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr	Reference years	kt/yr
European Union - 27 countries	2727.6	sum of available data	994.5	sum of available data	832.8	sum of available data	2316.4	sum of available data	767.6	sum of available data	717.4
European Union - 28 countries	3708.9	sum of available data	994.5	sum of available data	839.5	sum of available data	2560.7	sum of available data	769.3	sum of available data	922.3
Austria	48.7	2018-20	46.6	2018-20	0.3	2018-20	116.9	2018-20	19.4	2018-20	0.0
Belgium	34.6	2018-20	0.0	2018-20	0.0	2018-20	116.8	2018-20	3.7	2018-20	10.4
Bulgaria	26.0	2017-19	3.2	2017-19	4.1	2017-19	0.0	2017-19	7.0	2017-19	15.1
Croatia	0.8	2018-20	0.6	2018-20	0.7	2018-20	0.3	2018-20	1.8	2018-20	16.5

	Agricultural use		Compost and other applications		Landfill		Incineration		Other		Unspecified1
Cyprus	1.2	2016-18	2.8	2016-18	0.0	2016-18	0.6	2016-18	3.1	2016-18	0.0
Czechia	102.5	2018-20	79.3	2018-20	18.7	2018-20	22.3	2018-20	0.0	not available	0.0
Denmark	74.0	2010	0.0	not available	1.4	2010.0	33.8	2010	5.6	2010	26.2
Estonia	8.6	2018-20	7.8	2018-20	1.9	2018-20	0.0	2009	0.0	2009	3.0
Finland	67.4	2017-19	81.1	2017-19	4.6	2017-19	2.5	2017-19	0.5	2016-18	-0.1
France	342.7	2015-2017	294.3	2015-2017	9.0	2015-2017	141.0	2015-2017	27.3	2015-2017	325.0
Germany	293.2	2017-19	168.8	2017-19	0.0	2017-19	1259.5	2017-19	12.0	2017-19	32.2
Greece	10.2	2017-19	0.0	not available	36.8	2017-19	37.7	2017-19	18.6	2017-19	0.0
Hungary	35.4	2017-19	158.3	2017-19	1.4	2017-19	35.1	2017-19	0.0	2017-19	12.7
Ireland	49.3	2018-20	7.7	2018-20	0.1	2018-20	0.0	2018-20	0.3	2018-20	0.0
Italy	315.6	2010	0.0	not available	462.2	2010.0	36.7	2010	94.7	2010	193.5
Latvia	5.7	2018-20	6.3	2018-20	0.3	2018-20	0.0	2018-20	8.5	2018-20	3.2
Lithuania	14.4	2018-20	16.5	2018-20	2.9	2018-20	6.1	2018-20	0.3	2018-20	1.6
Luxembourg	1.9	2018-20	1.7	2018-20	0.0	2018-20	2.0	2018-20 (estimation)	3.6	2018-20 (estimation)	0.0
Malta	0.0	2018-20	0.0	2018-20	9.4	2018-20	0.0	2018-20	0.0	2018-20	0.0
Netherlands	0.0	2016, 18, 20	1.4	2016, 18, 20	11.5	2016, 18, 20	295.2	2016, 18, 20	4.3	2016, 18, 20	35.4
Poland	126.6	2018-20	28.4	2018-20	9.0	2018-20	93.4	2018-20	318.1	2018-20	0.0
Portugal	49.3	2012, 14, 16	0.0	not available	6.7	2012, 14, 16	0.1	2012	75.0	2014, 16	50.2
Romania	48.0	2018-20	7.1	2018-20	133.0	2018-20	1.3	2018-20	54.7	2018-20	0.0
Slovakia	0.0	2018-20	25.8	2018-20	9.3	2018-20	12.2	2018-20	8.1	2018-20	0.0

	Agricultural use		Compost and other applications		Landfill		Incineration		Other		Unspecified1
Slovenia	0.0	2018-20	0.5	2018-20	0.5	2018-20	10.5	2018-20	23.2	2018-20	0.0
Spain	997.1	2016-18	0.0	not available	105.8	2016-18	89.3	2016-18	0.0	not available	0.0
Sweden	74.3	2016-18	56.2	2014, 16, 18	3.0	2014, 16, 18	3.1	2014, 16, 18	61.5	2014, 16, 18	9.0
United Kingdom	981.3	2010, 12	0.0	not available	6.8	2010, 12	244.3	2010, 12	1.7	2010, 12	204.9

[1] Determined with the mass balance

Annex E: Detailed data related to CS3: Agricultural sector

The detailed data that describe the quantities of agricultural value chain flows are displayed in detail in the following Tables. The illustrated data constitute estimations based on FAOSTAT data about the production quantities for each agricultural commodity, as described in Section 4.4.4.1.

Table E-1: Obtained straw quantities derived from wheat, barley, oats, rye, triticale and soybean cultivations for each EU country (mean value for 2019-2021)

Country	Available wheat straw (kt)	Available barley straw (kt)	Available oat straw (kt)	Available rye straw (kt)	Available triticale straw (kt)	Available soybean straw (kt)
Austria	399	243	23	75	107	111
Belgium	454	103	5	1	13	-
Bulgaria	1607	183	8	5	15	4
Croatia	215	91	17	2	22	124
Cyprus	6	10	-	60	-	-
Czechia	1251	528	48	296	64	14
Denmark	1062	1124	94	32	17	-
Estonia	188	148	27	42	12	-
Finland	189	414	299	61	-	-
France	9531	3515	118	1323	539	218
Germany	5855	3276	188	7	721	43
Greece	292	110	21	34	13	2
Hungary	1381	458	21	-	111	86
Ireland	145	433	56	5	-	-
Italy	1829	332	68	67	20	530
Latvia	578	83	66	37	10	-
Lithuania	1033	179	58	2	114	1
Luxembourg	20	10	2	0	10	-
Malta	-	-	-	3	-	-
Netherlands	264	68	2	1027	2	-
Poland	2969	922	419	-	1477	8
Portugal	19	18	13	7	8	-
Romania	2485	50	72	12	103	224
Slovakia	513	187	9	18	11	61
Slovenia	38	34	1	1	9	2
Spain	1889	2848	319	129	197	3
Sweden	769	412	190	73	59	-
United Kingdom	3586	2312	302	45	19	-

Country	Available wheat straw (kt)	Available barley straw (kt)	Available oat straw (kt)	Available rye straw (kt)	Available triticale straw (kt)	Available soybean straw (kt)
EU-28	**38,569**	**18,542**	**2,448**	**3,363**	**3,672**	**1,429**

Table E-2: Obtained straw quantities derived from rice and stem/stalks derived from maize, sunflower and rapeseed cultivations for each EU country (mean value for 2019-2021)

Country	Available rice straw (kt)	Available maize stalks/stems (kt)	Available sunflower stalks/stems (kt)	Available rapeseed stalks/stems (kt)
Austria	-	777	33	48
Belgium	-	141	-	15
Bulgaria	20	1142	956	177
Croatia	-	758	59	48
Cyprus	-	-	-	-
Czechia	-	265	19	558
Denmark	-	14	-	316
Estonia	-	0	-	99
Finland	-	1397	-	19
France	23	4525	812	1648
Germany	-	1321	34	1605
Greece	78	406	130	5
Hungary	3	2503	870	411
Ireland	-	0	-	22
Italy	465	2082	148	23
Latvia	-	0	-	210
Lithuania	-	37	-	419
Luxembourg	-	0	-	4
Malta	-	0	-	0
Netherlands	-	53	-	3
Poland	-	1922	9	1351
Portugal	49	238	5	-
Romania	8	4604	1439	481
Slovakia	-	507	78	210
Slovenia	-	128	-	4
Spain	223	1413	412	94
Sweden	-	4	-	173
United Kingdom	-	-	-	614
EU-28	**870**	**24,237**	**5,004**	**8,555**

Table E-3: Obtained pruning quantities derived from olive, grape, almond and apple trees for each EU country (mean value for 2019-2021)

Country	Available olive tree prunings(kt)	Available grapevine prunings (kt)	Available almond tree prunings (kt)	Available apple tree prunings (kt)
Austria	-	59	-	6
Belgium	-	1	1	5
Bulgaria	-	38	-	4
Croatia	12	27	2	5
Cyprus	7	9	-	-
Czechia	-	21	-	7
Denmark	-	-	1	1
Estonia	-	-	-	1
Finland	-	-	-	1
France	11	990	-	51
Germany	-	132	-	34
Greece	541	129	12	11
Hungary	-	80	-	27
Ireland	-	-	-	1
Italy	702	917	34	54
Latvia	-	-	-	3
Lithuania	-	-	-	10
Luxembourg	-	2	-	-
Malta	-	1	-	-
Netherlands	-	-	-	6
Poland	-	1	-	155
Portugal	235	230	34	14
Romania	-	220	-	52
Slovakia	-	10	-	2
Slovenia	1	20	-	2
Spain	1615	1219	463	29
Sweden	-	-	-	1
United Kingdom	-	1	-	14
EU-28	3123	4104	548	498

Table E-4: Obtained pruning quantities derived from orange, peach, cherry and pear trees for each EU country (mean value for 2019-2021)

Country	Available orange tree prunings(kt)	Available peach prunings (kt)	Available cherry tree prunings (kt)	Available pear tree prunings (kt)
Austria	-	-	-	1
Belgium	-	-	1	12

Country	Available orange tree prunings(kt)	Available peach prunings (kt)	Available cherry tree prunings (kt)	Available pear tree prunings (kt)
Bulgaria	-	3	9	1
Croatia	-	1	1	1
Cyprus	1	-	-	-
Czechia	-	-	1	1
Denmark	-	-	-	-
Estonia	-	-	-	-
Finland	-	-	-	-
France	1	9	6	7
Germany	-	-	5	3
Greece	24	39	16	6
Hungary	-	4	3	3
Ireland	-	-	-	-
Italy	68	54	25	32
Latvia	-	-	-	-
Lithuania	-	-	-	1
Luxembourg	-	-	-	-
Malta	-	-	-	-
Netherlands	-	-	-	12
Poland	-	1	9	7
Portugal	14	4	6	13
Romania	-	-	3	4
Slovakia	-	-	-	-
Slovenia	-	-	-	-
Spain	116	69	25	24
Sweden	-	-	-	-
United Kingdom	-	-	1	2
EU-28	225	186	111	130

Table E-5: Produced olive kernels and olive pomace for European countries with reported olive oil production (mean value for 2019-2021)

Country	Olive kernel (kt)	Olive pomace (kt)
Croatia	3	3
Cyprus	4	4
France	4	4
Greece	247	221
Italy	255	229
Portugal	99	89
Slovenia	1	0
Spain	1140	1022
Total	1753	1572

Table E- 6: Imported and exported quantities of Cereal straw and husks (HS-Product code: 121300), mean value for the years 2019-2022 (Source: WITS database)

	Imports (t/y)*	Exports (t/y)*
Switzerland	360,709	231
Netherlands	184,818	58,077
Germany	124,263	165,268
France	50,731	524,749
Belgium	126,430	38,451
United Kingdom	37,533	15,505
Portugal	194,154	5,166
Hungary	69,343	45,938
Italy	31,672	56,680
Spain	39,660	271,669
Denmark	9,767	3,792
Luxembourg	6,983	4,442
Czech Republic	9,397	8,434
Romania	4,257	86,230
Poland	5,882	122,502
Sweden	2,725	3,727
Latvia	6,887	127
Slovenia	6,661	3,381
Ireland	9,415	4,205
Slovak Republic	2,442	21,736
Greece	2,626	485
Norway	1,975	101
Malta	2,200	-
Croatia	1,109	997
Finland	212	113
Bulgaria	1,518	10,091
Lithuania	119	18,812
Estonia	118	2,996
Cyprus	117	-

*Considering imports and exports among EU countries. In the total EU results, the traded quantities only with countries outside the EU are included.

Annex F: Detailed data related to CS4: Forestry sector

In Annex F the data that are retrieved for the forestry sector, are presented in detail.

Table F-1: Woodchips, bark and sawdust production quantities (mean value for 2019-2021); Calculated quantities based on FAOSTAT database

Country	Wood chips production (m^3)	Wood chips production (kt ^{db})	Bark production (kt^{db})	Sawdust production (kt^{db})
Austria	3,838,000	1458	483	202
Belgium	855,333	325	163	59
Bulgaria	110,654	42	122	32
Croatia	493,544	188	114	52
Cyprus	2356	1	0	0
Czechia	1,011,006	384	1008	398
Denmark	168,030	64	67	22
Estonia	2,387,350	907	254	90
Finland	9,939,344	3777	2077	501
France	6,345,115	2411	955	354
Germany	11,494,980	4368	2166	950
Greece	2500	1	16	7
Hungary	852,000	324	98	25
Ireland	655,000	249	138	51
Italy	4,215,406	1602	221	86
Latvia	3,740,933	1422	479	157
Lithuania	1,117,667	425	177	70
Luxembourg	422,460	161	10	2
Malta	0	0	0	0
Netherlands	82,533	31	26	5
Poland	2,791,148	1061	1420	366
Portugal	1,085,376	412	444	42
Romania	130,402	50	430	192
Slovakia	766,667	291	283	92
Slovenia	661,333	251	113	45
Spain	1,790,177	680	543	97
Sweden	11,336,000	4308	2611	783
United Kingdom	2,247,652	854	316	128
EU-28	68,542,967	26,046	14,736	4,808

Table F-2: Fiber sludge and black liquor production quantities (mean value for 2019-2021); Calculated quantities based on FAOSTAT database

Country	Fiber sludge (kt^{db})	Black liquor (kt^{db})
Austria	109	2290
Belgium	38	489
Bulgaria	8	367
Croatia	8	0
Cyprus	0	0
Czechia	19	1011
Denmark	3	0
Estonia	2	118
Finland	196	13720
France	159	2783
Germany	491	2765
Greece	7	0
Hungary	19	0
Ireland	1	0
Italy	202	27
Latvia	1	8
Lithuania	3	0
Luxembourg	0	0
Malta	0	0
Netherlands	64	0
Poland	114	1700
Portugal	47	4636
Romania	12	0
Slovakia	20	1222
Slovenia	16	0
Spain	143	2167
Sweden	205	14894
United Kingdom	81	0
EU-28	1970	48197

Table F- 3: Imported and exported quantities of Coniferous wood in chips or particles (HS-Product code: 440121), mean value for the years 2019-2022 (Source: WITS database)

	Imports (t/y)*	Exports (t/y)*
Latvia	89,752	1,701,190
Germany	328,210	1,189,910
Estonia	4,960	1,370,390
Slovenia	42,086	448,269
Lithuania	119,085	183,451
Sweden	1,078,100	235,341
France	309,369	236,953
Austria	712,745	194,327
Slovak Republic	22,672	177,016
Czech Republic	61,386	189,675
Norway	141,155	245,373
Portugal	187,753	56,766
United Kingdom	42,906	70,509
Belgium	190,559	176,469
Finland	738,035	102,591
Poland	616,455	62,034
Netherlands	62,137	29,289
Croatia	24,455	71,089
Spain	9,257	43,111
Italy	295,550	23,916
Luxembourg	46,153	70,336
Denmark	885,866	35,408
Switzerland	171,702	14,560
Ireland	16,173	961
Bulgaria	17	4,105
Hungary	18,923	2,700
Romania	76,351	88
Greece	1,533	49
Iceland	37,261	1

*Considering imports and exports among EU countries. In the total EU results, the traded quantities only with countries outside the EU are included.

Table F- 4: Imported and exported quantities of Non-coniferous wood in chips or particles (HS-Product code: 440122), mean value for the years 2019-2022 (Source: WITS database)

	Imports (t/y)*	Exports (t/y)*
Portugal	1,455,990	24,493
Denmark	572,435	3,029
Finland	429,341	29,205
France	123,733	386,516
Spain	141,393	134,230
Netherlands	36,532	397,816
Belgium	439,642	133,768
Sweden	182,700	1,758
Italy	40,363	45,086
Lithuania	98,392	6,965
Austria	123,480	14,022
Germany	80,486	180,462
United Kingdom	20,207	50,368
Slovak Republic	40,685	2,456
Switzerland	65,916	26,512
Latvia	43,129	406,467
Czech Republic	40,892	36,152
Slovenia	48,233	173,874
Luxembourg	6,546	10,475
Romania	22,816	1,072
Hungary	12,336	15,120
Greece	3,323	478
Norway	1,502	84,042
Iceland	1,754	-
Estonia	8,835	21,298
Croatia	1,032	98,632
Bulgaria	762	8,322
Malta	355	-
Cyprus	57	10

Table F- 5: Imported and exported quantities of Sawdust, wood waste and scrap (HS-Product code: 440130), mean value for the years 2019-2022 (Source: WITS database)

	Imports (t/y)*	Exports (t/y)*
Germany	2,121,690	1,866,780
United Kingdom	9,315,540	9,180,690
Italy	4,166,410	2,517,410
Switzerland	334,347	223,802
Latvia	642,528	1,951,900
Austria	1,520,750	1,118,510
Estonia	41,104	1,443,590
Belgium	1,763,320	886,722
Poland	313,561	560,820
Lithuania	458,643	667,873
Czech Republic	396,073	841,560
Netherlands	2,561,050	576,138
Croatia	107,855	547,732
Portugal	64,162	626,938
Romania	195,896	431,222
Denmark	3,297,710	278,470
Sweden	1,073,960	746,185
Slovak Republic	158,938	305,454
Slovenia	255,817	270,080
France	1,833,900	618,511
Bulgaria	170,154	153,601
Norway	323,039	539,433
Ireland	7,727	7,916
Luxembourg	8,972	48,553
Finland	523,698	33,997
Hungary	69,145	26,153
Greece	145,813	10,184