Ref. Ares(2025)9621923 - 07/11/2025

ESCIB

D2.1 Mapping of High TRL Industrial Biobased Systems in EU

November, 2025

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Document Information	
Work package and deliverable number	WP2 - Identification of industrial biobased systems and benchmark scenarios, D2.1
Authors	Muhammad Zeeshan Khan, Omar Hijazi, Gabriele Weber-Blaschke
Involved organizations	All consortium partners
Reviewers	All consortium partners
Document date/version	Revised version; 06.11.2025
Project Information	
Project acronym	ESCIB
Project title:	Developing environmental sustainability & circularity assessment methodologies for industrial biobased systems
Project number:	101135071
Coordinator	WIP Renewable Energies
Project website	www.escib.eu
Start date:	1 January 2024
Duration:	48 months
Dissemination level of this document	
☒	Public
☐	Sensitive
Disclaimer	
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ACKNOWLEDGMENT & DISCLAIMER

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Abbreviations

BBS	Biobased System
IBBS	Industrial Biobased System
BBPs	Biobased Products
BBMs	Biobased Materials
CEAP	Circular Economy Action Plan
EGD	European Green Deal
EoL	End of Life
TRL	Technology Readiness Level

1 Introduction

1.1 Background and Objectives of the Project ESCIB

Organizations and countries worldwide have instituted policies and regulations to reduce the environmental impacts and to increase the overall sustainability of products. Thanks to this push, many innovations and novel technologies are being developed to produce materials and goods that are based on biomass. To assess if these products are better than conventional products, life cycle assessments are used. The results of these assessments enable us to evaluate the environmental impacts of the products that are under development or in the market already. A challenge, however, is that these assessments can be complicated, especially for products that are still under development, products that are based on so called low technology readiness levels (TRL).

The main objective of the ESCIB project is to support the sustainability of the biobased economy in Europe. To achieve this, ESCIB will develop assessment methodologies and thus contribute to the standardisation of such methodologies. The aim is to develop a comprehensive, robust and fully operational methodology to assess the sustainability of biobased systems (BBS) at various TRLs. This methodology is based on holistic life-cycle approach to evaluate the environmental impacts and circularity along biobased value chains. Potential socio-economic trade-offs will be addressed and included in the methodology. ESCIB's integrated way of analysing environmental and circularity impacts along biobased value chains is also fully in line with the ambition of the European Green Deal (EGD) and the Circular Economy Action Plan (CEAP).

With the involvement of five innovative industry partners in the consortium, which produce biobased products (BBPs) in different sectors, ESCIB will ensure high applicability of the method which can be used by certification organisations to label and certify products for the benefit of consumers and society. Finally, the results will give orientations for research and innovation programmes in the biobased sectors.

1.2 Objectives of the Report

The objective of work package (WP)2 of the ESCIB relates to the identification of best practice industrial biobased systems (IBBS) in EU in terms of environmental sustainability and circularity and selection of benchmarks. Therefore, the consortium works on several tasks in WP2 to come up with the identifications of IBBS in the EU. This report presents the following main aspects of IBBS in the EU;

- Definitions of important terms related to IBBS.
- Potential of feedstock availability in the EU and its member states.
- Feedstock supply and import dependency.
- Distribution of biobased industries and biorefineries in the EU.
- Range of BBPs.
- Biomass utilization for different sectors including BBPs.
- End of life (EoL) of biobased waste and potential of waste as raw material for different BBP sectors.

1.3 Deliverable D2.1 of WP2

This report presents the deliverable D2.1 under WP2 as shown in Table 1-1. This deliverable will be made available to the public on the project's website after its acceptance by the European Commission.

Table 1-1: Deliverable D2.1 information from the project grant agreement

Deliverable D2.1 – Mapping industrial bio-based systems

Deliverable Number	D2.1	**Lead Beneficiary**	4. TUM
Deliverable Name	Mapping industrial bio-based systems		
Type	R — Document, report	**Dissemination Level**	PU - Public
Due Date (month)	9	**Work Package No**	WP2

Description
List and descriptions of the identified high TRL industrial bio-based systems in the EU; Description and maps of value chains for relevant industrial bio-based systems (Related Tasks: T2.1)

2 Materials and Methods

2.1 Information Compilation

To analyse the comprehensive and accurate mapping of high TRL IBBS in the EU, a well-structured approach is required for up-to-date data and information collection regarding the IBBS. The scope of IBBS includes a complete supply chain that includes feedstocks production, bioindustry including biorefinery, end products, and EoL. Therefore, to present a comprehensive overview of the complex IBBS in the EU, information was collected by search of EU platforms, literature, experiences of experts, and input from ESCIB industrial project partners. The main sources used for data collection regarding the overview of the current outlook into high TRL IBBS in the EU are EUROSTAT, JRC, FAOSTAT, EU Forestry and agricultural balances and the Knowledge Centre for Bioeconomy. Mostly the data refers to the EU-27 region. Besides this, an extensive review was done for the EU reports to get a complete overview of the current materials sector uses of biomass and their corresponding feedstock origin in the BBS. Data collection was done starting from the feedstock availability in EU and then following along the supply chain of IBBS going into wood industry and biorefinery and producing the end products. Similarly, the current rate of recovery and disposal was also taken into consideration to get an overview of the products end of life (EoL) of existing IBBS in the EU. Looking into the latest developments, mostly the original data sources were reviewed, and the latest data was collected regarding the information from any EU reports or grey literature.

Furthermore, a data collection matrix was created for ESCIB industrial partners to collect industrial data for a complete supply chain for BBPs starting from the product going downstream to the feedstock origin as an example of the high and low TRL IBBS in EU. This data matrix also includes the EoL that includes waste collection, waste recovery (material or energy), and disposal. This information from the data matrix is presented as practical examples of IBBS in the EU (see Annex III and supplementary data). Some of the main data sources and articles that are used in this study are below;

1. EUROSTAT database; Available online: https://ec.europa.eu/eurostat/data/database
2. FAOSTAT database; Available online: https://www.fao.org/faostat/en/#data/FO
3. Knowledge Centre for Bioeconomy: https://knowledge4policy.ec.europa.eu/bioeconomy/monitoring_en
4. EU biomass flows; Source: *Gurria Albusac, P; Gonzalez Hermoso, H; Cazzaniga, N; Jasinevičius, G; Mubareka, S; De Laurentiis, V; Patinha Caldeira, C; Sala, S; Ronchetti, G; Guillen Garcia, J; Ronzon, T and M`barek, R; Publications Office of the European Union, Luxembourg, 2022*; Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC128384
5. Biobased industry and biorefineries in the EU; Source: *Parisi, Claudia; Baldoni, Edoardo; M'barek, Robert; European Commission, Joint Research Centre (2020); European Commission, Joint Research Centre (JRC)* Available online: http://data.europa.eu/89h/ee438b10-7723-4435-9f5e-806ab63faf37
6. Chemical and material biorefineries in the EU; *Baldoni, Edoardo; Reumerman, Patrick; Parisi, Claudia; Platt, Richard; González Hermoso, Hugo; Vikla, Kaisa; Vos, John; M'barek, Robert (2021); European Commission, Joint Research Centre (JRC).* Available online: https://data.jrc.ec.europa.eu/dataset/bd890922-fc66-41ca-b032-e02754b34a22
7. EU forestry, cereals and Oil balance sheets; (Cazzaniga et al. 2021; EU cereals balance sheets; EU Oil Seeds Balance Sheet 2024) Available online: https://knowledge4policy.ec.europa.eu/publication/wood-resource-balances_en; https://agriculture.ec.europa.eu/data-and-analysis/markets/overviews/balance-sheets-sector_en

8. Biomass production, supply, use and flows in the European Union; Source: *Avitabile, V; Baldoni, E; Baruth, B; Bausano, G; Boysen-Urban, K; Caldeira, C; Camia, A; Cazzaniga, N; Ceccherini, G; De Laurentiis, V; Doerner, H; Giuntoli, J; Gras,M; Guillen Garcia, J; Gurria, P; Hassegawa, M; Jasinevičius, G; Jonsson, R; Konrad, C; Kupschus, S; La Notte, A; M'barek, R; Mannini, A; Migliavacca, M; Mubareka, S; Patani, S; Pilli, R; Rebours, C; Ronchetti, G; Ronzon, T; Rougieux, P; Sala, S; Sánchez López, J; Sanye Mengual, E; Sinkko, T; Sturm, V; Van Leeuwen, M; Vasilakopoulos P; Verkerk, PJ; Virtanen, J; Winker, H; Zulian G; Joint Research Centre (European Commission) (2023)*; Available online: https://op.europa.eu/en/publication-detail/-/publication/993be4a7-b74c-11ed-8912-01aa75ed71a1/language-en
9. Insights into the European market for biobased chemicals; Source: *Spekreijse, J; Lammens, T; Parisi, C; Ronzon, T. and Vis, M; EUR 29581 EN, Publications Office of the European Union, Luxembourg, (2019);* Available online: https://publications.jrc.ec.europa.eu/repository/handle/JRC112989
10. Assessment of EU Biobased Economy Sectors Based on Environmental, Socioeconomic, and Technical Indicators; Source: *Víctor Fernández Ocamica; Monique Bernardes Figueirêdo; Sebastián Zapata and Carmen Bartolomé,* Available online: https://doi.org/10.3390/su16051971
11. Manual on waste statistics A handbook for data collection on waste generation and treatment; Source: *EUROSTAT, European Commission (2013);* Available online: https://ec.europa.eu/eurostat/web/products-manuals-and-guidelines/-/KS-RA-13-015

2.2 Mapping of high TRL Industrial Biobased Systems

Mapping of high TRL IBBS requires a complete overview of the available feedstocks, their use in biobased industries, and EoL to understand the current circularity and aspects of different BBP sectors. For mapping the whole IBBS, information collection is necessary to identify and analyse the high TRL IBBS. Existing information about the whole value chain of BBPs is available but not prepared for the objectives of this project, including the information on BBS along the whole supply chain. Table 2-1 lists general information topics regarding the whole value chain of IBBS.

Table 2-1: Mapping of key components for qualitative information collection.

▪ Availability of feedstock or feedstock production
▪ Imports of feedstocks into EU biobased supply
▪ Regional implementation of processes/plants/ (types according to systemization, often regarding type/number of platforms or products, TRL)
▪ Application/use/markets/product sectors in EU
▪ Generation of biogenic waste
▪ EoL management (recovery, disposal)

2.3 Data Quality and Limitations

The data presented in this report is sourced from multiple databases and published literature. However, some datasets were incomplete or estimated values, and certain figures needed additional organization to ensure meaningful interpretation. Furthermore, data availability, reporting years, and estimation methods varied across sources, which may influence the precision of the exact reported values. Therefore, readers are advised to interpret the results with these limitations in mind or consult the original sources for clarification.

2.4 Definitions for this Project

A common understanding of the terminology is necessary to collect information and get an overview of the existing IBBS and develop further methodologies in other work packages. Therefore, in this task, some definitions were also made to correctly identify and understand the common terminologies related to IBBS. Based on the compiled literature, definitions were reviewed and adapted to the objectives of this ESCIB project.

2.4.1 Biobased Products (BBPs)

Different organizations have defined BBPs, including the European Commission Single Market Economy (EC 2024), the United States Department of Agriculture (USDA 2024), and the Knowledge Centre of Bioeconomy (Knowledge Centre for Bioeconomy 2024). These definitions are related but sometimes formulated according to the scope of the project, as in the case of USDA, which defined BBP that does not include food and feed products. Therefore, according to the scope of the ESCIB project, the definition of BBPs is also formulated based on the scope of the project, which is only related to BBPs, excluding feed, food, and energy uses of biomass.

EU Standard (DIN EN 16575 D 2014) defines BBPs as a direct connection between the definition of biomass (material of biological origin, with the exception of material embedded in geological formations and/or transformed into fossil material) and product (substance or mixture of substances, materials resulting from a production process, that can be an intermediate product, material, semi-furnished or finished products), for which an intermediate step is required to get a BBP. After being harvested or collected, biomass can serve as a raw material in numerous processes and products. It can undergo physical, mechanical, chemical, or biological processing, leading to biobased materials or substances. These materials or substances can be further processed, either alone or in combination with other materials or substances (such as those of fossil or mineral origin), to create BBPs (i.e., products derived entirely or partially from biomass) (DIN EN 16575 D 2014).

Based on the above discussion, a BBP, according to the scope of ESCIB, is defined as.

Box 1: Definition of biobased products (Adapted from (USDA 2024), (EC 2024) and (Knowledge Centre for Bioeconomy 2024)).

> *“Industrial or commercial products (not including food, feed, and fuels) that are partially or entirely derived from biological origin materials, including plants, animals, enzymes, and microorganisms such as bacteria, fungi, and yeast, and specifically exclude materials found in geological formations or that have become fossilized. These products encompass those traditionally manufactured from biomass, such as wood products and textiles, and products historically produced from fossil fuels but now increasingly synthesized from biomass through advanced processes like fermentation and biocatalysis, including detergents, chemical intermediates, and polymers and provide alternates to the fossils-based products”.*

2.4.2 Biobased Materials (BBMs)

BBMs defined as follow by (DIN CERTCO 2020);

"Material that consists of non-fossil organic compounds. Those may be natural (e. g. cellulose) or synthetic (e. g. polylactide acid)".

According to the definition of BBM, it is made of non-fossil compounds that can be obtained from nature, i.e., cellulose, lignin, or pulp, or may be synthetic, i.e., polylactide acid. This means it is only made from non-fossil compounds and does not contain fossil compounds, hence fully biobased. Therefore, based on this the BBM is defined as below.

Box 2: Definition of biobased materials (Adapted from (DIN CERTCO 2020)).

> *BBMs are materials that are made entirely from non-fossil biological resources and do not contain any fossil-based components. They can be either naturally sourced (cellulose, lignin, pulp) or synthetic (polylactic acid).*

2.4.3 Industrial Biobased Systems (IBBS)

According to the objectives to assess environmental sustainability and circularity, the IBBS considered in this project go beyond biorefineries and beyond the production step. Thus, the definition of IBBS includes biomass paths without and with component separation as well as the whole life cycle respectively. Additionally, the value chains take also end-of-life-management into account. Therefore, the suggested definition for this project adapts the definition of Spekreijse et al. (2019) for IBBS, which is based on the European Commission's Lead Market Initiative (EC 2007) to the objectives of the ESCIB project (Box 3). Defining industry or industrial is critical because there is no suggested capacity of production in the literature that the facility should produce and can be called an industry. However, a database of biorefineries created in IEA Bioenergy Task 42 (2022) reveals that the biorefinery's capacity range is from less than 1 kilotons per year (kt/y) to more than 1000 kt/y. So, it is difficult to define the industry based on the production capacity per year, and more general specifications are used for the industry. Therefore, industrial that is related to industry is a facility that produces BBPs on a large and commercial scale using advanced machinery and processes.

Box 3: Definition of industrial biobased system for the ESCIB project (Adapted from (Spekreijse et al. 2019)).

> *In this project, industrial biobased systems refer to the whole value chain from biomass feedstock production till end-of-life-management of biobased products, which are used for material applications. Biobased products are products derived from biomass with a focus on forestry and agriculture, because the focus of this project is land use. Therefore, Algae and marine organisms are not included. Biomass feedstock includes primary biomass (i.e., biomass harvested in forests or on agricultural land) and secondary biomass (i.e., residues from land use, industrial residues like sawmill residues, shives, other by-products, etc., as well as waste biomass, like post-consumer wood, bio-plastic waste, food waste etc.). Biobased products may range from high value added fine chemicals such as pharmaceuticals, cosmetics, food additives, etc., to high volume materials such as building products, biopolymers or chemical feedstocks.*

2.4.4 Definition of Technology Readiness Level (TRL)

For defining TRL, the definition from Horizon EU 2020 (Horizon 2020) also cited in Spekreijse et al. (2019) was used in addition to the description made by EARTO (EARTO 2014) to better understand the products or technologies at different TRL scales, especially high TRL scales, as shown in Table 2-2. Furthermore, the TRL self-assessment tool developed in Horizon EU, 2020 by BRIDGE2HE project is considered to identify the right TRL in case of any further explanation for a product or a manufacturing technology (see supplementary information). This tool provides more description separately for a product or manufacturing technology with the examples that are placed at the respective TRL scale.

Table 2-2: Technology readiness level definition according to the Horizon EU 2020 (Horizon 2020).

TRL Scale	***Description***
TRL 1	*Basic principles observed*
TRL 2	*Technology concept formulated*
TRL 3	*Experimental proof of concept*
TRL 4	*Technology validated in lab*
TRL 5	*Technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)*
TRL 6	*Technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)*
TRL 7	*System prototype demonstration in operational environment*
TRL 8	*System complete and qualified*
TRL 9	*Actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)*

Spekreijse et al. (2019) focused on BBPs with a TRL of 8 or higher, because they are expected to have substantial market volumes and are already commercially available. Therefore, this aspect is transferred to a definition of high and low TRL and refers also to the selected case studies, see Table 2-3.

Table 2-3: Definition of high (TRL 8-9) and low TRL (TRL 3-7) and classification of selected case studies.

Enterprise	***Case Study***	***TRL*** ***High TRL = TRL 8 & 9*** ***Low TRL = TRL 3 - 7***
GrownBio	*Fungi-wood-composites for protective packaging* *Fungi-wood-composites for insulative panels*	*TRL 8-9* *TRL 3-4*
Lenzing	*Textile fibres*	*TRL 5-7*
Stora Enso	*Lignin-based products*	*TRL 3-7*
Unilin	*Chipboards from recycled wood using biobased glue/adhesives*	*TRL 2-3*
Biobased Supply	*Biobased composites*	*TRL 7-8*

It is difficult to adopt the TRL scale to a whole BBS, because it might be that e.g., the technology for feedstock conversion is demonstrated in relevant environment, but the specific application (e.g., packaging) has only achieved proof of concept. Therefore, the TRL scale has limitations related to the single technology maturity approach, which means it is not focused on the whole system but only on one component of the system (EARTO 2014). EARTO, therefore introduces a multi-technological aspect or approach to solve this issue. EARTO introduced a 2D TRL model where on one axis there is the TRL scale of the main product, while on the other axis is the TRL of its supportive or manufacturing technology. EARTO considers three routes that can be followed.

- Route 1:
  In this route, the product already uses well-researched technologies, but manufacturing of this product to reach a high TRL scale still needs further development (EARTO 2014).
- Route 2:
  If the development of the technology is only focused on the specific product development, then the TRL scale or maturity of the manufacturing technology or other product is already high. For example, a new BBP that has state-of-the-art manufacturing technology. This route is applied in the industrial sector, where the technology focuses on product development (EARTO 2014).
- Route 3:
  In this route, the product, as well as the technology, must be developed simultaneously to achieve the TRL scale (EARTO 2014).

Since, in the ESCIB project, the focus is on IBBS and associated products, it is assumed that while analysing the TRL scale of BBS, the study follows route 1. It means that if the final product in IBBS is at high TRL, it is assumed that the manufacturing technology as well as the intermediate products are also at high TRL.

2.4.5 Definition of Product Integration into the Market

For the assessment of the circularity of BBPs, the integration into the market and thereby the existing infrastructure of EoL management is important to know, which is described for chemical products, e.g. (Spekreijse et al. 2019). This is transferred to the BBPs (Box 4) for this project adapted from the work of (Felix et al. 2021; Spekreijse et al. 2019; Platt et al. 2021; M. Sara et al. 2016; Carus et al. 2019; US Department of energy 2018).

Box 4: Definition of drop-ins and dedicated biobased products based on market integration.

Type of product	***Description of type of biobased product***	***Status of end-of-life-management***
Drop-in products	▪ *Products that are direct replacements of fossils-based products having same chemical or functional properties.* ▪ *Bio-copy of existing fossils-based products that have well established markets.* ▪ *Unrecognizable in terms of structure and performance with respect to its fossil-based counterparts.* ▪ *Examples are butanol, liquified biomass, sugar hydrocarbons, syngas complexes, ethanol, lactic acid, ethylene, polyethylene (PE), polypropylene, polyethylene terephthalate (PET) etc.*	▪ *Existing fossils-based infrastructure (machinery, equipment) is used completely or partially.* ▪ *Economically cheap replacement due to use of existing infrastructure and less R&D.*
Novel products	▪ *Products that have completely different production pathway and are not the replacements of existing fossil-based products.* ▪ *They don't have an identical or equivalent fossils-based counterparts.* ▪ *Completely different structure and function.* ▪ *Examples of chemicals: e.g., levulinic acid, succinic acid, polyhydroxy-alkanoate (PHA), polylactic acid (PLA)).*	▪ *Completely new infrastructure is needed.* ▪ *More R&D is needed hence can be economically expensive.*

2.4.6 Definition of Circular Biobased Systems

For the objectives of this project, it is important to extend the view from BBPs to high TRL IBBS including,

- the life cycle perspective for the assessment.
- the circularity perspective for the assessment, regarding if,
  - any residues and recovered biomass are used and processed in biobased value-chains resp. in BBS.
  - any industrial residues / by-products are produced within the BBS and further used as resources for material applications.
  - an infrastructure of end-of-life management regarding further material use of the recovered BBP is available.

Thus, the preliminary overall system of a circular bioeconomy adapted to the project's focus is presented in Figure 2-1. This will be further developed and deepened in the project.

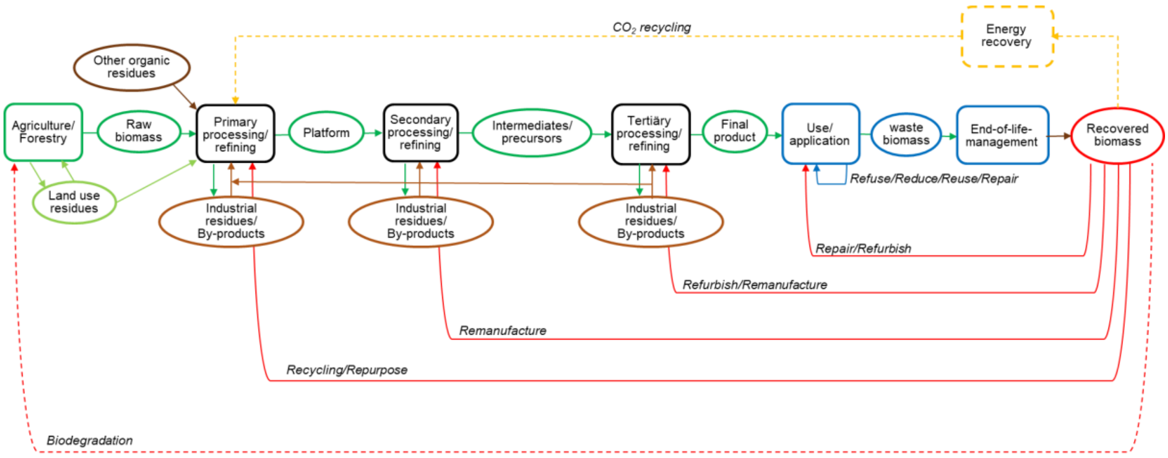

Figure 2-1: Preliminary overall system of circular bioeconomy Adapted to the projects focus (Modified based on the (German Federal Government 2012), and (vom Berg et al. 2022).

3 Overview and Description of Industrial Biobased Systems in EU-27

3.1 Range of high TRL Industrial Biobased Systems

To compile information about the IBBS, a complete overview is needed starting from the feedstock production, imports, production of BBPs, and EoL management that includes the recovery (energy, materials) and disposal (landfill, incineration) (Figure 3-1).

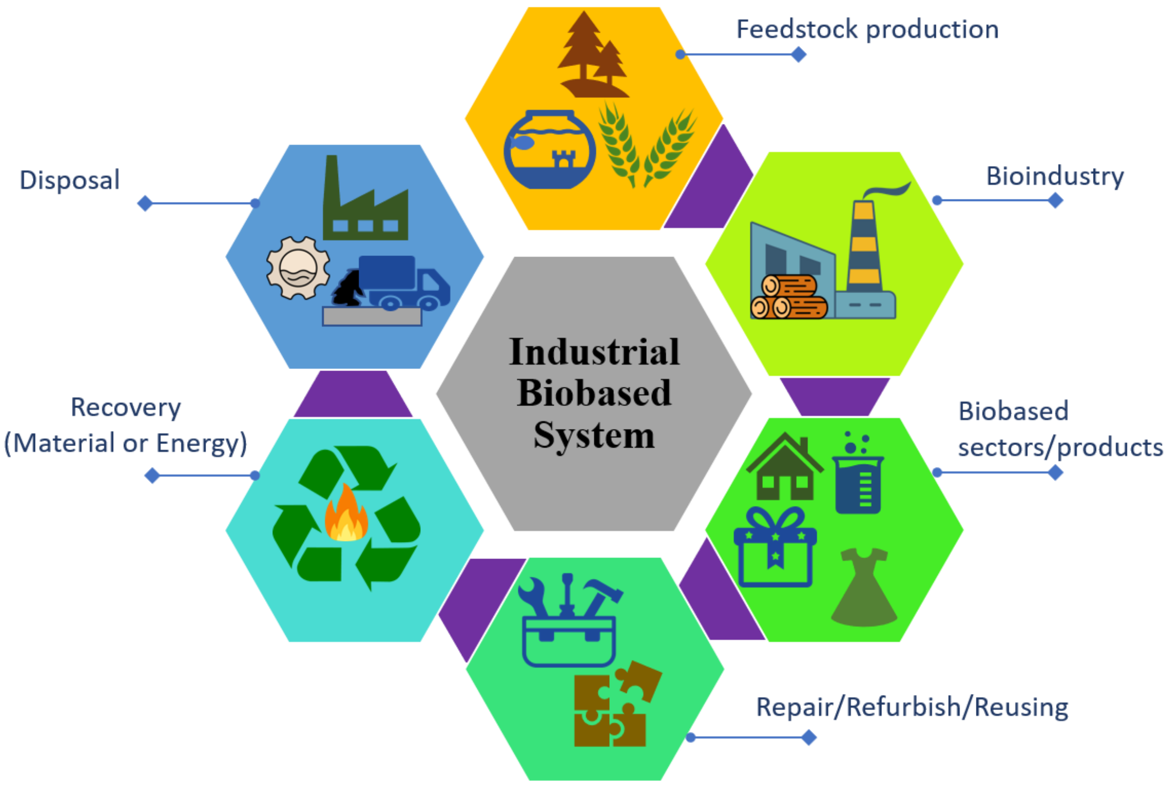

Figure 3-1: Elements and path of industrial biobased system.

According to the German Federal Government (German Federal Government 2012) there is a range of biomass utilisation options including both established and innovative approaches, whereby biorefineries complement this range with an additional path:

- Use of unmodified or modified biomass without component separation for chemicals/materials or bioenergy.
- Use of individual biomass components for chemicals/materials and/or bioenergy.
- Complete utilisation of the biomass components for chemicals/materials and/or bioenergy at various locations.
- Complete, integrated utilisation of the biomass components for chemicals/materials and/or bioenergy in one (networked) location for chemicals/materials and bioenergy.

In contrast, according to the "Biorefinery Outlook" (Platt et al. 2021), not only the integrated plants, but also the one platform plants are classified as biorefinery, i.e., except the first class listed above, the three other classes also fall into the concept biorefinery (refer also to (Buller et al. 2023; VDI 6310 2016). Thus, the differentiation between the following two main pathways/value chains seems useful to take the circularity perspective into account (Box 5).

Box 5: Classification of two different overall biobased paths

- Wood working and natural fibre industry:
  Processing without component separation and use of unmodified or modified biomass with the production of e.g., wood building products, packaging, furniture, which are often related to long-living products and reuse of solid materials.
- One and more platform biorefinery:
  Processing with component separation and use of individual and complete biomass components with production of e.g., materials (e.g., fibres), chemicals for further processing and refining.

Additionally, the value chains of the IBBS should go beyond the element “product” and should also include the elements “use/application”, “waste” and “EoL management”, because the whole life cycle as well as the circularity will be assessed. Thus, the elements of the BBS are extended based on the “elements of the biorefinery classification” of the German Federal Government (German Federal Government 2012) including information from (Aggestam and Giurca 2022; Spekreijse et al. 2019; Baldoni et al. 2021). These elements in the context of IBBSs that consists of modern biorefineries but also wood based industries, although look similar but have a differences based on the principle of component separation (*Box 5*) as shown in Table 3-1.

Table 3-1: Elements of industrial biobased system value chain categorized by component separation.

Elements of value chain	**Wood working and natural fibre industry** (processing without component separation)	**One and more platform Biorefinery** (processing with component separation)
Raw materials	→ Wood → Fibre plants → Agricultural and forestry residues → Industrial residues → Recovered wood, biomass See e.g., (German Federal Government 2012)	→ Oil crops → Starch crops → Sugar crops → Grasses → Wood → Woody biomass → Agricultural and forestry residues → Industrial residues → Recovered wood, biomass See e.g., (German Federal Government 2012; Gavrilescu 2014; Platt et al. 2021)
Primary processing/refining	→ Physical, mechanical processing (sawing, chipping, milling, grounding, defibrating, etc.) (Tobisch et al. 2023)	→ Mechanical, chemical and biochemical decomposition into complex molecules
Platform	→ Sawn wood → Veneers → Particles, Strands → Wood wool → Natural fibres See e.g., (Tobisch et al. 2023)	→ C5/C6 sugars → Lignin → Bio-oils → Proteins → Plant fibres → Vegetable oils, lipids → Pyrolysis oil → Press juice → Biogas → Syngas (See e.g., (Platt et al. 2021; Baldoni et al. 2021))
Secondary processing/refining	Composition of intermediate engineered wood/fibre products	Conversion, decomposition, use of complex molecules See e.g, (Platt et al. 2021; German Federal Government 2012))(Baldoni et al. 2021)
Intermediates	→ Solid wood products → Wood-based panels → Particle and fibres boards → Veneer sheets	See e.g.(Spekreijse et al. 2019; Baldoni et al. 2021).
Tertiary processing/refining	Composition of final engineered wood/fibre products	Refining products for further application
Products	→ Building products/construction elements → Furniture → Packaging products → Outdoor products	→ Chemicals → Materials See e.g. (Spekreijse et al. 2019; Baldoni et al. 2021; Dahiya et al. 2020)
Use/application	→ Construction sector → Furniture sector → Packaging sector → Other sectors	→Chemical sector →Plastics sector See e.g.,(BMBF 2015)
Waste biomass	Depending on level Assembling – product – material → pure → composite See e.g., (Waste Wood Ordinance - AltholzV 2020)	Depending on level product – material – chemical → pure → composite

Table 3-1: (continued)

End-of-life-management	Depending on - Waste wood regulations - Collection, sorting, separation, processing systems - Waste management systems i.e., (Waste Wood Ordinance - AltholzV 2020)	Depending on - Regulations - Collection, sorting, separation, processing systems - Waste management systems i.e., EU Waste Frame Directive (EC 2008)

3.2 Biomass Flows

In this chapter, a brief overview is given of the biomass flows in EU-27 that are associated with the forestry, agriculture, and fisheries sectors to know about the relevance of biomass feedstocks in BBPs sector in the EU. Based on these information, relevant feedstocks were analysed in details including biomass flows by sector type in the section 3.4.

According to the latest available data (forestry (2017), agriculture (2020), and fisheries (2016)) (Gurría et al. 2022), total biomass flows into the EU-27 supply stands at 1,044,489 thousand tons of dry matter (1000tdm). Among the total supply highest supply is coming from the agriculture sector, followed by the forestry sector, and has a very small share from the fisheries and aquaculture sector (Figure 3-2). The total domestic production stands at around 937,430 (1000tdm), with a minor share of imports of 41,508 (1000tdm). The end consumption reveals that the highest sector is food and feed use, followed by bioenergy, which has the least share of 133,455 (1000tdm) associated with biomaterials (Figure 3-2). This is further discussed in detail in the section 3.6.

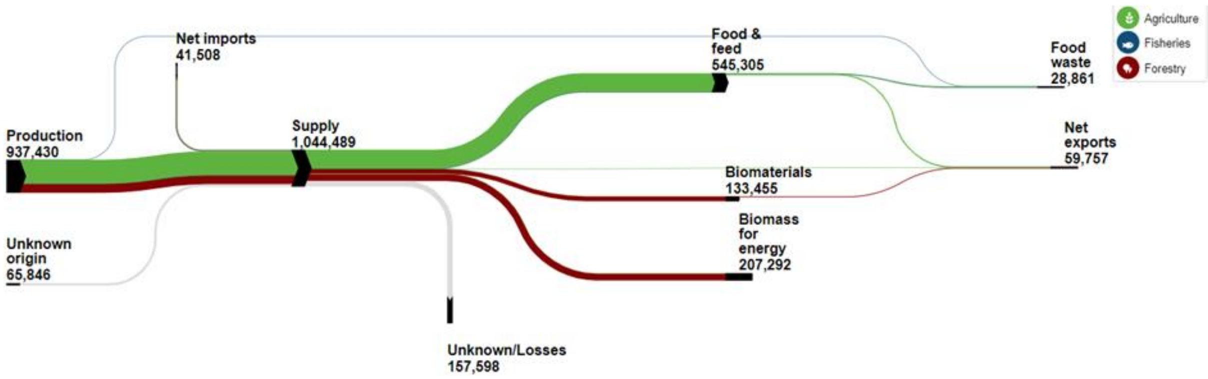

Figure 3-2: Biomass flows by sectors in the EU-27, net trade, latest available data (1000tdm) (Gurría et al. 2022).

Agriculture biomass flows in the EU-27 in the year 2020 show that the total supply is 714,220 (1000tdm), amongst which crop production has the highest share and has less import dependency, which is 26,273 (1000tdm). There is a big portion of residues amounting to 331,302 that is not harvested and potentially can feed into the supply (Figure 3-3). The end sector consumption reveals that the largest sector is feed and bedding supply, followed by biomaterials (fibres and others) and least share related to biofuels production. The end consumption of agricultural sector does not depicts a clear picture regarding end consumption for BBPs. Therefore, further detailed overview is presented from EU agricultural balance sheets (EC and Agriculture and rural development 2025) in the section 3.6.

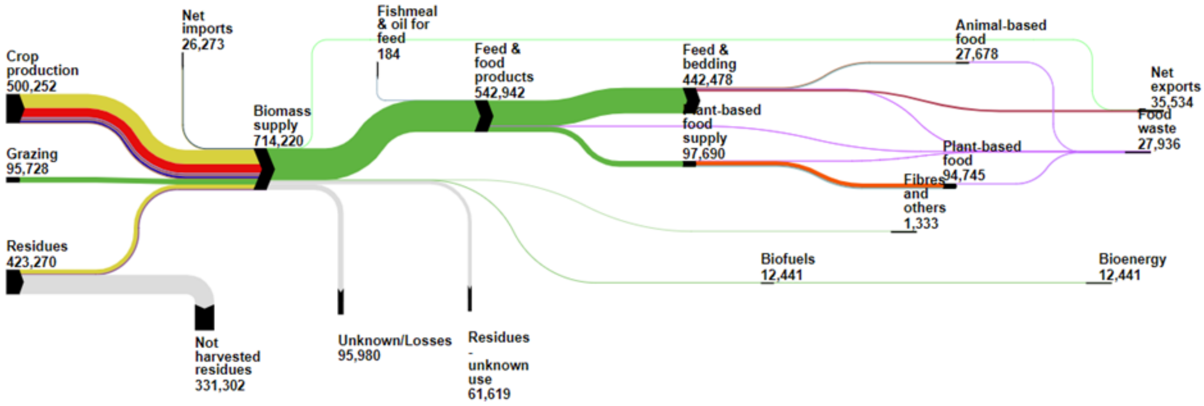

Figure 3-3: Biomass flows for agriculture in the EU-27, net trade, 2020 (1000 tdm) (Gurría et al. 2022).

Forestry biomass flows in the EU-27 reveal that the total domestic production in the year 2017 stood at 248,061 (1000tdm), having a very low share of net imported wood that is around 5570 (1000tdm). The end sector consumption reveals high materials use (without the use of by-products, post-consumer wood for energy use) compared to bioenergy use. The materials sector consumes a total of 207,556 (1000tdm), which includes 17,531 (1000tdm) from post-consumer wood as well as some supply from the by-products (Figure 3-4). There are also imports of some end products, such as wood pulp and wood pallets, but that is very minor as compared to domestic production, showing very little dependency on the imports in the forestry sector. Wood resource balance and flows are further analyzed in detail in section 3.4.

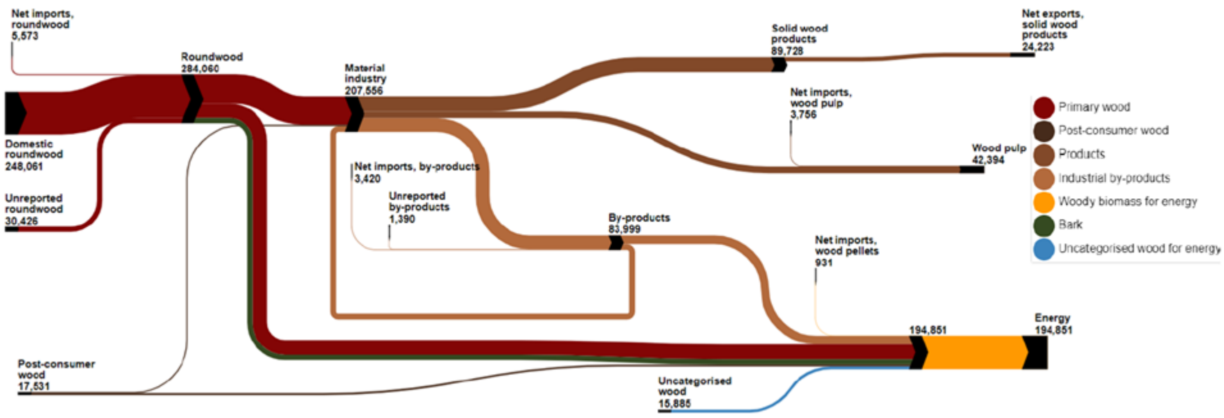

Figure 3-4: Woody biomass flows in the forest-based sector, in the EU-27, net trade, 2017 (1000 tdm) (Gurría et al. 2022).

The fisheries and aquaculture sector in the overall biomass flows in the EU-27 have less than 1% share, and also, the main dependency is on imports, standing at 1,555 (1000tdm) in the total supply of 3296 (1000tdm) in year 2016. The end consumption reveals a high share of aquatic-based food, fish meal, and oil (Figure 3-5). Since the ESCIB project focus is on the materials sector therefore, fisheries and aquaculture are not discussed in more detail in the following chapters.

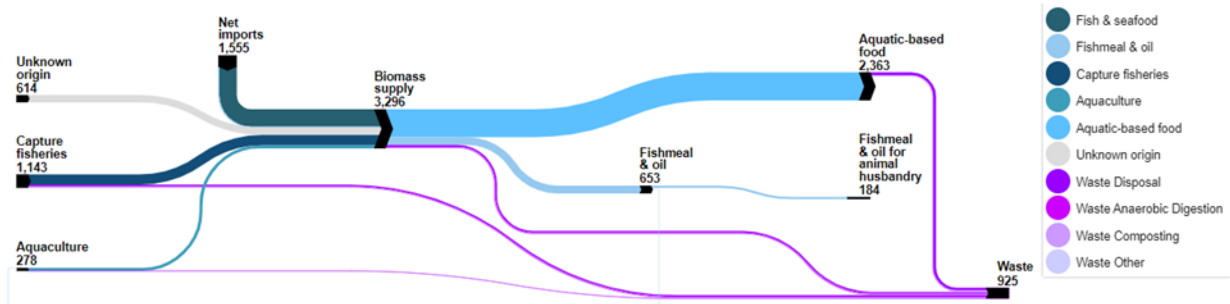

Figure 3-5: Biomass flows for fisheries and aquaculture in the EU-27, net trade, 2016 (1000 tdm) (Gurría et al. 2022).

3.3 Biobased Feedstock Availability

3.3.1 Agricultural Feedstock Production

Agriculture is the main source of biomass in the EU, with the total biomass being almost equally divided between economic or primary (i.e., grains, fruits, roots, etc.) and residue (secondary products, i.e., leaves, stems, and husks) production. Among the EU-27 member states, France, Germany, Italy, Poland, Spain, and Romania produce almost 70% of the total agricultural feedstock. Wheat and maize are the major contributors to agricultural biomass, with residual biomass outweighing the primary portion for both crops. Over the past 20 years, the availability of agricultural biomass has increased due to changes in cultivated areas and advancements in agro-management practices, which have led to improved crop yields. Therefore, there is a chance of an increase in biomass availability in the coming years, although this may be influenced by the impact of climate change on agriculture (Avitabile et al. 2023).

The data for agricultural crops production has been sourced from EUROSTAT 2024. The main agricultural crops categories are as follows: cereals, root crops, industrial crops, fibres crops, and medicinal and aromatic crops. Additionally, data is available for energy crops, fresh vegetables, and fruits. The EU-27 countries produced half of their crop dry matter as cereals, followed by fodder crops (31%) and root crops (8%) in 2019 (Avitabile et al. 2023). Since the ESCIB project is specifically focused on non-food/feed and non-energy, but material use of biomass, the data for cereals and industrial crops are important as defined by the Annual Crop Statistics Handbook 2023 (EC 2023).

According to the Annual Crop Statistics Handbook (EC 2023), cereals, i.e., annual plants, generally of the graminaceous family, yielding grains used for food, feed, seed, and industrial purposes such as ethanol production, are all harvested dry, regardless of the use. These cereals include buckwheat, barley, canary seed, common wheat, durum wheat, einkorn wheat, emmer wheat, khorasan wheat, grain maize, millet, oats, perennial sorghum, quinoa, rice, rye, sorghum, cereal seeds, cereals grains harvested just before the maturity, cereals used for renewable energy production, rye and winter cereal mixture (maslin) and spring cereal mixtures (mixed grain other than maslin). However, they do not include the maize harvested green, sweet corn cobs/sweet maize for human consumption, and cereals (excluding maize) harvested green or yellow as a whole plant for fodder or renewable energy.

According to the data from EUROSTAT, the total cereal production in EU-27 (excluding Italy, Malta, Latvia due to unavailability of data for that year) is 255.47 million tons in the year 2023. Among the member states, France is the biggest producer contributing around 25% of the total cereals production in EU-27, followed by Germany contributing 17% (Figure 3-6). The three countries France, Germany and Poland contributes together more than 50% of the total cereal production.

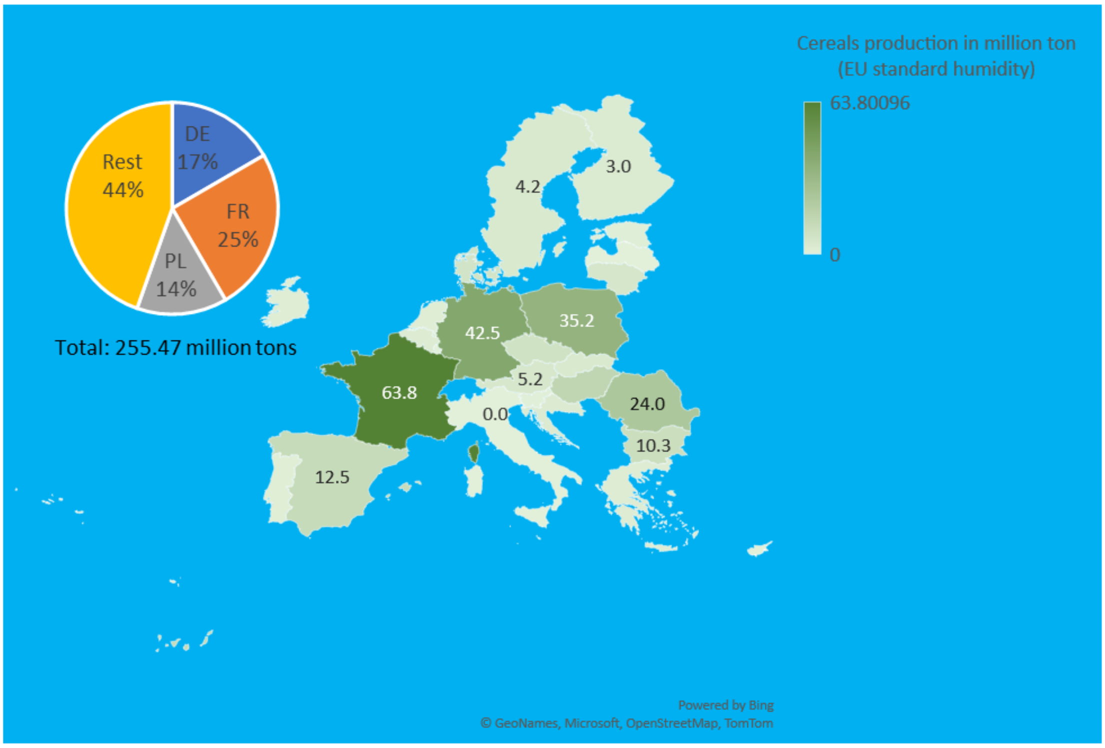

Figure 3-6: Cereal production distribution (million tons) in EU-27 states in the year 2023 (Own figure based on data source: (EUROSTAT 2024))) FR: France, DE: Germany, PL: Poland.

In 2021, the production is estimated at almost 297.6 million tons (Figure 3-7). In 2022, it declined to an estimated 270.9 million tons, which is 26.7 million tons (almost 9%) less than in 2021. In 2023 there is a further decline of 5.7% in the production compared to 2022. The overall decline in the EU-27's production of cereals in 2022 was driven by drought events in Romania, France, Spain and Hungary (ec.europa.eu 2023; Meehan and Stella 2023). Only in very few countries the overall cereals production increased. Among others, the production increased in Germany (+3%, + 1.1 million tons), Finland (+39%, + 1.0 million tons after a poor harvest in 2021) and Poland (+3%, + 1.0 million tons) (ec.europa.eu 2023).

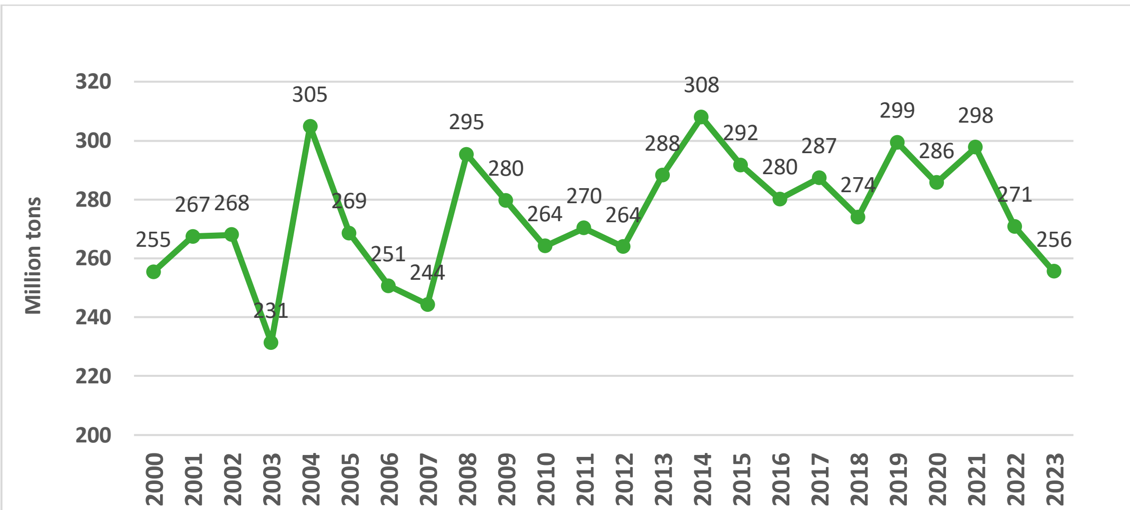

Figure 3-7: Yearly cereals production in the EU-27 (Own figure based on data source: (EUROSTAT 2024)).

The lowest production occurred in 2003, in which the production was 231.4 million tons, while the highest production was 307.9 million tons in the year 2014 (Figure 3-7). The average production for all years was 275.1 million tons. The production range between the values of

255 and 303 million tons had the highest frequency over the last 22 years (Figure 3-8). This range is also the expected potential of cereals production in the coming years.

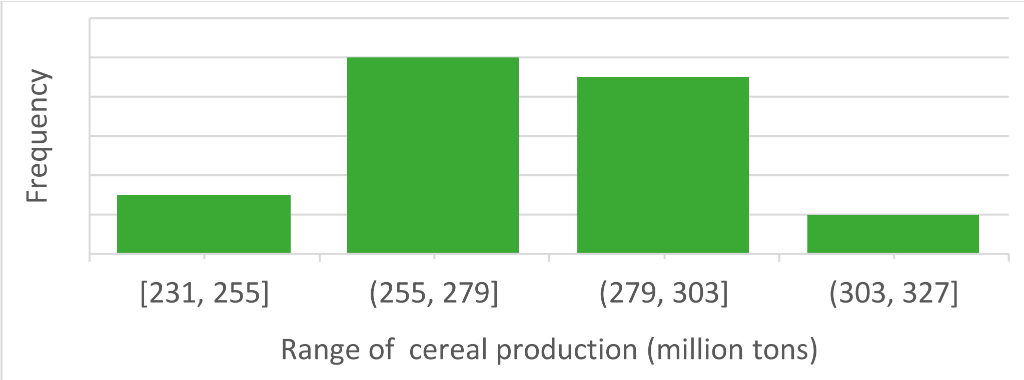

Figure 3-8: Frequency distribution of a range of cereal production is categorized into four ranges (Own figure based on data source: (EUROSTAT 2024)).

The industrial crops are defined by the Handbook on Crops Statistics (EC 2023) as the crops that need industrial processing prior to its final use and are not sold directly for consumption. These include oilseeds, fibre crops, tobacco, hemp, hops, aromatic and medicinal crops, energy crops, crops used for renewable energy production, seeds for herbaceous oilseed plants and seeds for linseed. Among the EU-27 member states, France had the highest contribution with almost 20%, followed by Romania with 15%, and Germany with 10% of the total production area (Figure 3-9). Seven member states together, France, Germany, Romania, Spain, Poland, Hungary, and Belgium, produced crops on almost 78% of the total production area of industrial crops in EU-27 in the year 2023.

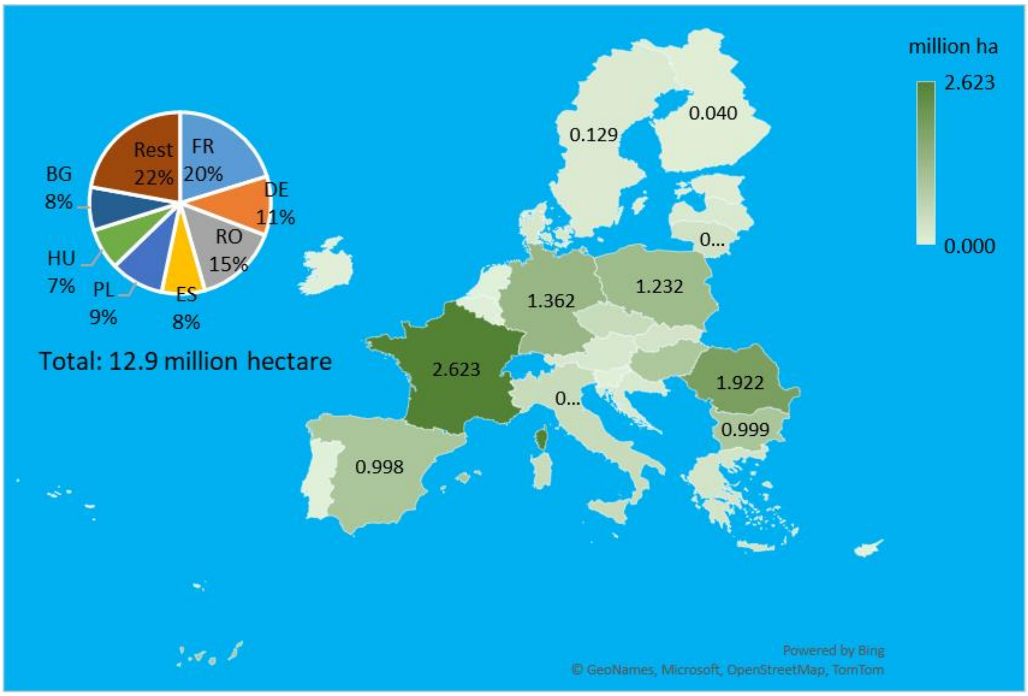

Figure 3-9: Industrial crops harvested area in million hectares in EU in the year 2023 (Own figure based on data source: (EUROSTAT 2024) (FR: France, DE: Germany, RO: Romania, ES; Spain, PL: Poland, HU: Hungary, BG: Belgium).

In the year 2023, the total harvested area for industrial crops in the EU-27 was estimated for around 12.9 million hectares (ha), in 2022 at around 13.1 million ha (Figure 3-10). The average harvesting area for the past six years was 12.5 million ha. The last harvest was for the year

2021, where harvested area amounted to 11.9 million ha, while the highest values were around 13 million ha in the years 2018, 2022, and 2023.

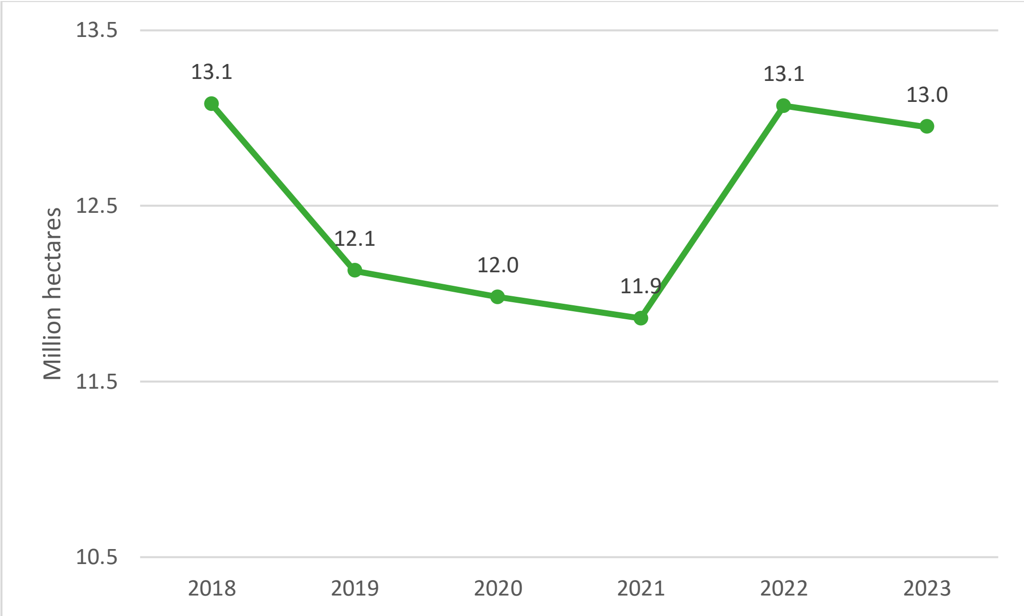

Figure 3-10: Industrial crops harvested area from 2018 to 2023 in EU-27 in million hectares (Own figure based on data source: (EUROSTAT 2024).

The future outlook of cereal production in EU-27 is anticipated to show a modest increase until the year 2035. The EU-27 is expected to produce 281.2 million tons of cereals by 2035, which is an increase of 1.4 million tons from 2021-2023. Soft and durum wheat production is expected to rise marginally, with soft wheat reaching 128.5 million tons and durum wheat 7.5 million tons by 2035, which is slightly higher than the 127.7 million tons and 7.4 million tons produced in 2021-2023. Maize production is predicted to increase by 3% to 64 million tons in 2035 from 62.1 million tons in 2021-2023. However, barley production will slightly decrease by -3.4% to 49.1 million tons in 2035, from 50.9 million tons in 2021-2023. This decrease is due to a decrease in the planted area without compensating it with increases in yield. Similarly, the area of cereals in EU-27 is also expected to slightly decrease until the year 2035 to below 51 million hectares from 51.1 million hectares in the year 2023 *(European Commission et al. 2023)*.

Similarly, protein crops and oil seeds production will also show an anticipated increase of up to 31.8 million tons by the year 2035 in EU-27. This is an increase of 0.4 million tons compared with the 2021-2023 average. Driving factors for this increase include EU supportive policies for protein crops, changes in agricultural practices such as crop rotation, the EU’s agricultural research and innovation programs, and an increase in the demand for plant proteins, especially pulses. Rapeseed production is predicted to decrease slightly, while sunflower production is expected to increase by the year 2035. Regarding the land use change, oilseeds and pulses areas are expected to increase as a result of incentives by EU policies. Pulses and soyabeans area will potentially rise from 2.1 and 1 million hectares in 2023 to 2.7 and 1.3 million hectares in 2035. On the other hand, the sunflower area is anticipated to remain same at 4.6 million hectares in 2035, while the rapeseed area will potentially decline in 2035 from 6.2 to 5.7 million hectares in 2023 *(European Commission et al. 2023)*.

3.3.2 Forestry Feedstock Production

With a total aboveground living biomass stock (i.e. all aboveground biomass compartments of the living trees with the aboveground part of the stump, stem, branches and foliage) of 18.4 billion tons of dry matter on 157 million hectares forest area, the forests of the EU-27 member states had an average biomass density (i.e. biomass stock per hectare) of 117 tons/ha in 2020 (Table 3-2). Forests of central EU-27 countries have the largest biomass stock (10 billion tons) and the highest biomass density (176 tons/ha). While the forests of northern EU-27 countries cover a similar area to central EU-27 forests, they store less than half of their biomass (4.7 billion tons). Northern and southern EU-27 forests have similar biomass densities (81 and 86 tons/ha, respectively), but the smaller extent of southern forests results in a lower biomass stock (3.6 billion tons) (Avitabile et al. 2023).

EU-27 has a total forest area of around 160 million ha in year 2021, that was almost 152 million ha in year 2020, which is around a 5% increase in the forest area. At the national level, the countries with the largest forest areas are located in northern Europe (i.e., Sweden, Finland) and central west (France, Germany) (Figure 3-11). While the countries with the largest biomass stock are mostly found in central (Germany, France, Poland) and northern (Sweden, Finland) Europe reported by Avitabile et al. (2023) with data sourced from JRC based on National Forest Inventories. Similarly, the countries with the most biomass per hectare are mainly in central-east Europe (Czech Republic, Slovenia, Slovakia, Austria, Poland, Romania) (Table 3-2). In contrast, the countries with the lowest biomass density are in northern and southern Europe (Portugal, Greece, Spain, Finland, and Sweden) (Avitabile et al. 2023).

Table 3-2: Forest area, aboveground living biomass stocks and biomass density in the EU-27 regions (regions defined from SoFE 2020 report Adapted to EU-27) for the year 2020 and the round wood production for year 2022 (Avitabile et al. 2023; FAOSTAT 2024a).

EU-27 regions	Forest area [1,000 ha]	Aboveground living biomass stocks [million tons]	Biomass density (Stock per hectare) [tons/ha]	Round wood production [million m^3] (year 2022)	Countries in Regions
North	58,301	4,740	81.3	179.8	Denmark, Estonia, Finland, Latvia, Lithuania, Sweden
Central west	33,516	5,687	169.7	163.7	Austria, Belgium, France, Germany, Ireland, Luxembourg, Netherland
Central east	23,350	4,357	186.6	100.1	Czech Republic, Hungary, Poland, Romania, Slovakia
South-west	30,850	2,352	76.2	48.4	Italy, Malta, Portugal, Spain
South-east	11,115	1,262	113.5	16.5	Bulgaria, Croatia, Cyprus, Greece, Slovenia
EU-27	157,132	18,398	117.1	508.4	

According to the FAOSTAT (2024a), the total roundwood production in the EU-27 member states is estimated at around 508.4 million m^3 for the year 2022 (Figure 3-12), whereas EUROSTAT 2024 estimates it for almost 509.2 million m^3. The difference is because the FAOSTAT has almost all countries data except for Malta and Cyprus and after adding individual countries production the total amount is presented here. While EUROSTAT data missing individual countries data and the value is only an estimation, therefore the FAOSTAT is selected for further analysis.

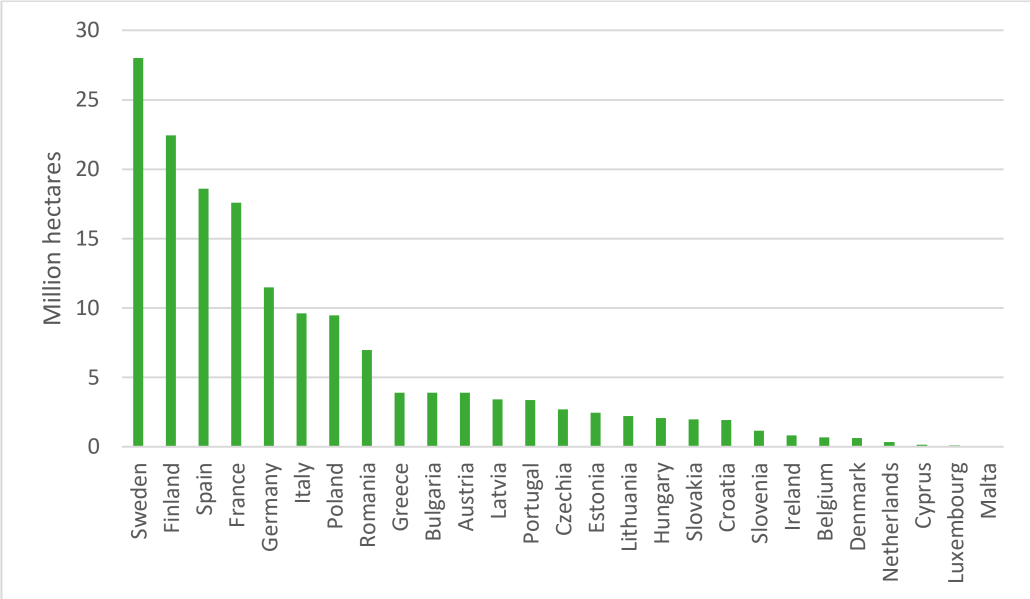

Figure 3-11: Forest area in EU-27 member countries in the year 2021 (Own figure based on data source: (EUROSTAT 2024)).

Furthermore, to get an overview of the trade of the roundwood in EU-27, consumption of the roundwood for the year 2022 was determined by adding the total production and total imports and subtracting the total exports. Total round wood production as per for year 2022 was 509.3 million m^3, total imports was around 56.9 million m^3, while the total exports reported were around 69.6 million m^3 (EUROSTAT 2024). The total consumption for the year 2022 determined is 496.6 million m^3, which is less than by almost 12.7 million m^3. This shows the EU-27 self-sufficiency in the round wood supply. Furthermore, the total imports reveal a decline from the year 2021, where the imports reported were 60.7 million m^3, while the exports saw a rise from 67.9 million m^3 in 2021 to 69.6 million m^3 in 2022.

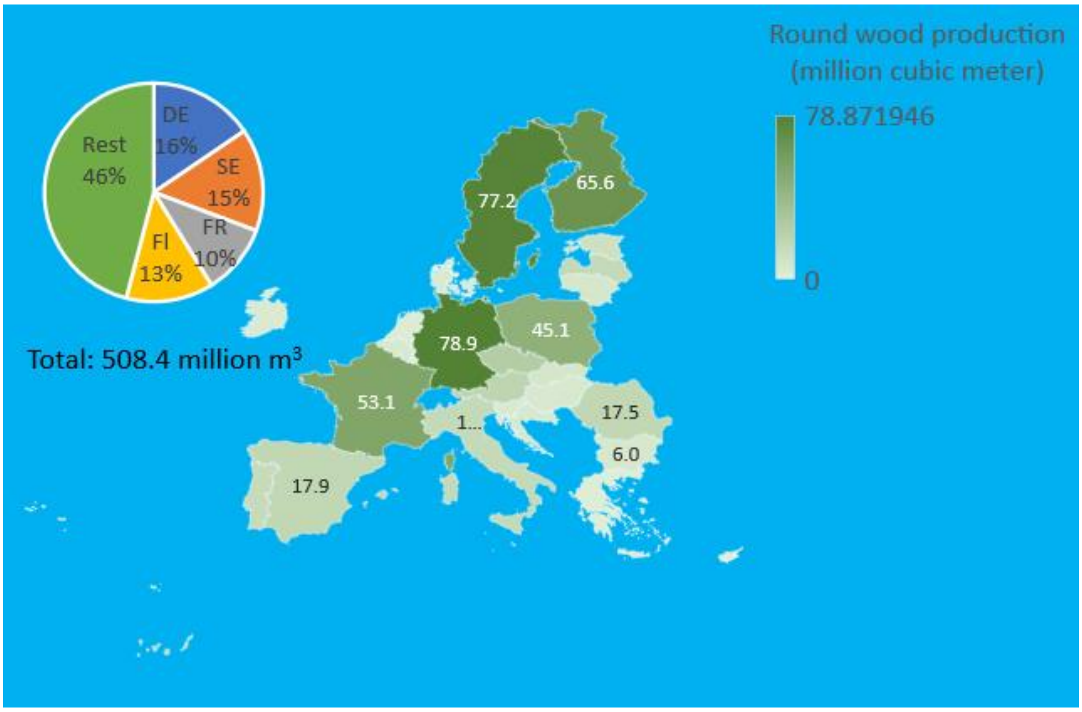

Figure 3-12: Total round wood production (under bark) in EU-27 member states in million m^3 in year 2022 (Own figure based on data source: (FAOSTAT 2024a)).

Roundwood production as defined by FAOSTAT (2024b) is an aggregate that comprises wood fuel, including wood for charcoal and industrial roundwood. It includes the volume of all trees, living or dead, that are felled and removed from the forest, other wooded land, or other felling sites. It is solid volume under bark (i.e., excluding bark). Among the EU-27 member states, Germany has the highest amounts of roundwood production in the year 2022 producing up to 16% of the total production, followed by Sweden (15%), France (10%) and Finland (13%) (Figure 3-12). These four countries are producing almost 54% of the total roundwood production in EU-27 countries. Moreover, the roundwood production increased from 446.5 million m^3 to 508.4 m^3 in the period of 2010 till 2022, which is almost 12% increase (Figure 3-13).

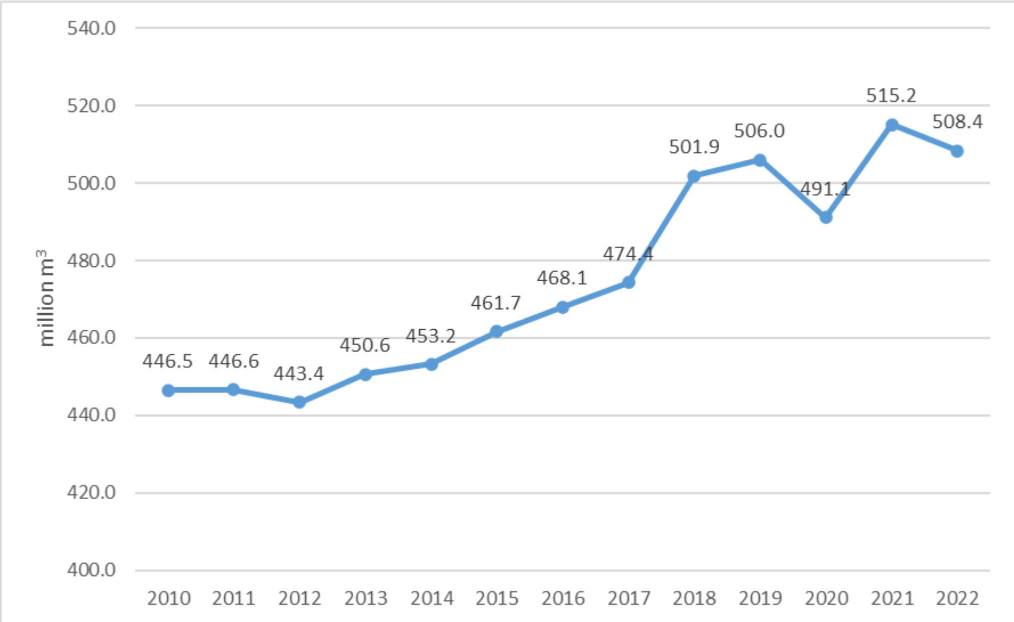

Figure 3-13: Yearly production of roundwood in EU-27 region (Own figure based on data source: (FAOSTAT 2024a)).

3.3.3 Land Use Development

By 2035, the overall area of agricultural and forest land in the EU-27 is predicted to remain almost unchanged at 322.4 million ha. The area for forestry is anticipated to go up slightly from 160.3 million ha in 2023 to 160.7 million ha in 2035. Between 2023 and 2035, there will likely be a 1 million ha drop in arable cropland and a 0.7 million ha decrease in permanent grassland. It is anticipated that the areas devoted to permanent crops and fodder (such as silage maize and temporary grassland) will remain relatively unchanged, with only minor increases of 0.1 million ha. Because newer, more efficient production systems are replacing older plantations, it is anticipated that the amount of land required for permanent crops won't change significantly. Any attempt to expand the area is thwarted by the EU's arable crops' uncertain competitiveness and the growing scarcity of water *(European Commission et al. 2023)*.

3.4 Biomass Supply

According to the latest data from JRC (Gurría et al. 2022), that refers to year 2020 for agriculture, 2017 for forestry and 2016 for fisheries and aquaculture, the total biomass supply in EU-27 was around 1 billion tons dry matter. By categorizing by land use type, the agriculture supply (crops and animal production) was almost 714.2 million tons (69%), the supply from forestry (roundwood) 261.7 million tons (25%), and from fisheries almost 2.6 million tons (0.26%). There were additional 65.8 million tons (6%) of biomass from an unknown source which has been produced for unidentified purposes, or which was unused or rendered unusable during the harvesting or processing (Figure 3-14, left).

According to the categorization by origin type, the domestic production was 937.1 million tons of dry matter in EU-27, which is around 90%, while the import was 41.5 million tons of dry matter that is around 4% of the total supply (Figure 3-14, right). These values are only related to the feedstock imports into EU-27 for further processing or use and do not include the import of end products.

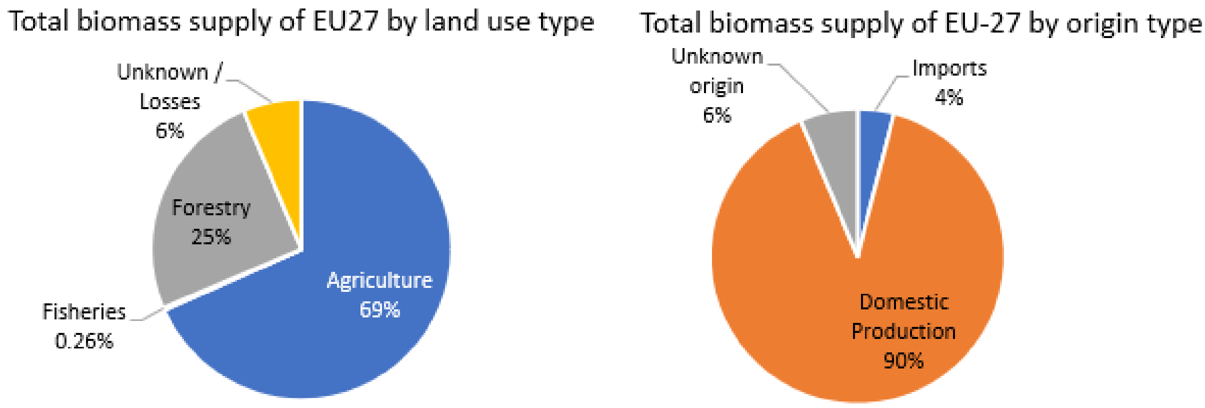

Figure 3-14: Total biomass supply in EU-27 based on tons dry matter categorized, left: by land use type, right: by origin type (Own figure based on data source: (Gurría et al. 2022)).

Regarding the supply from forestry and agriculture in the EU-27, the forestry sector relied on almost 87% of the domestic production, while the agricultural sector on almost 96% respectively. In both land use type sectors, the dependency on imports in quite less (2% and 4%), while 11% is unreported roundwood amounts, thus, no information is available. However, it is important to understand that this only refer to the import of primary feedstock into EU supply and does not include intermediate or final products. The supply from agriculture, which is the biggest sector of the biomass supply in EU-27, consists of almost 45% of cereals, 22 % of fodder crops, and 5% of root crops, while oil crops contribute 4.5% and fibre crops less than 1% (Gurría et al. 2022).

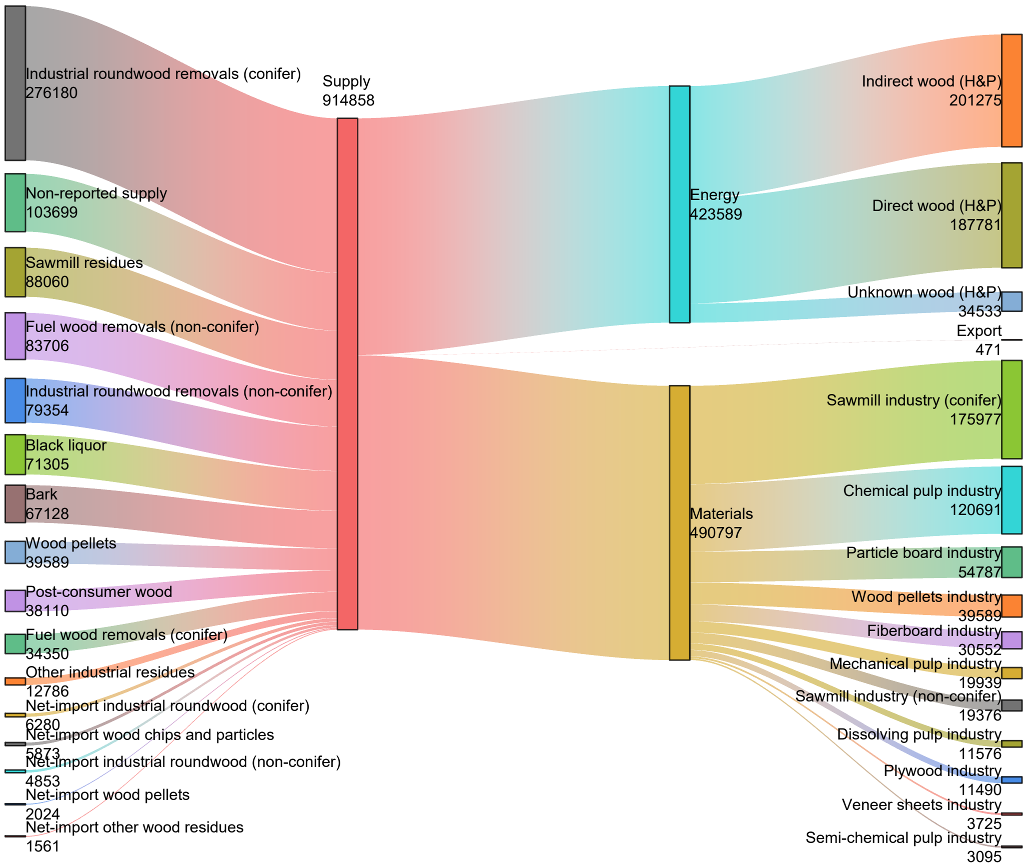

Figure 3-15: Wood resource balance in the EU in year 2017 in thousand m^3 (Own figure based on data source: (Cazzaniga et al. 2021)).

The analysis of the wood resource balance data shows that in 2017, the EU-27 reported total wood (primary + secondary + imports) supply of 914.8 million m^3. Out of this, the primary wood resources (industrial wood + fuel wood+ imports + bark) supply was 551.4 million m^3, accounting for nearly 68% of the total supply (Figure 3-15). Additionally, the secondary wood resources (i.e., the industrial residues) supply was 221.2 million m^3, constituting approximately 27% of the total supply. The post-consumer wood supply was the smallest amount at 38.1 million m^3, making up almost 5%. The share of import for primary wood resources was almost 2%, while for secondary wood resources almost 4% (Cazzaniga et al. 2021). This demonstrates that the EU-27 is largely self-sufficient in terms of primary and secondary wood supply.

In the agricultural sector, the total oil seeds (rapeseed, soyabean and sunflower) supply in year 2022-23 amounted for almost 56 million tons. The domestic production accounted for almost 56% (31 million tons), existing stock 4%, while imports accounted for almost 40% (22 million tons respectively) showing huge import dependency of EU-27 in oil seed supply (EU Oil Seeds Balance Sheet 2024). According to the EU sugar balance (sugar + Isoglucose) sheets (EU Sugar Balance Sheet 2023-2024), the beginning stocks amounts to 2087 ktons, production 16054 ktons (82%) and imports (raw form) amounted to 1389 ktons (7%) respectively. Beside imports the exports (raw form) amounted to 1645 ktons showing -256 ktons of net sugar imports. EU-27 rice balance sheets shows significant import dependency. The total production amounted to 1675 thousand metric tons (49%), imports 1250 thousand metric tons (37%) and beginning stocks amounted to 459 thousand metric tons (13%) (EC and Agriculture and rural development 2025). The net imports amounted to 850 thousand metric tones in year 2020-2021.

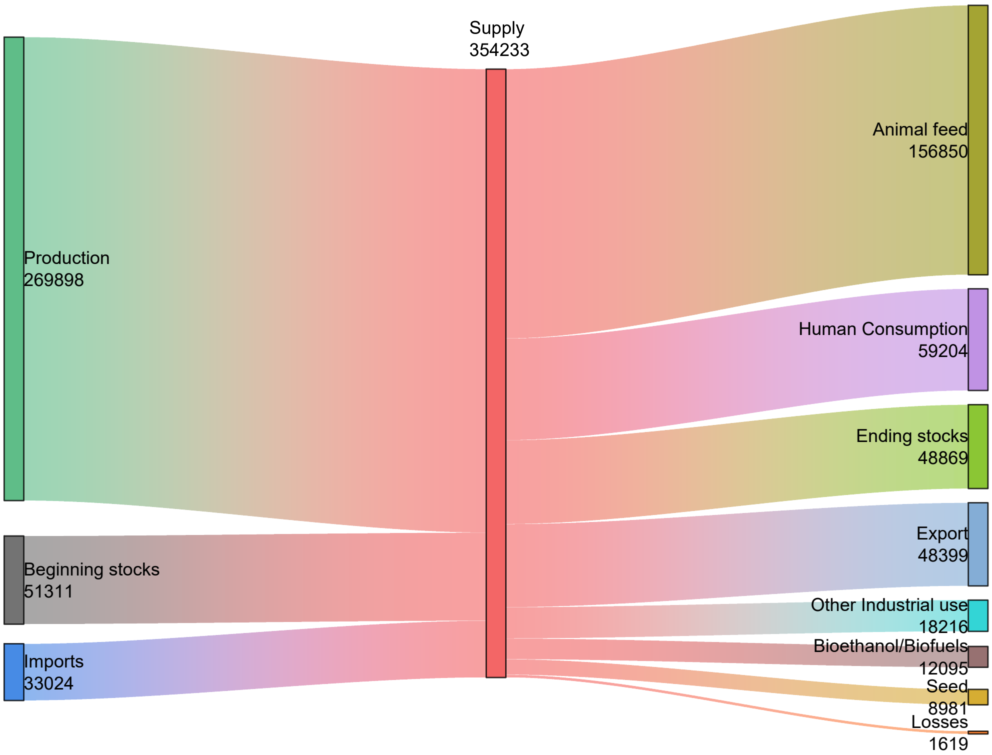

Figure 3-16: Cereals resource balance flows in EU in 2023-2024 in kilotons (Own figure based on data source: (EU cereals balance sheets).

Furthermore, EU cereals resource balance data (EU cereals balance sheets) for the year 2023-2024 data shows that the total supply for cereals was almost 354.23 million tons, out of which domestic production was 269.9 million tons, beginning stocks 51.31 million tonnes, while the imports accounted to 33.02 million tons (Figure 3-16). This means that the total production and beginning stocks is almost 90 %, while there is 10% import dependency. However, the exports stands higher than imports. Furthermore, data reveals that there will be -2.44 million tons ending stocks for year 2023-2024 and will continue same trend in the year 2024-2025 where the expected negative balance at the ending stocks will be -2.30 million tonnes, showing the import dependency of cereals in EU.

3.5 Distribution of the Biobased Industry

3.5.1 Biobased Industries by Range of Biobased Products

The IEA Bioenergy Task 42 (2022) provides an extensive database of biorefineries of the world including EU, that are classified based on TRL, feedstock origin, capacity, refining technology and products mainly sourced from nova-institute (nova-Institute and BIC 2017) and JRC (Parisi et al.; Parisi et al. 2020) including other data sources. However, the focus is centred on biorefineries designed to produce energy and renewable fuels.

In this respect, the most up-to-date databank that covers the whole range range of biobased industries are provided by the Joint Research Centre (JRC) of the European Commission (Gurría et al. 2025). Therefore, this information is integrated in order to identify range of high and low TRL biobased industries in relation to biomass feedstocks and BBPs. According to the latest data as per Gurría et al. (2025), total biobased industries in EU amounted to 3455 plants. The analysis of biobased industry distribution by feedstock type shows that the majority of biobased industries rely on forestry feedstock (1,265 plants), followed by agricultural feedstock (855 plants), alongside a significant share categorized as unknown (Figure 3-17). The distribution by product category indicates that biomethane dominates with 1,366 plants, followed by pulp and paper (549) and timber (491) respectively (Figure 3-17). The majority of biobased industries operate at a commercial scale (TRL 8–9), accounting for 3,252 plants, while 162 biobased industries are at the pilot stage and only 41 at the laboratory scale. Since some biobased industries produce multiple products or use multiple feedstocks, the number of industries by product and feedstock category may involve double counting. Therefore, percentages are presented in the chart to provide a clearer overview of the range of biobased industries by product and feedstock type (Figure 3-17).

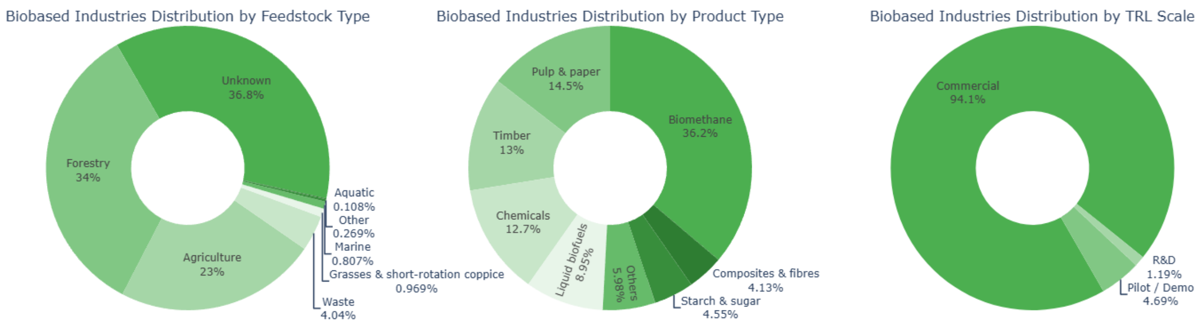

Figure 3-17: Biobased Industries distribution in EU by feedstock type, products type and TRL scale (Own figure based on data source: (Gurría et al. 2025)).

The geographical distribution of bioindustries across the EU-27 indicates that France has the highest number of industries (963), followed by Germany (726) and Italy (351) with high concentration of biomethane, chemicals, pulp and paper and timber industries. Sweden, and Finland on the other hand, shows highest proportion of industries related the timber product category. These biobased industries encompass a broad range of products having different concentration of biobased industries based on biomass feedstocks in different EU-27 member countries.

Box 6: Definition and differentiation of biobased industry (Adapted from (Galanakis 2020) and biorefinery (IEA Bioenergy Task 42 2022).

Biobased Industry:

"Industry that utilizes biological resource as a raw material to manufacture wide range of products helping to manage the current biological resources efficiently while reducing waste generation".

Biobased industry/facility is an umbrella term and includes traditional biobased industries i.e., sawmill industry, that process logs into lumber and other wood products but also include the concept of biorefinery.

- May or may not be completely market-focused; focus is on using the naturally available resources, i.e., using wood in construction.
- Sustainability is an important aspect of bioindustry, but the focus is on the efficient use of biological resources, i.e., the use of wood and natural fibres.
- Examples include wood products, biochemicals, biopolymers, pulp, and paper products etc.

Biorefinery:

"Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy'. 'Biorefining' can be seen as a concept, facilities, processes, or clusters of industries. 'Sustainable' means that the biorefinery has economic, environmental, and social benefit. 'Spectrum' refers to multiple energy and non-energy products. And 'marketable' indicates that there needs to be a current or forecasted market volume at a profitable price. And finally, 'products' can be of the types of food/feed ingredients, chemicals, materials, and bioenergy (IEA Bioenergy Task 42 2022).

- There is an intermediate products or platform involved in biorefinery to make the final usable product.
- Focus is profitable products that have good market value.
- Sustainability is the core value of the biorefinery.
- Examples includes biofuels, biochemicals, biopolymers, composites etc.

3.5.2 Chemical and Material Driven Biorefineries

Regarding the available information, the focus of BBS is in fact on biorefineries which are the main part of the supply chain of IBBS. Baldoni et al. (2021) extended the database and dashboard visualization regarding the level of detail for the represented biorefineries (TRL 8 or 9), the information on location, feedstock, platforms, conversion processes, products (value chain), and the presence of non-EU biobased sectors. This work integrates only biorefineries producing chemicals, biobased composites and fibres, and other (agrochemicals, cosmetics, pharmaceuticals etc.) in EU-27. This database identifies a total of 298 high TRL (8-9) biorefineries only producing biochemicals and biomaterials as main products. Pulp and paper, wood industries and bioenergy plants that produce chemicals as coproducts are also excluded from this database.

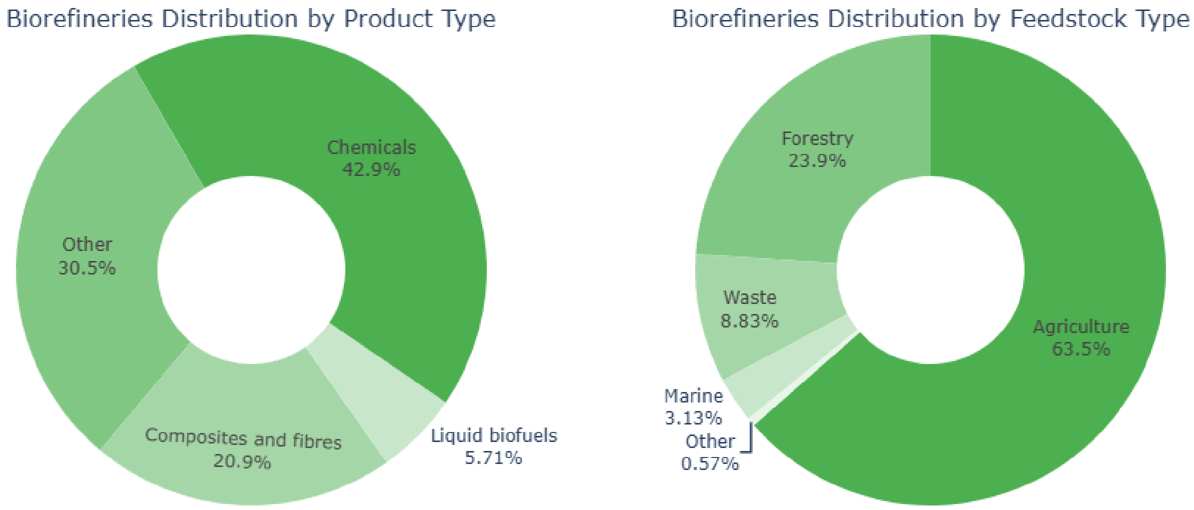

Figure 3-18: Percentage distribution of material and chemical biorefineries in EU-27, left: by feedstock, right: product category. Others product category refers to agrochemicals, feed, pharmaceuticals (Own figure based on data source: (Baldoni et al. 2021)).

An analysis of materials and chemical biorefineries reveals, that approximately 64% are linked to agricultural feedstock, 24% are associated with forestry, and the remaining portion is related to waste and marine feedstocks (Figure 3-18). Since most chemical biorefineries utilize agricultural feedstock, particularly oil crops, a higher proportion of refineries are tied to agricultural feedstock. This observation is specific to the materials and chemical refineries in the EU-27.

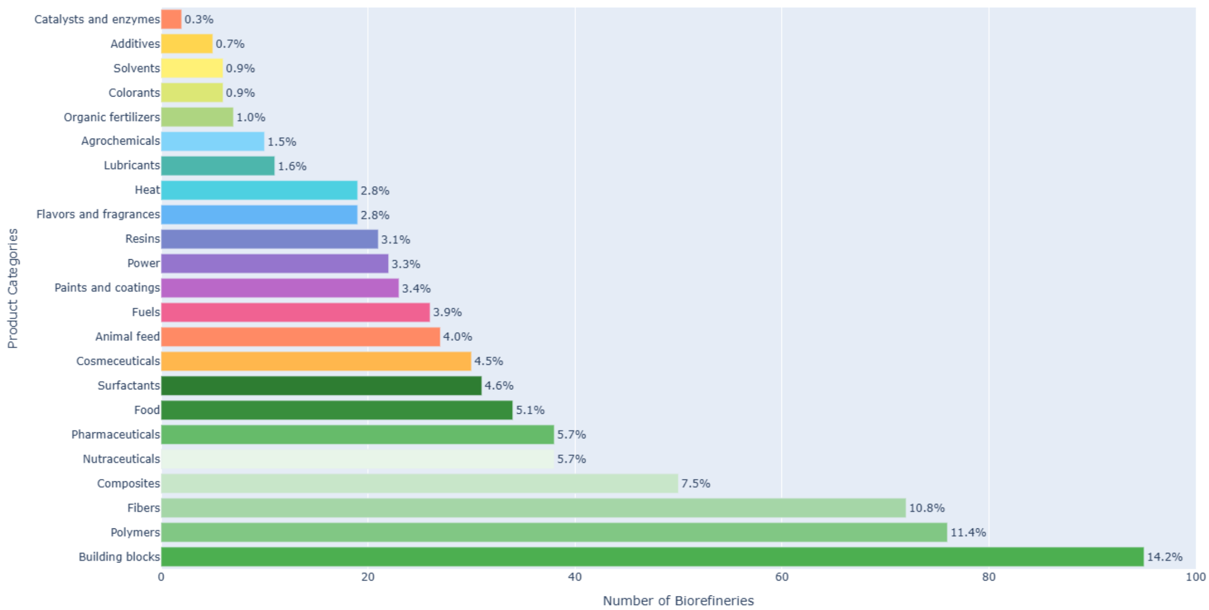

Figure 3-19: High TRL material and chemical biorefineries distribution by product category in the EU (Own figure based on data source: (Baldoni et al. 2021)). Number may be double counted when a biorefinery produce more than one product category.

Furthermore, Baldoni et al. (2021) identified that the highest number of materials and chemical biorefineries are in France, followed by Germany and Netherlands. Mostly, the biorefineries are using agricultural feedstock as their raw material for production of chemicals and materials (Figure 3-18). Regarding the range of BBPs, the highest number of biorefineries are associated with building blocks (platform chemicals) production (95 plants), followed by polymers (76 plants), fibers and composites (Figure 3-19). The distribution of materials and chemicals biorefinery platforms indicates that C5/C6 sugars account for approximately 29%, followed by oils at 24% and organic fibers at 17% (Figure 3-20). Collectively, these three platforms, along with lignin platform, represent nearly 82% of all biorefinery platforms in the EU. However, this data only represents the number of biorefineries, but not the capacity of biomaterial and biochemical production.

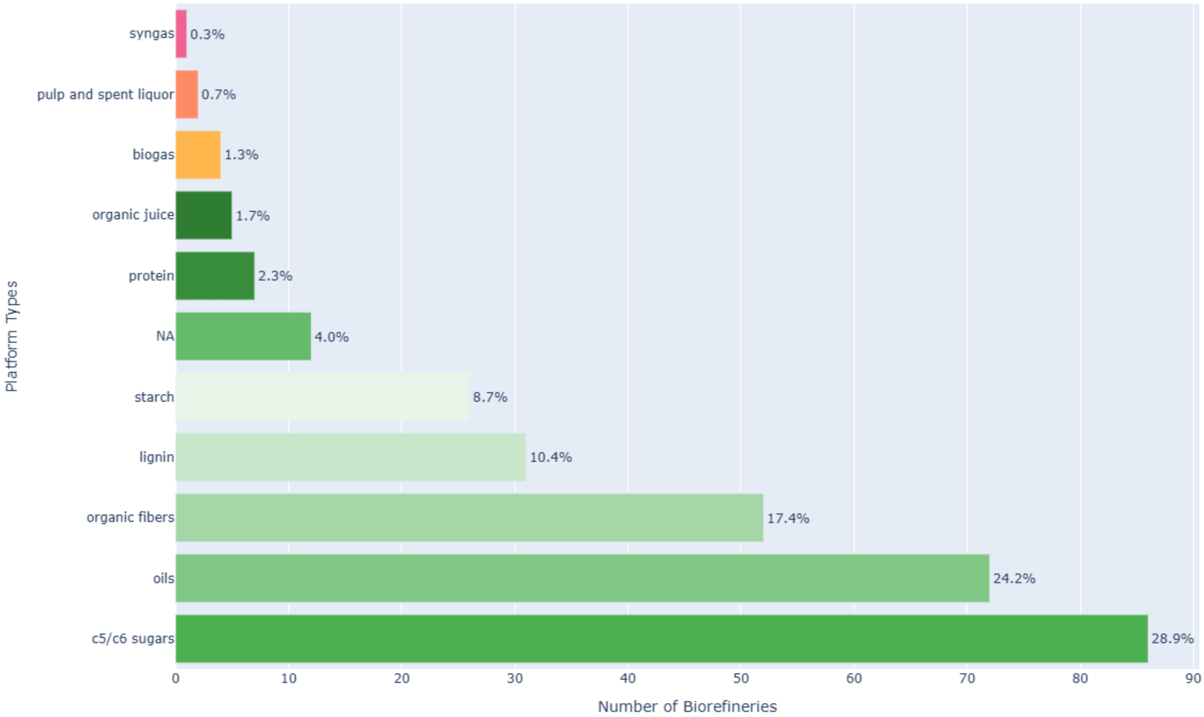

Figure 3-20: High TRL material and chemical biorefineries distribution by platform type in the EU. NA category refers to three platform (C5-C6 sugars and lignin) and two platforms (pulp and spent liquor + organic fibres and organic juice) biorefineries (Own figure based on data source: (Baldoni et al. 2021)).

This database provides extensive information about the feedstock and its associated final products along with the conversion processes used to manufacture the biobased materials or chemicals. This data source also perfectly aligns with the ESCIB project goal in identifying and mapping high TRL IBBSs in the EU.

3.5.3 Biorefineries Outlook for 2030

Platt et al. (2021) estimated an outlook for deployments of future biorefineries in the EU in the year 2030 in two scenarios. The low scenario assumes low demand for BBPs and also low support from policymakers, while the high scenario means high demand and more support provided by the policymakers. It is estimated that by 2030, in the low scenario, almost 27 new biorefineries would be operational, while in the high scenario, almost 44 new biorefineries (almost 3.1 million tons capacity) would be built by 2030, with pathways D and E showing the highest potential in both scenarios. Pathway D biorefineries are mostly located in Scandinavia, France, and Germany, while pathway E biorefineries are in France and Germany. The biorefineries deployment will include small, medium and large-scale plants, ranging from 6 to 220 kilo ton annual (kta) product capacity. Considering the material and chemicals, this study only takes chemical building blocks, plastics, and ethanol biorefineries, and does not include jet, fuels, or pulp refineries.

3.6 Utilization of Biomass

3.6.1 Overview

JRC et al. (2022) analysed that the main end-use of biomass in the EU is food and feed with 52% of the total biomass usage. Energy production follows with around 20%, while the material utilization contributes only with 13% (Figure 3-21).

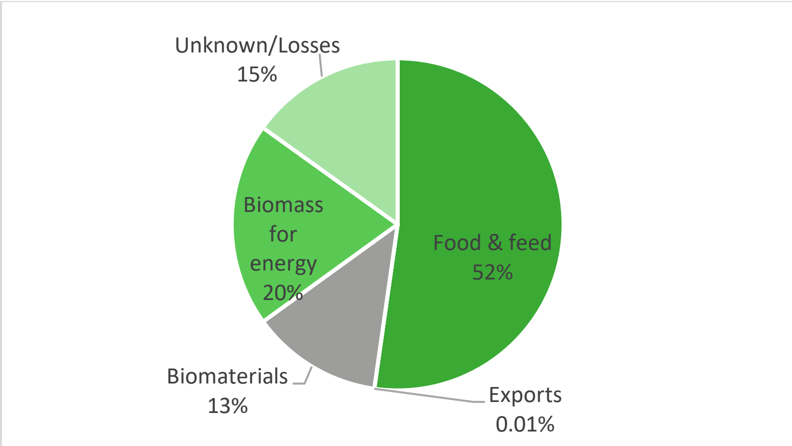

Figure 3-21: Utilization of the supplied Biomass in the EU-27 (Own figure based on data source: (Gurría et al. 2022)).

Regarding the overall trend for the EU-27, the biomass used for biomaterials and energy shows a slight increase, while for food the use is nearly stagnant (Figure 3-22). The biomaterials usage has increased from 95 to 109 million tons of dry matter, showing an overall increase of almost 12.5% from 2009 to 2017. On the other hand, the energy sector has shown an increase of almost 25%, which is double that of the biomaterials sector growth during the same period.

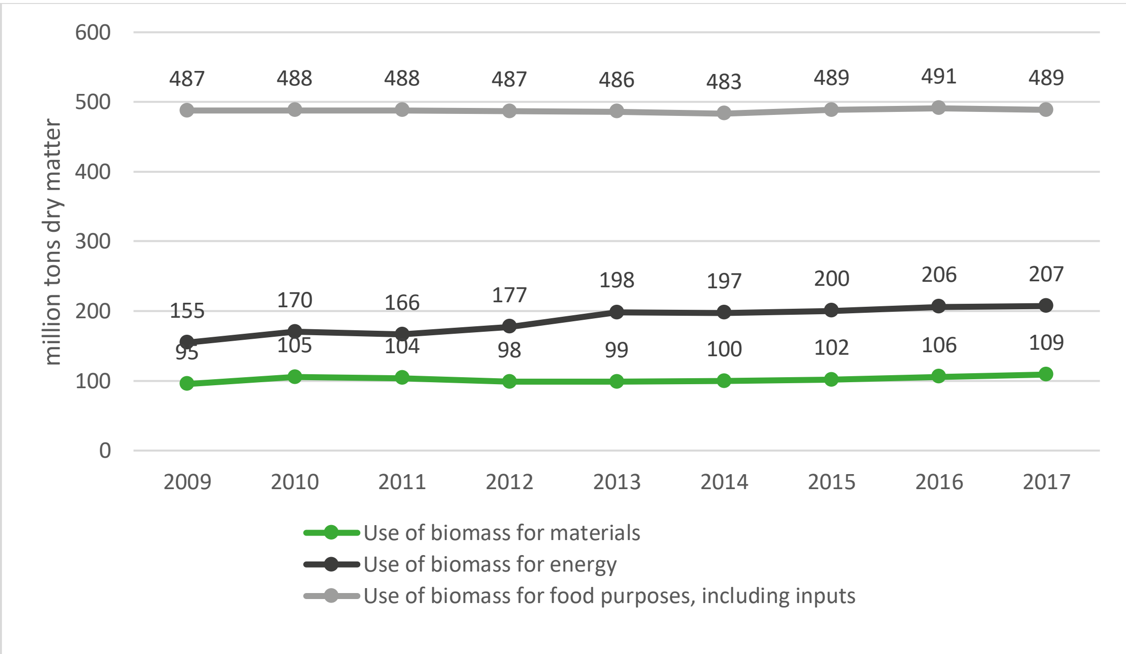

Figure 3-22: Utilization of the supplied biomass in EU-27 (Own figure based on data source: (Knowledge Centre for Bioeconomy 2024)).

The biomass origin of almost all the biomaterials is woody biomass, i.e., from forestry feedstock (Figure 3-23). The agricultural biomass contributes only with a small amount to the biomaterials (bioplastics, biochemicals). Energy production also heavily relies on forestry feedstock. Since the ESCIB project focuses on biomaterials, the discussion will mainly revolve around the use of biomaterials derived from forestry feedstock. According to the wood resource balance in 2017 (Cazzaniga et al. 2021), the total supply of wood resources, including primary, secondary, and post-consumer wood, was 810.7 million m^3. 54% was used for material production and 46% for energy production. Within the material utilization, the sawmill industry had the highest share, accounting for up to 22%, followed by the pulp and panel industry (Figure 3-23). Wood pallets industry had the lowest share with almost 4% of the material utilization based on forestry related biomass.

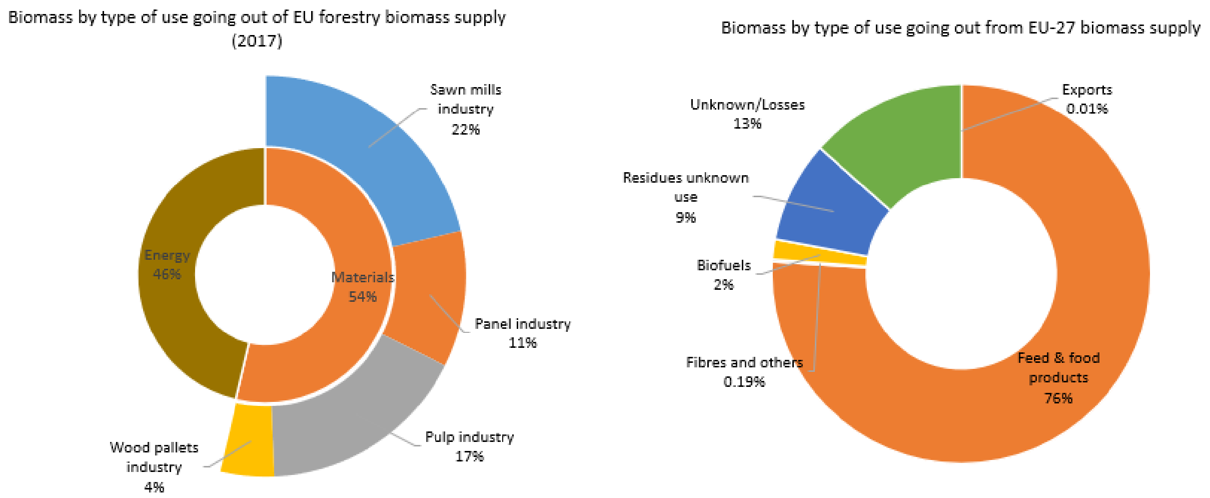

Figure 3-23: Utilization of biomass, left: based on forestry biomass(Own figure based on data source: (Cazzaniga et al. 2021)), right: based on agricultural feedstock (Own figure based on data source: (Gurría et al. 2022)).

3.6.2 Utilization of Woody Biomass

The use of primary wood for material production increased from 303 million cubic meter (Mm^3) in 2009 to 363 Mm^3 in 2017. Similarly, secondary wood used for material production increased from 62 Mm^3 in 2009 to 73 Mm^3 in 2017. The proportion of secondary wood used in total material production varied from 14.2% in 2009 to 13.6% in 2010. Recovered woody biomass (post-consumer wood and recovered paper) used for material purposes increased from 65 Mm^3 in 2009 and reached 78 Mm^3 by 2017. The overall secondary woody biomass recovery for material uses increased from 127 Mm^3 in 2009 to 151 Mm^3 in 2017. Furthermore, the paper and paperboard industry utilizes a relatively small amount of wood pulp, around 9 Mm^3, which is net imported and represents less than 2.5% of the total uses (Avitabile et al. 2023).

The total woody biomass recovery for material uses increased from 127 to 151 Mm^3 between 2009 and 2017. The primary driver of this increase in secondary woody biomass uses for materials was the contribution of by-products, followed by recovered paper and post-consumer wood. The increase in the use of by-products (black liquor, sawmill residues, wood chips and particles) for materials can mainly be attributed to their increased availability. This increased availability was a result of higher sawn wood production which led to an increased production of sawmilling by-products used in wood-based panels and wood pulp production (Avitabile et al. 2023).

Recovered paper on the other hand, witnessed an increase from 51 to 63 Mm^3 during the period from 2009 to 2017. After 2014, the use of recovered paper in the paper and paperboard industry stopped increasing and stayed at the same level. Despite an overall reduction in paper production, there has been an increase in the manufacturing of packaging paper in recent years (Avitabile et al. 2023). According to FAOSTAT (FAOSTAT 2024a), reported by Avitabile et al. (2023), the production of printing and writing papers in the EU-27 witnessed a 33% decrease, dwindling from 29.4 to 19.7 million tons during the 2014-2020 period. The net export of recovered paper undermines the potential for the cascading use of recovered paper in the EU-27. The quality of wood fibre in the recovered paper may offer a plausible explanation for this trend. Study by Scott (2019), reported by Avitabile et al. (2023) concluded that the fibre strength in recycled paper remains the primary impediment to further enhanced recycling (Avitabile et al. 2023).

The utilization of by-products, encompassing black liquor, sawmill residues, wood chips, and particles, rose from 148 to 182 Mm^3 between the years 2009 and 2017. On average, 40% of the by-products were dedicated for material purposes, whereas the remaining 60% were allocated to energy uses. The utilization of by-products for materials increased from 62 Mm^3 in 2009 to 73 Mm^3 in 2017, while over the same timeframe, the use of by-products for energy surged from 86 Mm^3 to 109 Mm^3 (Avitabile et al. 2023).

Over the period from 2009 to 2017, the utilization of post-consumer wood, encompassing wood sourced from construction, renovation, demolition, packaging, and used furniture, escalated from 29 to 38 Mm^3. Predominantly, post-consumer wood was allocated with 42% for material use and 58% for energy purposes. Especially the consumption for energy escalated from 15 to 23 Mm^3, whereas the utilization for material purposes showed a marginal increase from 14 to 15 Mm^3 in the aforementioned period. In the year 2017, the wood-based panel industry emerged as the principal consumer of post-consumer wood within the EU-27, absorbing 15% of the total wood input. Complementary to this, sawmilling by-products and primary wood constituted 34% and 51% of the total wood input, respectively. Notably, the bulk of post-consumer wood was channeled into the production of particleboard. Avitabile et al. (2023) reported from the study of Vis M et al. (2016) that although it is technically feasible to derive particleboard primarily from post-consumer wood and sawmilling by-products, the prevailing input composition largely comprises primary wood. This phenomenon can be attributed to the limited availability of high-quality post-consumer wood in the market, high processing costs, or an oversupply of primary wood (Avitabile et al. 2023).

3.6.3 Utilization of Agricultural Biomass

The highest feedstock supply in EU-27 is from agricultural origin, which is mostly used as food and feed with almost 70% based on tons of dry matter. Biofuels production is around 2%, while the materials used, i.e., fibre production and other materials (chemicals, plastics), are less than 1%.

Furthermore, EU-27 cereal balance sheet (EU cereals balance sheets) for the year 2023-2024 shows that the total consumption of cereals amounted to 257 million tons. Among the total consumption, almost 88% of the cereals were consumed as food, feed, and seed. Only 12% of the cereal was consumed for industrial purposes, out of which almost 5% was consumed for biofuels, while only 7% was used for other industrial purposes (materials and others).

Avitabile et al. (2023) report from the (European Commission et al. 2023) that in 2020, corn and soybeans were primarily used as feed in EU-27, while common wheat was used for both food and feed. Sugar beets were mainly used for food. 13.2% of corn, 7.4% of wheat, 8.2% of sugar beets, and 4.1% of seeds were allocated for material purposes. These percentages are based on the dry matter weight in 1,000 tons. The outlook of usage of arable crops in percentage for materials consumption reveals that the material use is projected to increase slightly from 8.2% in 2020 to 9.7% in 2050.

3.6.4 Utilization of Feedstock by Different Biobased Sectors

Feedstock is an important part of BBS, and it is essential to know the supply chain and the feedstock that is used for manufacturing different BBPs. Different woods and agricultural biomass flows are used for producing different BBPs in different sectors, i.e., textiles, wood products, chemicals, and plastics. The study by Ocamica et al. (2024b) presents the use of different feedstock ratios in percentage for the production of BBPs in different sectors in the EU. It is revealed that the wood sector uses softwood (79%) and hardwood (21%) for the production of wood-based products in the EU (Figure 3-24). Furthermore, the textile sector mainly depends on cotton, almost 73%, followed by wood pulp (17%) and jute (10%). Similarly, palm oil (35%), soybean (31%), maize (12%), rapeseed oil (11%), wheat (6%), and sugar cane are used least (5%) for the production of biobased chemicals and polymers in EU.

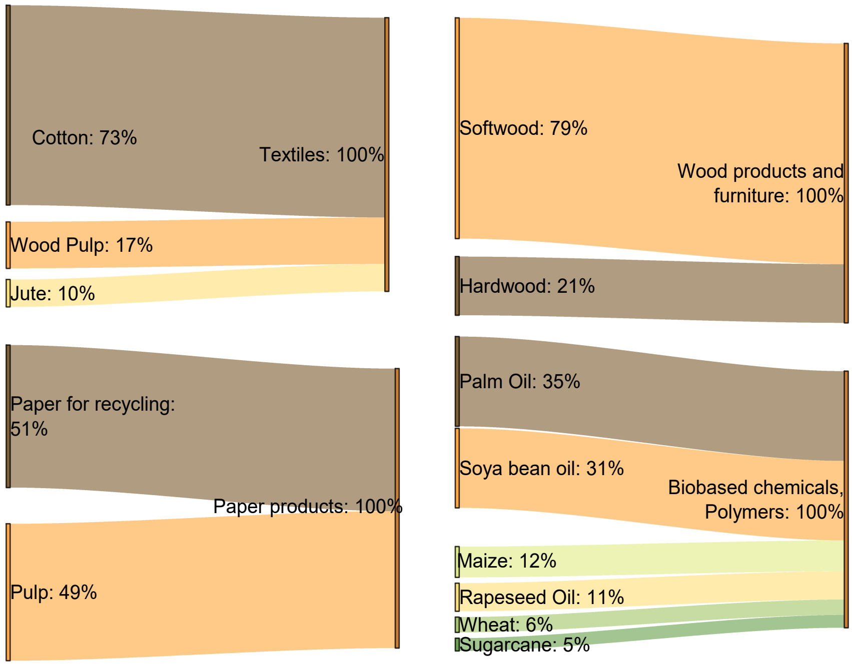

Figure 3-24: Percentage use of feedstocks for producing different biobased products sectors-wise in the EU (Own figure based on data source: (Ocamica et al. 2024b)).

3.6.5 Production of Biobased Chemicals

Most of the diverse biobased chemicals in the EU-27 were derived in biorefineries from agricultural feedstock (oil crops, starch, and sugar crops, etc.), only less from forestry and aquatic biomass (Baldoni et al. 2021; Sturm et al. 2023; Cefic.org 2024). Besides biofuels, agrochemicals, surfactants, cosmetics, and food and feed-based chemicals make significant contributions to the EU biochemicals sector (Sturm et al. 2023). RoadToBio project (Panchaksharam et al. 2019) assessed the share of biobased chemicals/products of the overall production of chemicals/products in the EU across nine specific product groups. These groups encompass surfactants, paints and coatings, man-made fibres, cosmetics, plastics/polymers, lubricants, adhesives, solvents, and agrochemicals. The biobased chemicals constitute slightly over 4% of the total production volume (1000 ton/year) of these nine product categories. Spekreijse et al. (2019) reported that the biobased share for all these categories, including one extra category, i.e., platform chemicals, was around 3% in EU-27 plus UK.

At product category level in EU-27, agrochemicals and solvents exhibit the lowest biobased chemicals share, amounting to less than 1%. The share of biobased chemicals within the adhesives, and plastic/polymers category is approximately 2%. Notably, biobased chemicals constitute a larger share in lower volume product groups, with surfactants with 31%, paints and coatings with 19%, and cosmetics with over 40% (Panchaksharam et al. 2019).

Regarding the biobased chemicals production of the member states in EU-27 and the United Kingdom (UK), Germany has the highest share of 24% followed by France having 15%. Germany, France, Spain, and Italy together have almost 57% of the total share in the biobased chemical production (Sturm et al. 2023).

Furthermore, Spekreijse et al. (2019) aimed to provide insights into the EU-27+UK biochemical products sector by categorizing the main products into 10 distinct categories. The study specifically focused on commercial-scale products, which are high TRL in the EU. It was found that platform chemicals and polymers for plastics have a dominating presence in total EU-27+UK production, with biobased shares of only 0.3% and 0.4% respectively. The categories of paints, coatings, inks, and dyes, as well as surfactants, exhibit substantial biobased production amounts, despite not being commonly associated with BBPs. Surfactants, in particular, demonstrate a remarkably high biobased share of 50%, possibly attributable to the prevalent use of biobased oleochemicals in this category. Overall, the total EU biobased production for all 10 product categories is estimated at 4.7 Mt/a, representing a 3.0% biobased share of the total 156 Mt/a EU-27+UK production. Furthermore, the study revealed that the EU-27+UK serves as a net importer for 8 out of 10 BBPs categories.

The analysis included the assessment of feedstock use and import dependence for each product category. It reveals that the paints, coatings, and lubricants categories exhibit the highest feedstock import dependency, while the lowest dependence is observed in the solvents and man-made fibres category. Future market size estimates have been derived through the calculation of the compound annual growth rate (CAGR) of the biobased market for each category. CAGR is the mean annual growth rate of the production of a product for a specific period of time (more than one year) based on literature and interviews. The forecast indicates substantial growth in the surfactants market due to its existing large size. Additionally, platform chemicals and adhesives are expected to experience the most significant CAGR of 10%. Conversely, minimal growth is projected for the market of biobased solvents, attributable to the low priority given to the production of biobased alternatives. Similarly, bio-lubricants are forecasted to experience a relatively low CAGR of 1% (Spekreijse et al. 2019).

3.6.6 Production of Biobased Plastics

Bioplastics represent a critical segment within the BBPs. In 2022, the global production of biobased plastic amounted to 1.9 million tons, the production in the EU-27+3 (Norway, Switzerland, Turkey) were around 0.4 million tons. Presently, Europe heavily relies on fossil-based feedstock for plastic production. However, there is a positive shift towards circular feedstock (recycled feedstock or biobased feedstock). The proportion of biobased plastic utilization rose from nearly 0.2% in 2018 to 0.7% in 2022, albeit not significantly. In order to realize its circularity and net-zero ambitions by 2050, the European plastics industry must substantially decrease its dependence on fossil-based feedstock and need a transition to circular feedstock, encompassing recycled, biobased, or carbon-captured alternatives (Plastics Europe 2021).

Upon analysis of individual member countries, it becomes apparent that the majority of EU member states produce less than 1% of biobased plastics. However, Italy and Germany stood out with 2.7% and nearly 1.5% of biobased plastic production, respectively. Although biobased feedstock currently represents a small proportion of plastic production, it is increasingly accessible and holds significant potential for future growth. This feedstock can be derived from primary sources like crops, as well as secondary sources such as organic waste (e.g., compost or cooking oils), crop and farm residues, animal fats, forestry waste, and sewage sludge (Plastics Europe 2021).

3.6.7 Outlook for Biobased Materials and Chemicals

Platt et al. (2021) reported that the demand for biobased chemicals and materials can increase up to 17 million tons per year (Mtpa) in high growth scenario, while almost half of this demand in low growth scenario. However, supply of materials and chemicals in biorefineries in EU is estimated 4.9 Mtpa in 2019. From the new biorefineries, it is estimated that the supply will grow by almost 3.1 Mt in 2030 in high-growth scenario and by 1.1 Mt in low-growth scenario. The additional supply for the year 2030 will be fulfilled by the expansion of operational biorefineries, and new commercial and demonstration-scale plants. On the demand side, the outlook for 2030 in low scenarios is almost 7.8 Mt, and hence, 2.2 Mt supply will be fulfilled by alternative ramp-up or imports. Alternative ramp-up will be provided by changing the route of biofuel biorefineries to focus on biochemical production. High growth among the product groups is expected to be almost 7.2% in polymers, 4.9 % in resins, and 1% in building blocks and additives, respectively (Platt et al. 2021).

3.7 End of Life and Waste Management of Biobased Materials and Products

3.7.1 Waste Generation and Recovery of Biobased Products and Materials

The waste statistics of the EU-27 reveal an upward trend in biogenic waste (agricultural and industrial biowaste) production since 2014 till 2020 (Figure 3-25) from almost 82 million tons dry matter to 86 million tons dry matter. Nonetheless, the recovery rate, denoting the fraction of biogenic waste recycled or utilized for energy recovery, has exhibited consistent growth within the same timeframe from 85% up to 90% (based on tons). Biogenic waste data include agricultural and industrial biowaste that includes animal waste (faeces, urine, manure), vegetal wastes, animal and mixed food waste, textile, wood, rubber, paper and cardboard waste (Knowledge Centre for Bioeconomy 2024). As a result, the proportion of biogenic waste disposed of in landfills and incineration without energy recovery has declined. Despite these advancements, there remains untapped potential for further increasing the recovery rate.

Box 7: Definition of waste management and waste hierarchy as defined in WFD (EC 2008).

Waste management:

"Waste management means the collection, transport, recovery (including sorting), and disposal of waste, including the supervision of such operations and the after-care of disposal sites, and including actions taken as a dealer or broker"(EC 2008).

Waste hierarchy:

"Waste hierarchy shall apply as following priority order in waste prevention and management legislation and policy: (a) prevention; (b) preparing for re-use; (c) recycling; (d) other recovery, e.g., energy recovery; and (e) disposal" (EC 2008).

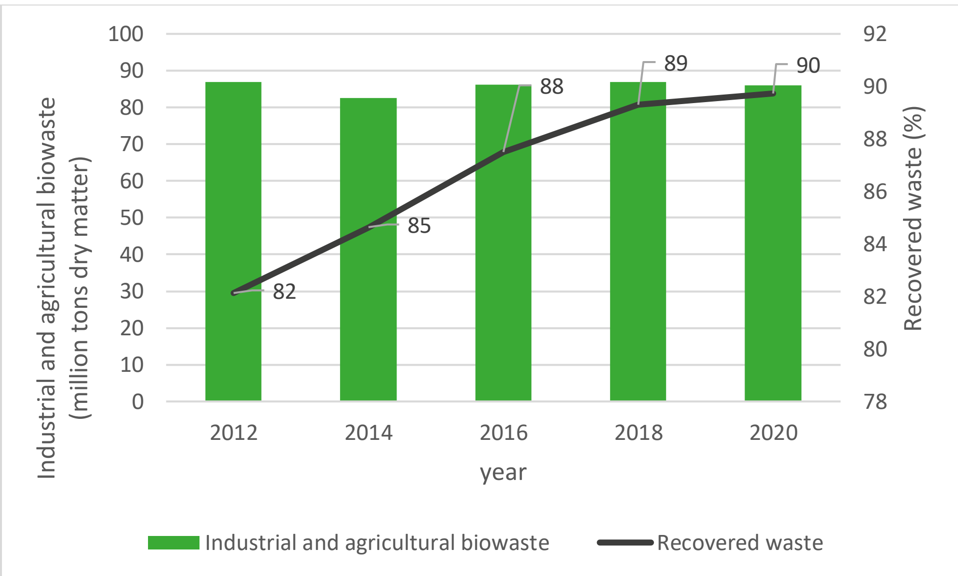

Figure 3-25: Biogenic waste (industrial and agricultural) generation and recovery rate (shares used for recycling and energy recovery in EU-27 (Own figure based on data source: (Knowledge Centre for Bioeconomy 2024).

Box 8: Definition of waste, residues and by-products (EUROSTAT and EC 2013; EC 2008).

Waste:

"Any substance or object which the holder discards or intends to or is required to discard" (EC 2008).

Residue:

Residues are materials that are not deliberately produced in a production process or during consumption in private households or businesses but may or may not be wasted (EUROSTAT and EC 2013).

Boundaries are set in WFD for production residues as follows.

By-products:

"Substance or object resulting from a production process the primary aim of which is not the production of that substance or object is considered not to be waste, but to be a by-product if the following conditions are met":

(a) further use of the substance or object is certain; (b) the substance or object can be used directly without any further processing other than normal industrial practice; (c) the substance or object is produced as an integral part of a production process; and (d) further use is lawful, i.e. the substance or object fulfils all relevant product, environmental and health protection requirements for the specific use and will not lead to overall adverse environmental or human health impacts (EC 2008).

Production residues, as defined in the manual on waste statistics is the un-deliberately produced material as a result of production process from economic activity, that may be or may not be waste.

If it fulfills the criteria as defined above according to the WFD, it is a byproduct; if not, it is primary waste and sent to a waste treatment facility (EUROSTAT and EC 2013).

Similarly, the consumption residues that arise from private households and businesses, such as food residuals, packaging materials, paper, glass, and plastic, are primary waste (EUROSTAT and EC 2013).

Both production and consumption residue (primary waste) go into waste treatment facilities, and the waste generated by such facilities during the processing of waste is called waste treatment residue or secondary waste. This waste includes waste for disposal and recovery operation (EUROSTAT and EC 2013).

Biowaste is a biodegradable waste that comes from garden and park waste, food and kitchen waste from households, restaurants. It does not include forestry and other waste (Environment-EC 2024). Waste frame directive (WFD) (EC 2008) definition for biowaste is adapted in ESCIB project. While biogenic waste is a broad term and can be used for all types of waste, including forestry and other waste besides food waste. Biogenic mean anything from biological origin such as plants, animals, enzymes, and microorganisms. Therefore, the definition is adapted as in (Box 9).

Box 9: Definition of biowaste (EC 2008) , biogenic waste and biobased waste.

Biowaste: "*Biodegradable garden and park waste, food and kitchen waste from households, offices, restaurants, wholesale, canteens, caterers and retail premises and comparable waste from food processing plants" (EC 2008).*

Biogenic waste: *Biogenic waste is any waste of biological origin including waste derived from living organisms (plants, fungi and animals) and waste composed of organic matter, i.e. remains of dead plants and animals, and faeces(biorecer 2025).*

Biobased waste: *Biobased waste is waste that arises from biobased products. This include all biobased waste that may or may not be biodegradable. For example, forestry and agricultural residues, sewage sludge, bio textiles and biopolymers waste.*

The data presented here is from EUROSTAT which uses special definition for the key terms. The recovery used here is a broad term and is defined in manual on waste statistics 2013 (EUROSTAT and EC 2013) in (Box 11). These definitions are important because the data reported in EUROSTAT use these definitions, but it will be further developed in the later stages of the project according to the ESCIB scope.

Based on the broad definition of the term "recovery," it is estimated that there is a high potential for a high recovery rate. Among the EU-27 member states, Austria, Denmark, Finland, Germany, Italy, Luxembourg, Poland, and Sweden have a recovery rate higher than 90%. In Germany, e.g., landfilling of organic material is forbidden. Instead, Bulgaria, the Czech Republic, and Latvia have a recovery rate between 70% and 80% (Figure 3-26).

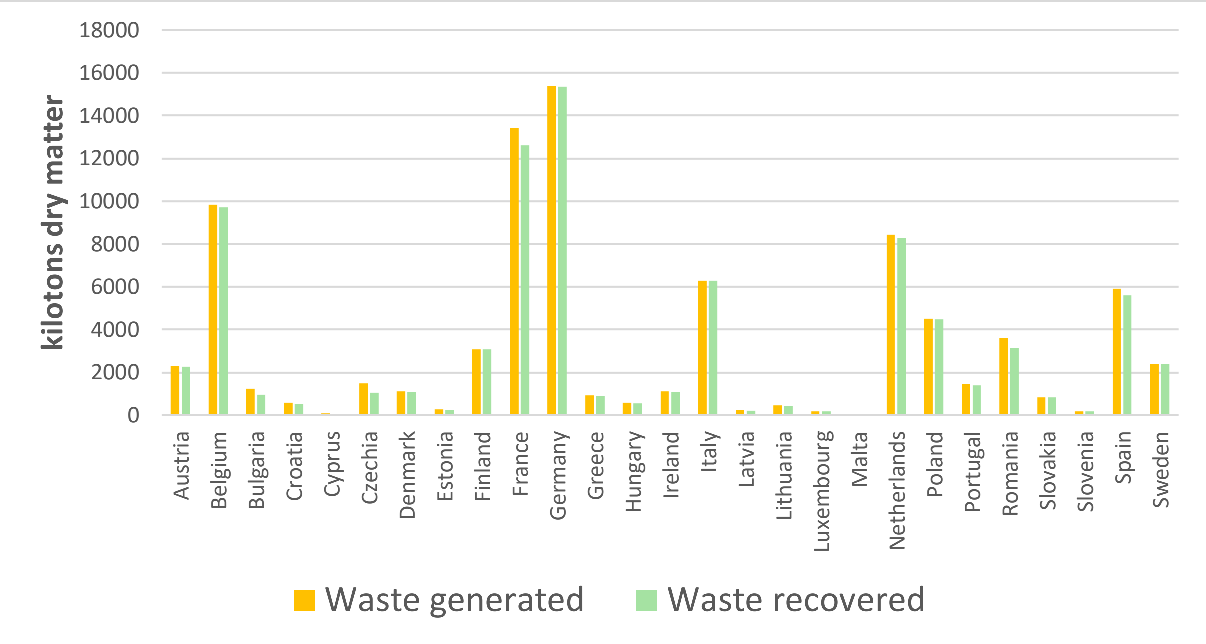

Figure 3-26: Biogenic waste generated and recovered by member states in EU-27 (2020) (Own figure based on data source: (Knowledge Centre for Bioeconomy 2024)).

Furthermore, analyzing the capture of food and biowaste, the current (that refers to year 2016-2019 based on data availability) food waste capture in the EU27+UK stands at 9.5 million tons annually, representing only 16% of the theoretical potential, that estimated at 59.9 million tons. In contrast, the capture level for biowaste (food + garden) during the same period is 32%. The concept of 'operational potential', set at approximately 85% of the theoretical potential, is utilized to evaluate the recoverable food waste left in mixed waste. An analysis of national data demonstrates that the capture of biowaste exceeds that of food waste, indicating that food waste collection is in a relatively nascent stage compared to garden waste. Consequently, the implementation of effective strategies and practices for food waste collection is deemed pivotal for enhancing overall recycling rates in the foreseeable future (Favoino et al. 2020). Among the EU-27 member states, Denmark, France, Germany, and Italy exhibit a biowaste capture level exceeding 50%. Conversely, while Italy, Norway, and Germany demonstrate high levels of food waste capture, the percentage capture falls below 50% (Favoino et al. 2020). This huge potential of untapped waste can be useful in the future to be used a raw material for biobased products manufacturing as discussed in section 3.7.4.

3.7.2 Waste Generation by Type of Waste

Ocamica et al. (2024b) identified seven non-hazardous categories as biogenic waste and reported that the total biogenic waste generation in the EU-27 in 2020 amounted to 201.9 million tons. These amounts include 53.6 million tons of vegetal waste, 46.4 million tons of wood waste, and 43.5 million tons of paper and cardboard waste. These three categories collectively account for 70% of the total waste generated (Figure 3-27) (Ocamica et al. 2024b).

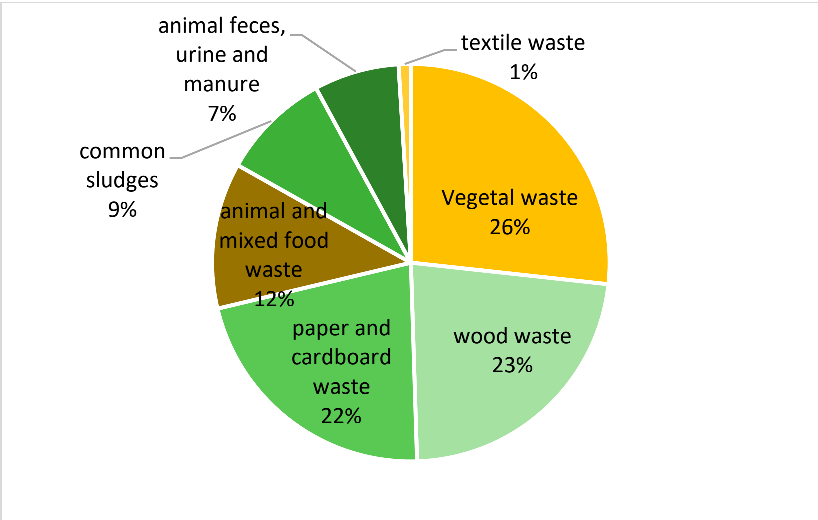

Figure 3-27: Share of non-hazardous biogenic waste generation by waste types in EU-27 in the year 2020 (Own figure based on data source: (Ocamica et al. 2024b)).

Moreover, the analysis of waste generation across various economic activities shows that household waste accounted for the highest mass, reaching 58.8 million tons in 2020 (Figure 3-28). Manufacturing waste closely followed, with 53.7 million tons of waste, water supply and sewerage activities with 32.6 million tons, services 26 million tons, and agricultural, forestry and fishing activity accounted for almost 18 million tons of waste in the same year. Furthermore, the waste categories vary across different economic activities. For instance, the households exhibited the highest share of vegetable waste, whereas the manufacturing demonstrated the highest share of wood waste.

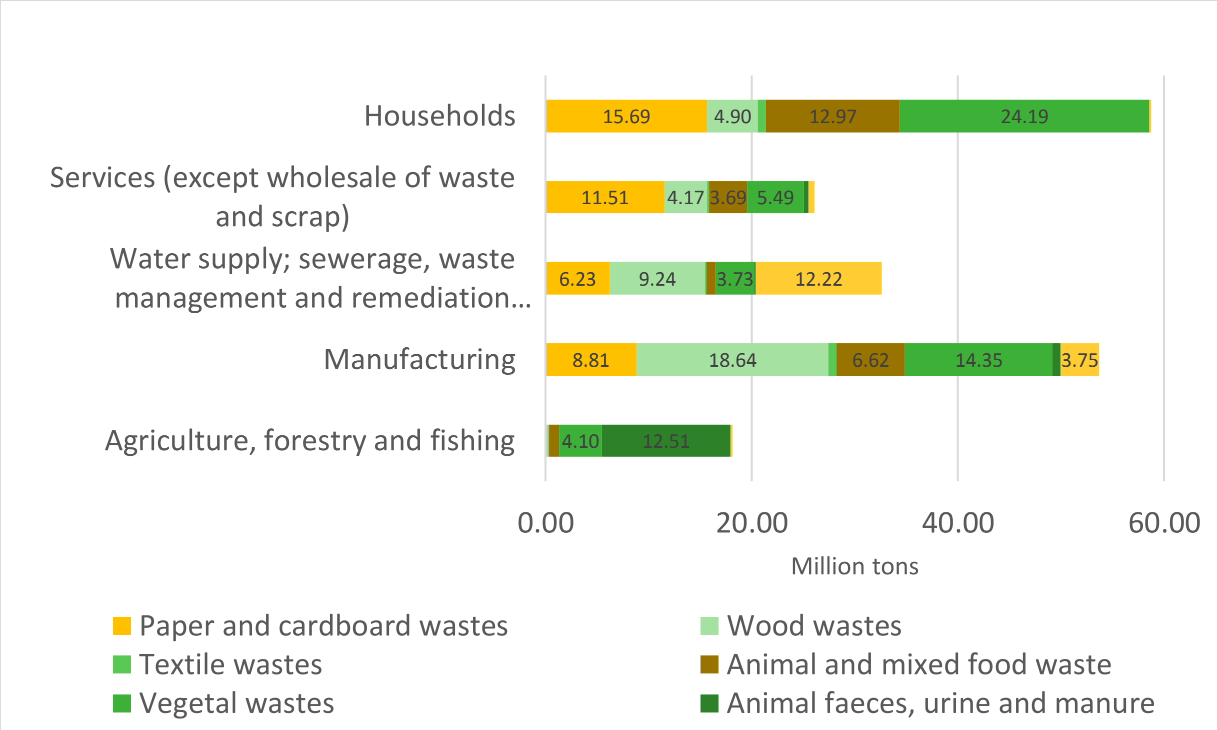

Figure 3-28: Biogenic waste generation by type of economic activity and biobased waste categories (based on (Ocamica et al. 2024a)) in EU-27 in the year 2020 (Own figure based on data source: (EUROSTAT 2024).

Looking into waste generation in the EU-27 member states according to the economic activities, it is revealed that the highest waste is produced in Germany, amounting to 65.2 million tons, France, 54.8 million tones, Italy 50 million tons, Netherlands 38.2 and Belgium with 33.6 million tons respectively (Figure 3-29). Looking into waste categories of individual member states, Germany, Italy, and France have the highest household waste among other waste categories, while the Netherlands has the highest manufacturing waste. Combined six member states (Germany, Italy, France, Netherlands, Spain, Belgium) are responsible for almost 72 % of the total biogenic waste generation in EU-27.

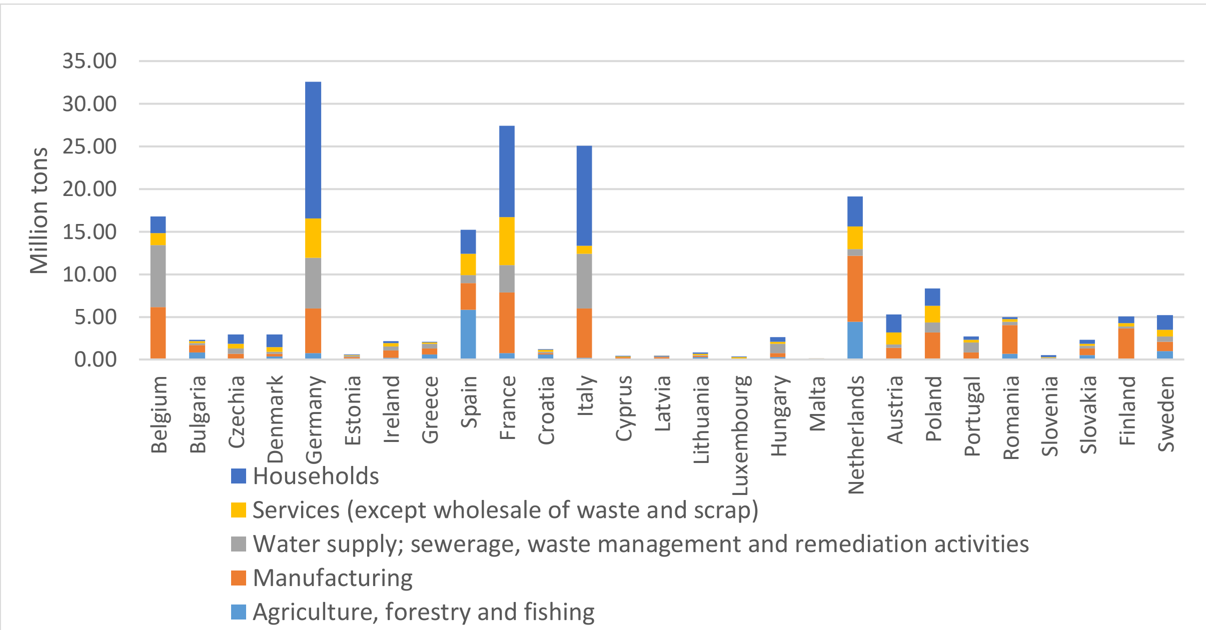

Figure 3-29: Biogenic waste generation among member states of EU-27 in the year 2020 based on the type of economic activities (Own figure based on data source:(EUROSTAT 2024).

3.7.3 Waste Treatment by Type of Technology

The waste treatment in the EU indicates that recycling holds the highest share among various waste categories. The method of recovery varies for different waste categories. Paper and cardboard, as well as vegetal waste, exhibit high recovery-recycling shares, reaching nearly 70% and 80% respectively. Conversely, wood waste and animal and mixed food waste demonstrate a considerable share of energy recovery beside the recovery-recycling. The overall disposal rate is elevated in common sludges and textile waste. Untreated waste, constituting up to 30%, remains in common sludges, textile waste, animal faeces and manure, as well as paper and cardboard waste (Ocamica et al. 2024b). Detailed definitions for these terms are provided in the manual on waste statistics (EUROSTAT and EC 2013) and the related terms are presented in Annex I and II.

Box 10: Definition of treatment (EC 2008).

Treatment:

"Treatment means recovery or disposal operations, including preparation prior to recovery or disposal"(EC 2008).

Box 11: Definition of reuse, recovery, recycling, disposal and backfilling as per WFD (EC 2008).

Reuse:

"Any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (EC 2008).

Recovery:

"Recovery means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function, in the plant or in the wider economy" (EC 2008).

Recycling:

"Recycling is a subset of recovery and '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 (e.g., composting, anaerobic digestion etc.) but excludes the use as fuels and the use for backfilling operations" (EC 2008).

Disposal:

"Disposal means any operation which is not recovery even where the operation has as a secondary consequence the reclamation of substances or energy" (EC 2008).

Backfilling:

"Any recovery operation where suitable non-hazardous waste is used for purposes of reclamation in excavated areas or for engineering purposes in landscaping. Waste used for backfilling must substitute non-waste materials, be suitable for the aforementioned purposes, and be limited to the amount strictly necessary to achieve those purposes"(EC 2008).

Considering the individual EU-27 member countries in terms of EoL management for the identified biogenic waste categories discussed above, Germany, France, and the Netherlands exhibit the highest share of recovery-recycling and backfilling by quantity (Figure 3-30). Furthermore, nearly all member states demonstrate a notable emphasis on recovery-recycling in comparison to recovery-energy. However, it is notable that Finland stands out with a high share of energy recovery, distinguishing itself from the predominant focus on materials recovery or recycling. Similarly, Germany and France have also the highest share of energy recovery among the member states. Furthermore, France has the highest disposal-landfill, while Netherlands has the highest disposal-incineration among member states.

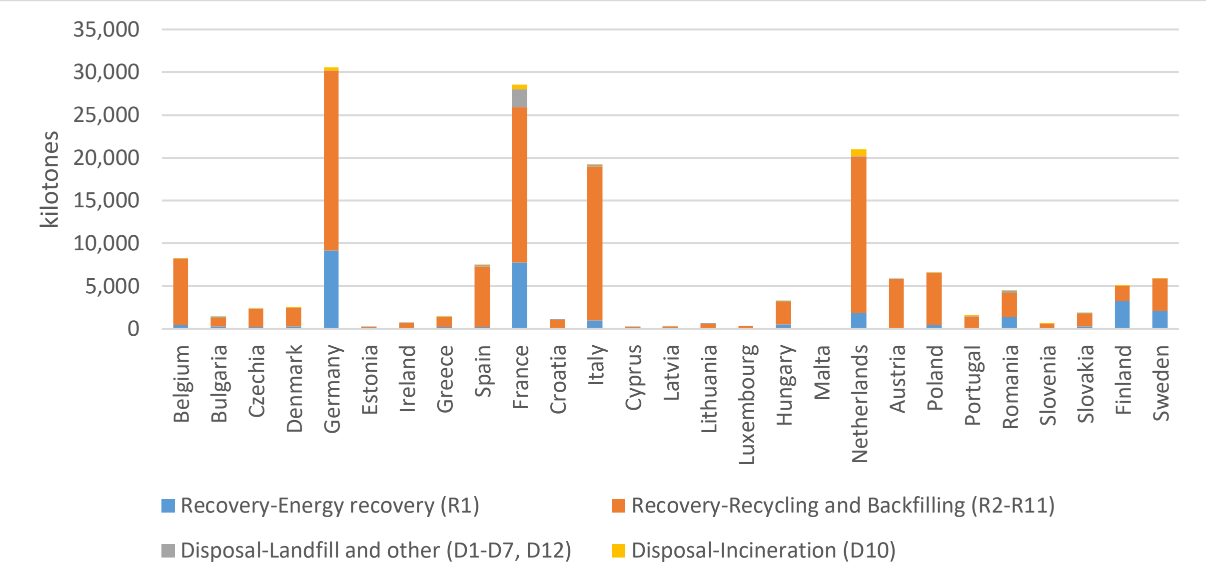

Figure 3-30: Biogenic waste recovered by type of end of life management operation for EU-27 in year 2020 (Own figure based on data source: (EUROSTAT 2024)). Biogenic waste categories and economic activities based on (Ocamica et al. 2024a). Waste management categories as per Annex I and Annex II in Annexes.

3.7.4 Biogenic waste Potential as Feedstock for Biomaterials Applications

The primary biomass feedstock is a crucial source for biobased materials production within the EU. Subsequent to the completion of the biomaterial supply chain and the genesis of waste, these materials undergo a process of reutilization, recovery, or disposal. Ocamica et al. (2024b) conducted an exhaustive literature review to explore the potential applications of various waste categories in both materials and energy sectors. The findings underscore the vast potential for biogenic waste to serve as raw material or feedstock across a spectrum of biobased sector applications, encompassing textiles, wood products, paper, biobased chemicals, and plastics. These observations substantiate the versatility of wood waste as an applicable feedstock across nearly all sectors. Furthermore, the study indicates that other waste types, with the exception of animal faeces, urine, and manure waste, hold promise as feedstock for nearly all biobased sectors, excluding the wood products sector. Similarly, biogenic waste can also be routed into manufacturing of products in construction sector (Duque-Acevedo et al. 2022; Leone et al. 2025).

4 Conclusions

The focus of this study is to give an overview of high TRL industrial biobased systems in EU-27 for having a common understanding and for agreeing to common definitions within the project partners. For the analysis and assessment of IBBS, the definitions of terms are very crucial. Therefore, the definition of BBPs, BBMs, IBBs, bioindustry, biorefinery, waste, residues, by-products, bio waste, and biogenic waste was adapted according to the scope of the ESCIB project, which will be used as a guideline in other tasks of the project. Furthermore, definitions of reuse, recovery, recycling, and disposal are presented for this task, which will be further developed in the project in circularity task to clearly differentiate between the different routes that can be adapted by a BBP after its useful life comes to an end.

The overview shows critical findings about biomass flows, feedstock availability, biorefineries concentration, utilization paths, whereby the ESCIB focus lays on materials utilization, and end of life management in the region. It was observed that the EU-27 biobased materials economy is mainly powered by primary forestry and agricultural feedstock and negligible extent by waste and marine feedstock based on quantity.

Agricultural feedstock analysis reveals that EU-27 production for 2023 was 255.47 million tons (total supply), with France, Germany, and Poland accounting for up to 56% of the total supply. Industrial crops covered almost 12.9 million hectares, with an average of 12.51 million hectares for the period 2018–2023. France, Romania, and Germany are the member states with the largest harvesting area in the EU-27 with together almost 45% of the total harvesting area for industrial crops. Future outlook shows a modest increase in cereal production up to 281.2 million tons and for oil and protein crops production up to 31.8 million tons until 2035. Forestry feedstock data reveals that the total biomass density (forest stock per hectare) in EU-27 forests averaged at 117 tons/ha in 2020 with a total forest area of 157 million hectares. While the countries with the largest forest area are located in the northern and southern Europe (Sweden, Finland, Spain), the largest forest stocks are found in central Europe (Germany, France, Poland) and northern Europe (Sweden, Finland). Four countries produce up to 54 % of roundwood of the total EU-27 supply, which is the key feedstock for materials production, namely, Germany (16%), Sweden (15%), Finland (13%) and France (10%). Overall, the roundwood production has a positive trend in the period from 2010 till 2022 with an increase from 446.5 million m^3 to 508.4 m^3 with an almost 12% increase in this period.

The total biomass supply in the EU is around 1 billion tons of dry matter, with almost 70% from agricultural feedstock, 25% from forestry and less than 1% from the fisheries sector. Among the total supply, almost 90% is domestic production, 4% is imports, and the rest include unknown origin. It shows that the EU is much less dependent on the import of raw feedstock for its biomass supply.

The wood resource balance of EU-27 reveals that the primary wood resources supply accounts for 68%, secondary supply for 27% and post-consumer wood for almost 5% of the total wood supply (for materials and energy use) with minor shares of imports in each supply origin. The EU-27 is almost self-sufficient in terms of primary and secondary wood supply for materials and energy purposes. On the other hand, there is an import dependency of oil seeds (sunflower, rapeseed, soyabean) supply of EU-27 shows almost 40% of import dependency in the total oil seeds supply.

Bioindustries data reveals that there are almost 3,455 industries, including materials and chemicals biorefineries, utilizing a wide variety of biomass feedstocks to make different BBPs. These bioindustries are developed almost 94% to high TRL and produce already on commercial scale BBPs with TRL 8-9. According to the product category, most of the industries are related to biomethane, pulp and paper followed by timber and chemicals.

On the utilization side, the dominant utilization of biomass in the EU-27 is food, feed and energy production, while the materials utilization contributes only 13% of the total biomass usage in the EU-27. Currently, most of the biobased materials have forestry-based feedstock origin, due to the fact that almost 54% of wood is used for materials production. In comparison agricultural (cereals) feedstock has only a little contribution in the biobased materials production such as fibres, chemicals, and plastics, because only around 2%-7% (EU-biomass flows and EU cereal balance sheet) of agricultural feedstock is used for industrial use including material utilization.

The EoL management of biogenic waste (industrial and agricultural) provides a high potential of recovery rate. Industrial and agricultural biogenic waste experienced an almost 96% materials and energy recovery in the EU-27 in year 2020. The member states Austria, Denmark, Germany, Finland and some other countries have more than 90% recovery rate. The non-hazardous biogenic waste, which is currently generated in EU-27, is predominantly composed of vegetal waste, wood waste and paper and cardboards waste making up to 70% of the total biogenic waste. The waste generation depends strongly on the different economic activities providing very different biogenic waste categories in the different sectors. The households are responsible for the highest biogenic waste generation followed by the manufacturing sector.

The waste treatment in the EU-27 is very differently implemented regarding the different waste categories across the economic activities. For instance, recovery-recycling hold a big share among all waste categories. Paper and cardboard waste and vegetal waste exhibits high shares of recovery-recycling amounting to 80% and 70% respectively, while the wood and animal and mixed food waste exhibits considerable shares of energy recovery amounting to 40 % and 20% respectively, beside recycling. The common sludges and textile waste are mainly recycled but also includes notable disposal operation accounting to almost 10%, that include landfill and backfilling and incineration. There is also some untreated waste ranging from almost 10% to 30% among different waste categories with highest accounting for common sludges and paper and cardboard waste. Although, currently primary biomass is mainly used for BBPs production, there is huge potential of biogenic waste to be used as raw materials for BBPs production that can help to achieve the circularity, to be less dependent on imports and to prevent the negative impact on land use change.

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5 Annexes

Annex I: Recovery operations pursuant to Annex II of the Waste Statistics Regulation (EUROSTAT and EC 2013).

Code	Types of 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

Annex II: Disposal operations pursuant to Annex I of the Waste Statistics Regulation (EUROSTAT and EC 2013).

Code	Types of disposal operations
D1	Deposit into or onto land (e.g., landfill, etc.)
D2	Land treatment (e.g., biodegradation of liquid or sludgy discards in soils, etc.)
D3	Deep injection (e.g., injection of pumpable discards into wells, salt domes or naturally occurring repositories, etc.)
D4	Surface impoundment (e.g., placement of liquid or sludgy discards into pits, ponds or lagoons, etc.)
D5	Specially engineered landfill (e.g., placement into lined discrete cells which are capped and isolated from one another and the environment, etc.)
D6	Release into a water body except seas/oceans
D7	Release into seas/oceans including sea-bed insertion
D10	Incineration on land
D12	Permanent storage (e.g., emplacement of containers in a mine, etc.)

Annex III: Examples of Industrial Biobased systems (More examples in Supplementary information)

2. Unilin

Bioindustry type: Forestry-based industry or woodworking industry

TRL: Commercial scale TRL 9 products, also innovative products at TRL 3-5.

Feedstock: Primary biomass, Harvest residues, production residues, pre and post-consumer waste wood or primary waste.

Feedstock supply: 100 domestic EU

Conversion process: Mechanical and thermochemical processing

End products: Raw and decorative chip and fiberboards

Biobased share: 85% - 100%

Product use/sale: Above 80% of use for most of the products in the EU; the rest exported outside the EU.

End of life: Energy recovery is almost 52%, materials recovery (Recycling) 47%, and disposal 1%.

Future potential for materials recovery: Above 90%

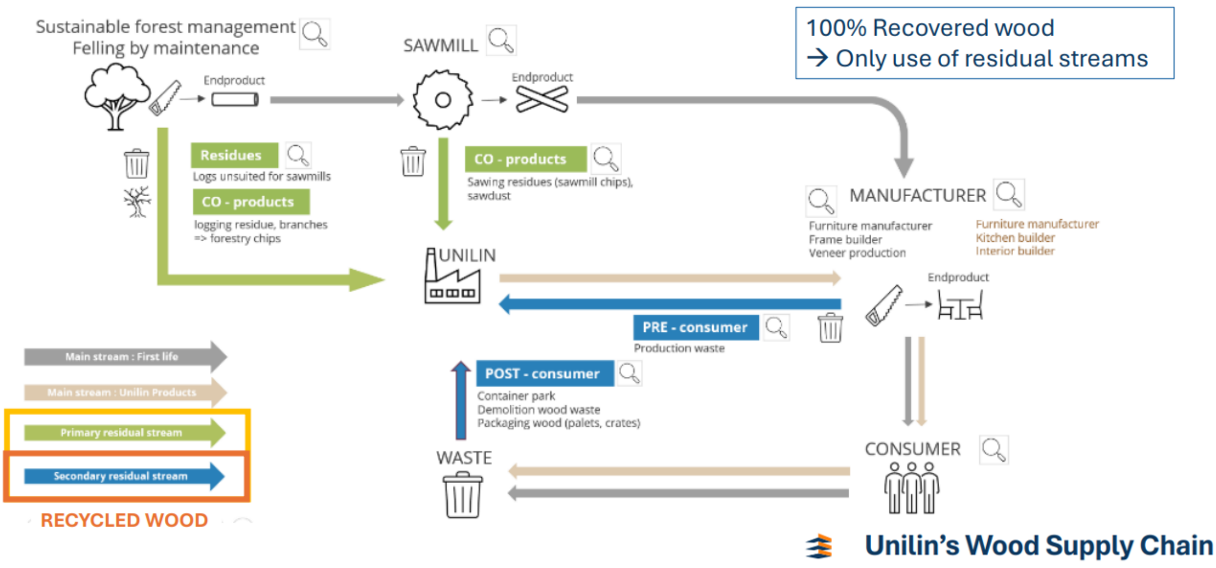


Figure 6-1: Supply Chain of wood based products at Unilin.

2. Grownbio

Bioindustry type: Lignocellulosic biorefinery

TRL: Commercial scale TRL7-8 and innovative products at TRL 3-6.

Feedstock: Grasses and short rotation coppice, primary waste

Feedstock supply: 100% domestic EU (Spain, France, Hungary, Netherlands)

Conversion process: Moulding, growing, and drying

End products: Mycelium-wood composite-packaging and mycelium-wood composite-insulation panels

Biobased share: 100%

Product use/sale: 100% in EU

End of life: Energy recovery possibility is 99%, materials recovery (minerals) 1%, and disposal 0%.

Future potential for materials recovery: Unknown

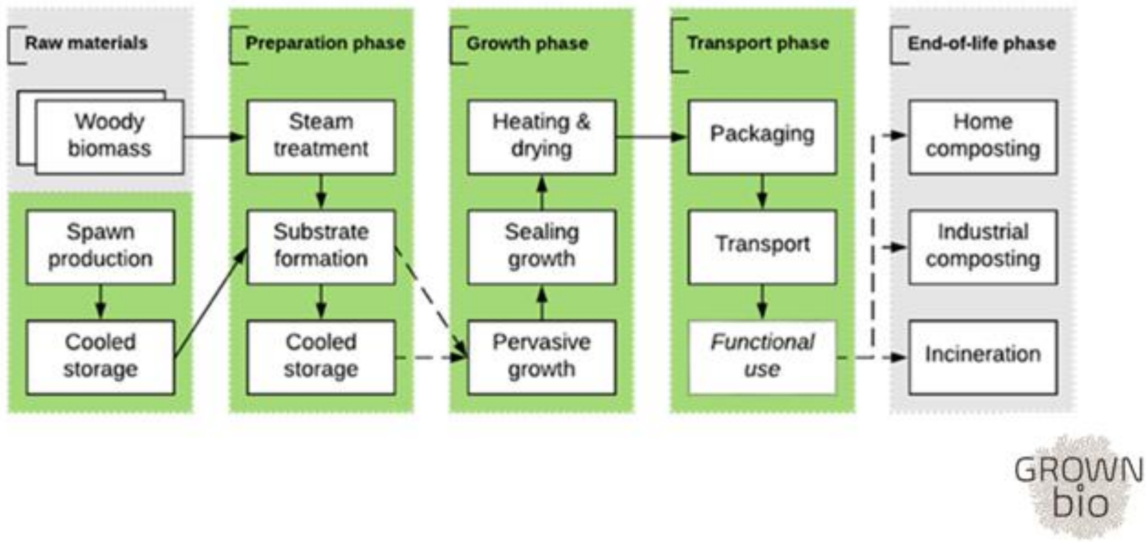


Figure 6-2: Supply chain of mycelium wood composite packaging at Grownbio.

3. Lenzing AG

1. **Pulp production**

Bioindustry type: Lignocellulosic biorefinery

TRL: Commercial scale TRL

Feedstock: Wood (for the Lenzing site, mostly beech) and other raw materials (waste textiles, agricultural residuals) are still in the development stage.

Feedstock supply: See graph below.

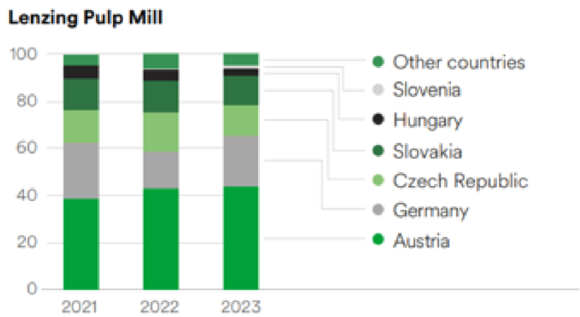
Conversion process: Pulping process

End products: Dissolving wood pulp (and other biorefinery products like acetic acid or furfural).

Product use/sale: Pulp mainly used internally for fibre production.

End of life: n.a

Future potential for materials recovery: n.a



2. **Filament production**

Bioindustry type: Lignocellulosic biorefinery

TRL: Pilot scale TRL 5-7

Feedstock: Wood (for the Lenzing site, mostly beech) and other raw materials (waste textiles, agricultural residuals) are still in the development stage.

Feedstock supply: At the moment 100% import, but Lenzing is working on pulp supply from within group (own pulp mills).

Conversion process: Lyocell filament production (NMMO as solvent).

End products: Different types lyocell filament TENCEL™ Luxe.

Product use/sale: Textile industry, technical applications under development.

End of life: Filaments are biodegradable and can also be recycled.

Future potential for materials recovery: Collection of used/waste textiles

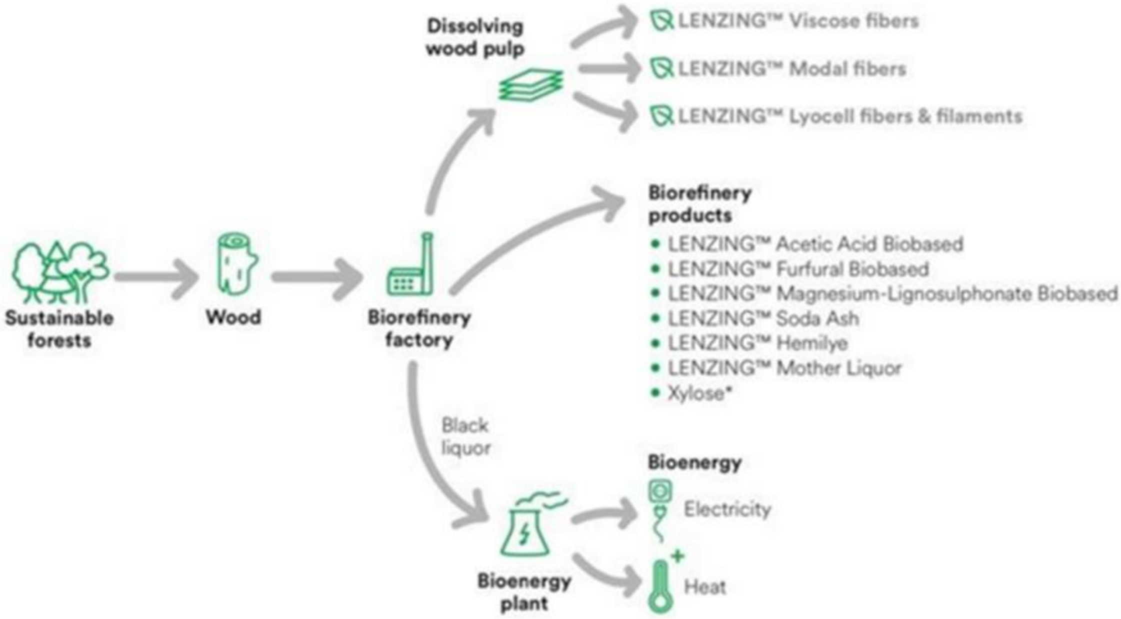


Figure 6-3: Fibre production process at Lenzing ((IEA Bioenergy Task 42 2022)).