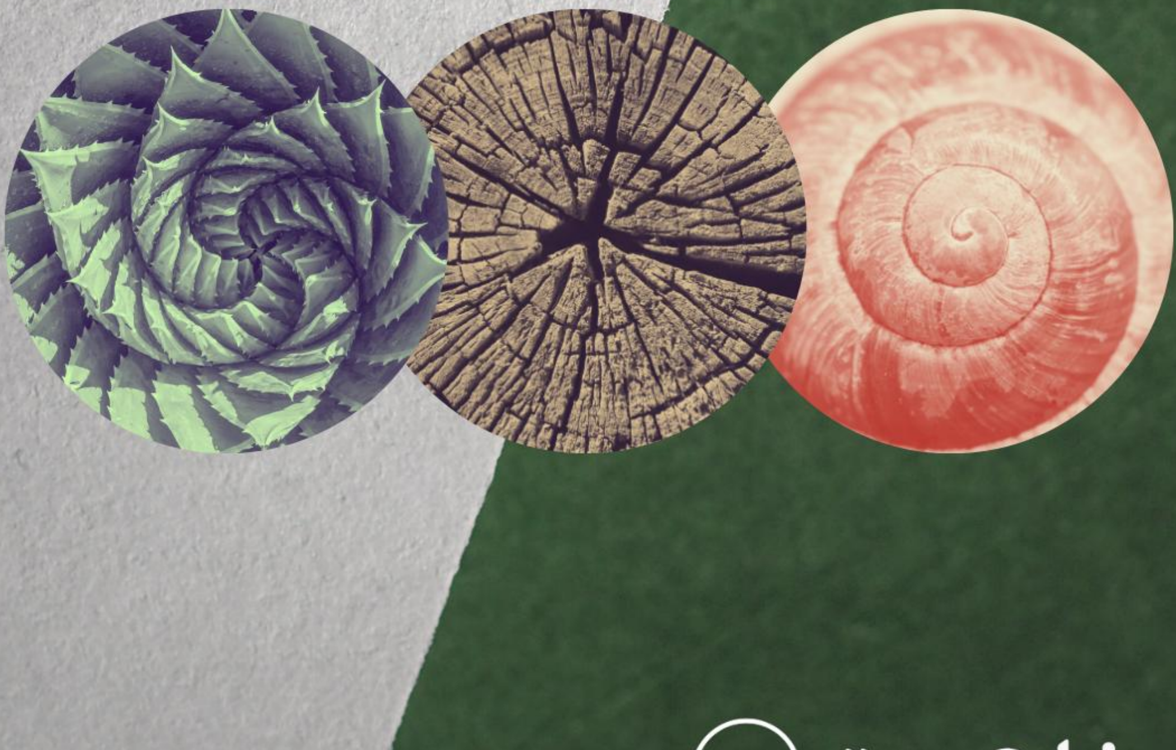
Assessing the potential to enhance the circularity of bio-based waste



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EXECUTIVE SUMMARY

This study assesses the potential to enhance the circularity of bio-based waste within the framework of the 2025 update of the EU Bioeconomy Strategy. The analysis focuses on identifying opportunities to move bio-based waste streams up the waste hierarchy, retain technical and economic value, and minimise environmental impacts. This means bio-based waste which is currently not recycled, but which could potentially be recycled into new materials or substances and is referred to, in this report, as the 'circularity potential'. A comprehensive assessment was conducted at EU level covering both municipal and non-municipal bio-based waste streams, including:

- **Food, garden and vegetal waste (bio-waste);**
- **Wood waste;**
- **Sewage sludge;**
- **Agricultural waste;**
- Paper and cardboard;
- Textiles;
- Bio-based plastics.

To evaluate the circularity potential of these streams, the study established a detailed picture of current waste generation, collection, treatment and reporting practices across the EU. This included the identification of persistent challenges related to data availability and harmonisation among Member States. The assessment also examined a wide set of technological options for managing bio-based waste, highlighting their maturity, associated opportunities and barriers. In addition, relevant policy options were reviewed for each waste stream. Feedback from relevant stakeholders consulted for the study is also reflected in the analysis.

The circularity potential estimated for the four bio-based waste streams subjected to more detailed analysis in this study, owing to their higher circularity potential, is presented in Table 1. The table also includes the data sources used to derive these estimates, which include statistical datasets and sector-specific research. The findings highlight the substantial quantities of bio-based waste that continue to be managed through linear routes, such as landfill, mixed waste streams or low-value recovery operations.

Table 1. Circularity potential and data sources for bio-based waste streams (DM: Dry Matter; WW: Wet Weight)

Mass flows (Mt)		Circularity Potential (Mt)	Basis	Circularity Potential (% of total generation)	Data Sources
Food, garden and vegetal waste (bio-waste)		58-68	WW	53%	ECN, 2022; Eurostat, 2025a, 2025e; EEA, 2022a, 2023; Sund et al., 2025
Wood waste		26-28	WW	53-54%	Eurostat, 2025f; EEA, 2022b
Sewage sludge		1.5-2.1	DM	24-27%	EEA – Wise Freshwater, 2025m; Eurostat, 2025m, 2025o; EC et al., 2022
Agricultural waste	Animal faeces, urine and manure	0.5	WW	4%	Eurostat, 2025p 2025q
	Crop residues	74.7	DM	26%	ICCT, 2021

Across all waste streams, data limitations were observed, including inconsistent definitions and divergent reporting practices between Member States. The impact of these limitations was minimised through cross-analysis of the different data sources, but the most significant knowledge gaps are related to the bio-based waste that is still included in mixed waste collection streams.

High-value recovery pathways remain insufficiently developed and large quantities of bio-based waste are either not collected separately or are lost in mixed waste streams. Selective collection is therefore central to achieving higher environmental and economic benefits. Although technological innovations may contribute to improved benefits, their feasibility and scalability require consideration.

Applying the waste hierarchy to bio-based materials is not always straightforward. Certain energy-intensive processes, such as gasification, may provide lower environmental benefits than conventional waste-to-energy options. In addition, some waste streams, particularly wood waste, face competing policy objectives, such as their use for decarbonising energy-intensive industries, which can limit higher-value circular pathways.

Public acceptance emerges as a critical enabler for circularity improvements, particularly for waste streams where safety, hygiene or contamination concerns are prominent. Certification schemes and more stringent regulatory frameworks could help build trust and drive behavioural change.

Ultimately, enhancing the circularity of bio-based waste strengthens resource security across the EU. By closing nutrient loops, such as reducing reliance on imported phosphorus, and increasing the use of secondary raw materials, demand for primary bio-based resources can be reduced. The key messages presented below summarise the main conclusions of the analysis carried out for bio-based waste streams.

KEY MESSAGES

Food, garden and vegetal waste (bio-waste)

- An additional 58 to 68 Mt of food, garden and vegetal waste could potentially be recycled (around 53% of total generation). 38-47 Mt of bio-waste remains in mixed municipal waste, resulting in the loss of ≈134 kt of nitrogen and 44 kt of phosphate.
- The environmental and economic benefits are maximised when separate collection is ensured. That enables high-quality treatment operations and higher yields of compost and biogas. Bio-waste that enters mixed waste collection has very little chance of being recycled.
- Increasing the separate collection of bio-waste is therefore crucial for increasing the circular use of the ‘untapped potential’ of food waste and garden and vegetal wastes in the EU (and contributing to the EU 2035 municipal waste recycling target).
- For food waste specifically, prevention - incl. prevention at source, donation or redistribution of surplus food, use for animal feed, and industrial use - remains the most impactful and cost-effective way to minimise environmental impacts. It is estimated that the GHG emission savings achieved through the prevention of food waste amount to 9% of the total GHG emissions from waste management (De Jong, B., et al., 2023).

Wood waste

- An estimated 48-50 Mt of wood waste is separately collected, yet only 48% is recycled, with the rest being mostly used for energy recovery. There is a strong competition between energy recovery and recycling for this waste stream due to its high calorific value;
- Environmental benefits are maximised if wood is used in long-lasting products and when there is a cascading use of wood waste that prioritises recycling and, only after losing material properties, energy recovery applications;
- When recycling is no longer an option, recovery pathways like biorefineries might yield significant environmental benefits, if this can offset virgin materials or fossil fuels;
- The presence of hazardous substances in wood waste, such as paints or preservatives, limits the potential for high-value recycling.

Sewage sludge

- An additional 1.5 to 2.1 Mt of sewage sludge (24-27% of total generation) could potentially be recycled.
- Phosphorus and nitrogen can be recovered from sludge and reused as fertiliser, reducing reliance on synthetic fertilisers. When uncontaminated and sanitised, sludge is one of the most cost-effective soil improvers.
- Public acceptance is key for sludge reuse in agriculture and other applications, such as construction. Policies such as the ban on landfilling of sewage sludge, certification schemes and stricter legislation regarding the presence of contaminants in sewage sludge could enhance circularity.
- Thermal treatment remains a necessary option for sewage sludge which cannot be valorised through agricultural use and composting due to risks from contaminates.

Agricultural waste

- An additional 75.3 Mt of agricultural waste, including animal faeces, urine and manure, as well as crop residues, could potentially be recovered.
- Definitions of agricultural waste vary across the literature. For this analysis, only animal faeces, urine and manure (14.4 Mt), which are published by Eurostat, and crop residues (286.4 Mt) are considered, with these two streams reported separately.
- Data on crop residues are not covered by waste statistics, as they are not classified as waste but rather as by-products of agricultural production. Their quantities are typically estimated using theoretical models, whereas data on animal faeces, urine, and manure are reported by Member States to Eurostat as part of the Waste Statistics.
- A considerable fraction of crop residues should remain in the soil to maintain its quality, estimated at 181.6 Mt (63% of total generation). The remaining fraction is primarily used for heat, power and biogas production, though circular interventions could support their use in material feedstock, animal feed and bedding, mushroom cultivation, and horticultural applications.
- There is a lack of data on residue collection practices and on the current uses of crop residues.
- The animal faeces, urine and manure stream is predominantly directed towards recycling processes such as anaerobic digestion and composting, amounting to approximately 12.6 Mt (87% of total generation). Only a limited fraction (4%) is estimated to be sent to landfill and incineration (without energy recovery).

Other biobased streams

- Paper and cardboard: In 2022, 43.9 Mt of paper and cardboard were separately collected in the EU-27 (34 Mt packaging), of which 83% (31.1Mt) was recycled, while 17% (12.8 Mt) enter mixed waste and was not recycled. Strong recycling potential exists, but quality constraints and complex packaging formats limit recyclability and compostability. Enhancing design for recyclability and improving separate collection and sorting, particularly for composite or contaminated packaging, is essential to secure high-quality recycling inputs.

- Bio-based textiles: Approximately 7.2 Mt of post-consumer textile waste is generated in the EU-27, with less than 15% separately collected in 2022. High-quality fibre-to-fibre recycling is very limited (≈1%), hindered by technical, logistical, and regulatory challenges; downcycling offers a preferable alternative to landfill or incineration. Improving sorting systems and applying eco-design criteria for textiles and footwear are essential to raise recycling rates.
- Bio-based plastics: Some bio-based plastics polymers are identical to fossil-based and can be handled in the same waste management systems, while others (e.g., PLA) require dedicated infrastructure, which is currently insufficient. Mechanical recycling offers the best environmental outcomes but is limited to specific polymers (e.g., bio-PE, bio-PET). Transitioning to bio-based plastics based on biomass waste and by-products is preferable to avoid competition with food production.

1 INTRODUCTION

1.1 Why does Europe need to increase circularity in bio-based streams?

The European bioeconomy is entering a decisive phase, shaped by the growing urgency of climate action, the need to reduce human impact on ecosystems and restore them, and resource constraints. In this context, circularity in bio-based systems is gaining prominence as a strategic approach to ensure sustainability, climate resilience and long-term competitiveness.

At the heart of the discussion on how circular economy principles can be applied to the bioeconomy, and what this means for current and future policy developments, lies a set of ambitious political strategies that position the circular bioeconomy as central to Europe's green transition. The 2020 Circular Economy Action Plan, one of the flagship initiatives of the European Green Deal, emphasises the need to decouple economic growth from resource use and highlights the bioeconomy as a key area where circularity must be strengthened. The EU Bioeconomy Strategy, adopted in 2018, further promotes a vision of a sustainable and circular bioeconomy that supports both economic development and environmental protection. The new 2025 EU Bioeconomy Strategy, aims to drive innovation and uphold the leadership of EU in the bioeconomy. It outlines actions to unlock the potential of bioeconomy innovations, enabling their market uptake and supporting green jobs and growth. The Strategy will also reinforce circularity and sustainability, contribute to EU decarbonisation efforts and define the framework conditions needed for bioeconomy start-ups, entrepreneurs and new business models to thrive. Complementary policy frameworks reinforce the imperative to align bio-based production and consumption with ecological boundaries and food system sustainability, including the Biodiversity Strategy for 2030, the Farm to Fork Strategy, the Forest Strategy for 2030, the Common Agricultural Policy, the Regulation on Deforestation-free Products, the EC Communications 'Building the future with nature: Boosting Biotechnology and Biomanufacturing in the EU' and 'EU policy framework on biobased, biodegradable and compostable plastics', and the upcoming New European Biotech Act. Beyond the new EU Bioeconomy Strategy, the implementation of the Nature Restoration Law, and the forthcoming proposals under the Sustainable Food Systems framework point to a renewed momentum in mainstreaming circularity across bio-based value chains.

However, translating these ambitions into concrete action remains complex. The concept of circularity in bio-based flows goes beyond traditional recycling models. It requires a systemic perspective that integrates resource loops, cascading use of biomass[1], nutrient cycling and value retention over time and across sectors such as agriculture, forestry, food, waste management and the production of bio-based materials and energy. While biological resources are renewable by nature, they are not unlimited. Their availability is shaped by spatial and temporal factors, including land use competition, ecosystem capacity, seasonality, and climate variability. This means that circularity in the bioeconomy must be designed with a strong understanding of ecological limits and competing uses for biomass.

Achieving this vision entails difficult trade-offs. Maximising the value of biomass through long-lived applications, for instance, may conflict with the urgent demand for renewable energy or short-term economic gains. Similarly, the integration of organic waste and by-products into new value chains must be carefully assessed to ensure environmental safety and avoid burden shifting. The measurement of circularity in bio-based systems is also not straightforward, as current indicators tend to overlook biological cycles or fail to capture the full environmental footprint of different uses of biomass.

Considering these challenges, the European Environment Agency (EEA) has commissioned this study to support the actions following the revision of the EU Bioeconomy Strategy. Drawing on recent assessments and technical work, the aim is to identify the untapped circularity potential in key bio-based waste streams, to clarify how circularity principles can be meaningfully applied to enhance the circularity of bioeconomy, and to highlight the environmental benefits that can be achieved.

1.2 Objectives and approach

The study aims to assess the potential to enhance the circularity of bio-based waste in the context of the 2025 update of the EU Bioeconomy Strategy, focusing particularly on exploring strategies to move up the waste hierarchy, retain technical and economic value, and reduce environmental impacts. A detailed assessment of relevant bio-based waste streams originating from municipal and industrial sources at the European Union (EU) level was carried out, with the following specific objectives:

- Identify data availability and key data gaps for relevant waste streams;
- Consolidate existing data on bio-based waste in Europe, including the destination of this waste;

[1]cascading principle aims to achieve resource efficiency of biomass use by prioritising biomass material use over energy use (cf. EU 2023/2413)

- Identify current practices and assess the potential to move bio-based waste up the 'waste hierarchy', including key challenges and opportunities;
- Identify key tangible policy options for how to increase the circularity of bio-based waste in Europe.

To assess the potential for increasing circularity, a snapshot of the current state of bio-based waste management across the EU is established, which involves understanding how these waste streams are generated, collected, treated and reported. This baseline allows to identify areas of untapped circularity potential in which policies, technological solutions and innovative business models can be implemented to increase the recovery of these waste streams.

Given the persistent challenges in obtaining reliable and harmonised data, due to differences in definitions, reporting methods and data coverage among Member States, the first stage of the assessment focused on gathering, assessing and structuring the best available datasets to serve as the foundation for the circularity potential assessment. An analysis on the data gaps and limitations of the available datasets was also carried out and described in this study. Information from Eurostat, national statistical offices and environmental agencies, was used to characterise waste generation and treatment. Information from sectoral studies and independent research, including reports from the EEA, the European Commission's Joint Research Centre (JRC), academia, and industry associations were used to complement the assessment.

Moreover, a key part of this assessment involved exploring a wide range of technological solutions available for managing bio-based waste, focusing on the challenges and opportunities associated with their implementation. These technologies vary widely in their maturity, environmental performance and ability to support circular economy principles.

An analysis of the available policy options for each bio-based waste stream is carried out based on the review of policies implemented by EU Member States, by regional authorities or by key stakeholders, such as business associations. These measures are presented as concrete examples of regulatory, economic and operational instruments already in place or under development across Europe. They reflect diverse governance approaches and levels of ambition, yet all share a common alignment with the overarching objective of moving bio-based waste up the waste hierarchy.

This comprehensive assessment of the circularity potential in bio-based waste management also includes insights from relevant stakeholders which were consulted during the development of this study.

1.3 Scope and definitions

The report focuses on assessing the current practices, challenges and opportunities in managing (i) bio-waste: food, garden and vegetal waste, (ii) wood waste, (iii) sewage sludge, and (iv) agricultural waste (straw, manure). The report also provides an overview of other waste streams, including paper and cardboard waste, plastics waste and textile waste. For these waste streams, the focus is on identifying the main challenges and opportunities to increase circularity beyond mechanical recycling, exploring potential synergies with other bio-based waste management pathways and investigating existing lines of research and development (R&D) on these streams. By definition, by-products are excluded from waste statistics. For those reasons, the mapping and the discussion on opportunities exclude by-products, with the exception of crop residues.

The definition of each bio-based waste stream analysed in the report and their respective scope of assessment, including the types of waste included in each waste stream, are described in Table 2.

Table 2. Scope of assessment of each bio-based waste stream

Bio-based waste	Scope
Food, garden and vegetal waste	**Animal and mixed food waste:** Animal waste of food preparation and products, including sludges from washing and cleaning and mixed wastes of food preparation and products including biodegradable kitchen/canteen wastes and edible oils and fats. These wastes are from food preparation, agriculture and from separate collection (Eurostat, 2010).
	Vegetal wastes: vegetal waste from food preparation and products, including sludges from washing and cleaning from agriculture and food production. It also includes green waste from separate collection (Eurostat, 2010).
Wood waste	**Wood waste:** According to Bioenergy Europe (2025) wood waste refers to "all types of wood material that have no further possible recovery except by treatment and disposal. (…) These woods come mainly from the collection of bulky and industrial waste, as well as container parks and construction sites". It includes separately collected wood waste, wooden packaging, sawdust, shavings, bark, cork and wood waste from pulp and paper production, as well as wood from construction and demolition activities; wood waste generated by households, the service sector and industrial activities (e.g., pallets, construction debris, and other wood-based items, including both uncontaminated and contaminated wood). It excludes wood waste present in mixed waste; forest residuals (e.g., logging residues, branches, stumps, or other by-products from forest management) and pulp and paper products.
Sewage sludge	**Sewage sludge**: According to the Sewage Sludge Directive (SSD), sewage sludge is defined as "(i) residual sludge from sewage plants treating domestic or urban waste waters and from other sewage plants treating waste waters of a composition similar to domestic and urban waste waters; (ii) residual sludge from septic tanks and other similar installations for the treatment of sewage; (iii) residual sludge from sewage plants other than those referred to in (i) and (ii)" (The Council of the European Communities, 1986).
	Manure: also known as livestock manure, is organic matter, mainly derived from animal faeces and urine, but which normally also contains plant material, such as straw, which is used as bedding for animals and absorbs their faeces and

Bio-based waste	Scope
Agricultural waste	urine. Manure from dairy cattle, beef cattle and swine can be solid or slurry. Manure from houses and poultry is solid (Eurostat, n.d.). Manure is therefore defined as an organic mixture rich in nutrients, resulting from digested and partially digested feed, bedding materials and other components, serving purposes such as organic fertiliser and a bioresource for energy production. It contains essential nutrients such as nitrogen, phosphorus, and potassium, along with a diverse population of microorganisms (ScienceDirect, n.d.a).
	Crop residues: defined as the part of the crop that remains after the main product has been harvested, varying according to local conditions and the type and variety of crops planted. They can be used for various purposes, although a large part is often left unused or burned (ScienceDirect, n.d.b). The crop groups considered in this analysis include cereals, oilseed crops, permanent crops, sugar and starchy crops, pulses and industrial crops. Within these groups, the specific crops analysed are wheat, maize, barley, rapeseed, sunflower, olive trees, vineyards, sugar beet, potatoes, field peas, broad and field beans, tobacco, fibre flax, and cotton fibre (JRC, 2018). Even though crop residues are not considered waste but rather by-products from a legal perspective, their inclusion is deemed relevant within the scope of this assessment, as they are naturally generated during crop harvesting and hold significant potential for circular use.
Other bio-based streams	**Paper and cardboard waste:** includes paper and cardboard from sorting and separate collection (including paper and cardboard packaging waste), and excludes mechanically separated rejects from pulping of waste paper and cardboard, wastes from sorting of paper and cardboard destined for recycling and fibre, filler and coating sludges from pulp, paper and cardboard production (Eurostat, 2010).
	Bio-based plastics: plastics fully or partially produced from bio-based feedstock (grown crops such as maize, or organic residuals and waste, as agricultural waste, frying oils and manure), instead of fossil raw materials. However, these polymers are not necessarily biodegradable or compostable (Plastics Europe, 2024).
	Bio-based textile: textiles produced from "renewable biomass sources such as wood or fibre crops, but also algae, fungi, agricultural waste or end-of-life textiles that can be converted into fibres for textile applications" (JRC, 2025b).

Food, garden and vegetal waste

2 ASSESSING THE POTENTIAL TO ENHANCE THE CIRCULARITY OF BIO-BASED WASTE STREAMS

2.1 Food, Garden and Vegetal Waste (bio-waste)

KEY MESSAGES

- An additional 58 to 68 Mt of food, garden and vegetal waste could potentially be recycled (around 53% of total generation). 38-47 Mt of bio-waste remains in mixed municipal waste, resulting in the loss of ≈134 kt of nitrogen and 44 kt of phosphate.
- The environmental and economic benefits are maximised when separate collection is ensured. That enables high-quality treatment operations and higher yields of compost and biogas. Bio-waste that enters mixed waste collection has very little chance of being recycled.
- Increasing the separate collection of bio-waste is therefore crucial for increasing the circular use of the 'untapped potential' of food waste and garden and vegetal wastes in the EU (and contributing to the EU 2035 municipal waste recycling target).
- For food waste specifically, prevention – incl. prevention at source, donation or redistribution of surplus food, use for animal feed, and industrial use – remains the most impactful and cost-effective way to minimise environmental impacts. It is estimated that the GHG emission savings achieved through the prevention of food waste amount to 9% of the total GHG emissions from waste management (De Jong, B., et al., 2023).

2.1.1 Mapping of food, garden and vegetal waste flows in Europe

The baseline of food, garden and vegetal waste management in the EU was established, based on a detailed data analysis whose findings are presented in Annex 1. A critical part of this analysis is to estimate the quantities of food waste and garden and vegetal waste currently being lost by not being separately collected and ending up in low-value routes such as landfilling or incineration. The data analysis was consolidated in the mapping summarised in Table 3, which aims to conciliate the best available information, starting with waste generation where the ranges represent the lowest and highest estimates (ECN, 2022; Eurostat, 2025a; Eurostat, 2025e; EEA, 2022a). Regarding the used data from Eurostat

(2025a), the waste categories of 'animal and mixed food waste' and 'vegetal waste' were considered. The 'animal faeces, urine and manure' category was excluded from the scope of assessment (see section 2.4 concerning agricultural waste). A key limitation in the assessment of food, garden and vegetal waste streams is the lack of data on the quantities collected as part of mixed waste, as detailed composition data for these streams are not reported.

Table 3. Data for mapping of food, garden and vegetal waste generation in EU-27

Mass flows (Mt)		ECN, 2022[a]	Eurostat – Municipal waste EEA (2022)	Eurostat - Waste Generation
Municipal waste	Generation - municipal	76	85	-
	Separate collection	38	38[b]	-
	Mixed waste collection	38	47	-
Non-municipal waste	Separate collection	21	-	30[c]
	Mixed waste collection	-	-	13[d]

Notes: ([a]) Data published by the ECN (2022). It is important to highlight that these values might be underestimates, as the European Compost Network only reports quantities treated in their member organisations' facilities. According to the reported information, a capture rate of 50% of bio-waste is considered.

([b]) Data for total municipal solid waste generation published by Eurostat (2025e). It was considered that, on average, bio-waste accounted for 37% of the municipal solid waste generated (EEA, 2023a). A weighted average capture rate of bio-waste was considered in the EU-27 of 45% (EEA, 2022a).

([c]) Animal and mixed food waste and vegetal waste published by Eurostat (2025a) for all NACE activities, except households and services.

([d]) In order to provide an estimate on the bio-waste produced from industrial and commercial sources that is not separately collected, data on the quantity of mixed and undifferentiated materials generated from all NACE activities, except households, from Eurostat (2025a) was considered (30.3 million tonnes). It was assumed that 43% of this fraction consists of bio-waste (Sund et al., 2025).

Sources: ECN, 2022. Available online
Eurostat, 2025a. Available online
Eurostat, 2025e. Available online
EEA, 2022a. Available online
EEA, 2023a. Available online
Sund et al., 2025. Available online

Regarding treatment, an estimated 12% of the separately collected food, garden and vegetal waste is sent for disposal and energy recovery, based on Eurostat (2025b). The share of food and garden waste subject to composting and anaerobic digestion was taken from the data reported by the European Compost Network (ECN, 2022). Bio-waste not separately collected must be treated as mixed waste. Based on data from selected Member States, which are more reliant on Mechanical-Biological Treatment (MBT), it was estimated that approximately 8 to 10 million tonnes of food and garden waste within mixed waste are treated in these types of plants. The remaining bio-waste (30 to 37 million tonnes, approximately 27-29% of total generation) is assumed to be roughly equally split in landfill and energy recovery, considering that these treatment options have approximately the same weight in the treatment profile of total municipal solid waste.

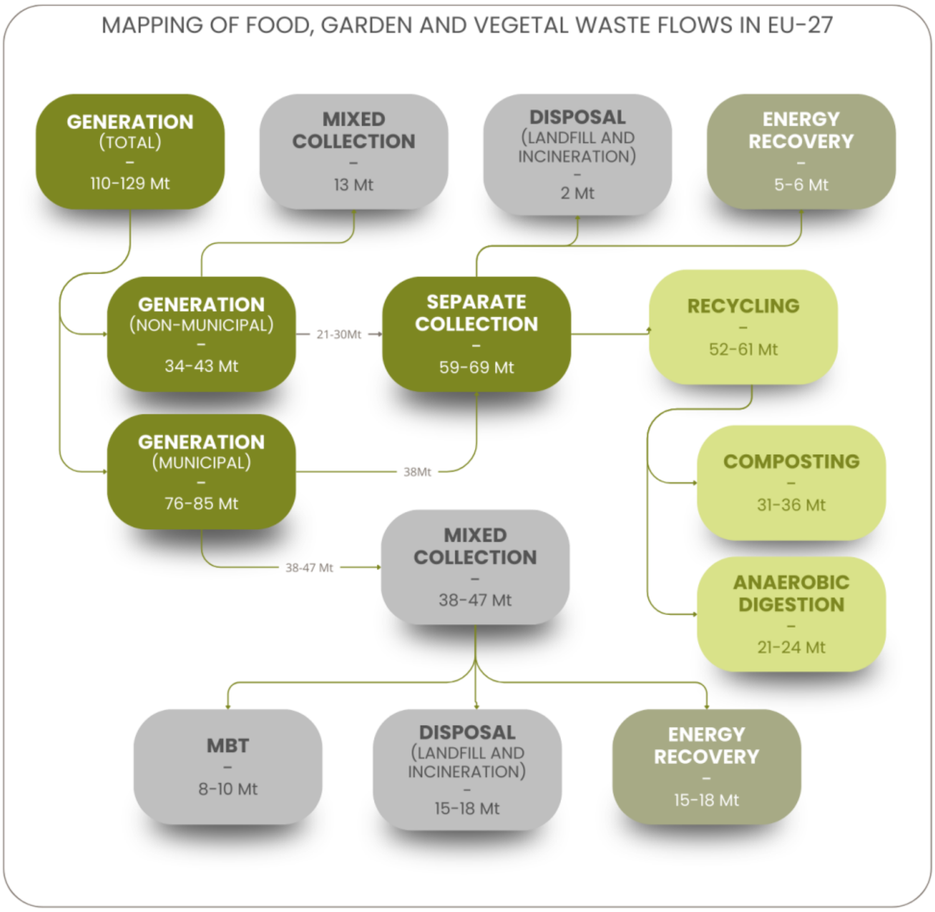

Figure 1. Mapping of food, garden and vegetal waste flows in EU-27, 2022 (figures in the grey boxes represent the 'untapped' potential; light green boxes represent recycling)

The bio-waste that is already separately collected is primarily directed towards recovery operations, where it can be processed into valuable products like compost, biogas, or other forms of resource recovery. Bio-waste in mixed municipal waste collection represents a loss in value, as bio-waste is being sent directly to disposal, energy recovery, or MBT processes. **Increasing the separate collection of bio-waste is therefore crucial for maximising resource recovery in this waste stream** and for contributing to the Waste Framework Directive's target to recycle 65% of municipal waste by 2035. **This represents a key untapped circularity potential of approximately 38 to 47 million tonnes that could, through further processing, help increase the amount of available biobased feedstocks in Europe,** although not all of this bio-waste can be captured in reality.

Other treatment options, such as transformation in high-value biochemical products, were identified, but found to be at a pilot-scale and therefore not relevant at the scale represented in Figure 1.

From the mapping, it can be concluded that between 58 to 68 million tonnes of food, garden and vegetal waste are not recycled (around 53% of total generation), with an estimated 17 to 20 million tonnes being landfilled (around 15-16% of total generation). This is especially relevant as the environmental impacts of food, garden and vegetal waste are highest when deposited in landfill without prior treatment (Serafini et al., 2025). Composting and anaerobic digestion have different outputs and therefore different environmental profiles, but while composting maximises the recovery of nutrients, anaerobic digestion maximises energy recovery of the bio-waste. The environmental benefits are therefore region-specific and related to the avoided use of other fuel sources or soil enrichment materials.

2.1.2 Challenges and opportunities to enhance circularity in food, garden and vegetal waste

Based on the analysis of the identified technical solutions aimed at maximising the potential of bio-waste, presented in Annex 1, Table 4 presents the main challenges and opportunities associated with the potential to move biobased waste up the waste hierarchy. These aspects highlight both the barriers that need to be overcome and the strategic advantages that can be leveraged to enhance the sustainable management and valorisation of bio-waste.

Regulatory Challenges

The implementation of circular bio-based solutions for food, garden and vegetal waste face a range of challenges that span regulatory, economic, technological, and operational dimensions. From a regulatory perspective, several **high-potential strategies, such as the direct use of food waste in animal feed, are limited by strict legal frameworks**. Notably, **EU Regulation (EC) No 1069/2009 limits the use of food scraps of animal origin in livestock feed due to health and safety risks**. In addition, compost and digestate applications are subject to varying restrictions, particularly regarding **contamination levels and their use on agricultural land**. Energy recovery through incineration is deprioritised in the waste hierarchy while **anaerobic digestion is characterised as recycling as it both generates energy and captures nutrients**. However, the restrictive nature of these regulations is justified and should be the general rule. A case-by-case approach could be taken to widen the number of opportunities to use food waste as animal feed.

Contamination and quality concerns

The contamination of the different bio-waste streams with **physical impurities (e.g., glass, metal, plastics), heavy metals and other hazardous chemicals and pathogens** raises significant concerns and poses **potential risks to human and animal health, as well as to the environment**. These contaminants can also lead to **process malfunctions, equipment damage, and negatively impact the quality of the resources extracted** (Murcia et al., 2024; Schaap et al., 2025). **Separate collection of bio-waste**, as well as the management systems, can increase the quality of these waste streams by decreasing the number of impurities, and enhance the quality of compost, digestate, and other bio-based products from these waste streams (ECN, 2018; EEA, 2020). **The guarantee of low contaminant** in bio-waste collected is essential for achieving **higher-value solutions, as well as for building trust in the products derived from bio-waste** (e.g., soil improvers, fertiliser). However, the quality level achieved through separate collection can only be maintained if the waste is treated properly, i.e., if the treatment capacity is in line with the bio-waste produced and separately collected (EEA, 2020).

Incentives

Incentives for proper sorting and clear guidance on the appropriate disposal of bio-waste contribute to **enhancing the quality of the collected bio-waste**. One of the main objectives of the LIFE BIOBEST project was to improve bio-waste collection and treatment systems, **increasing both the quantity and purity of the input material**, reducing process losses and facilitating the conversion of bio-waste into **high-quality compost and digestate**. The project aimed to identify and validate best practices in bio-waste management and recycling across the EU. Among its outputs, the 'Guideline on Governance and Economic Incentives' specifically addressed governance tools and economic instruments necessary to improve management schemes, presenting examples of their application and including an analysis of the economic viability of best practices. In addition, the LIFE BIOBEST guidance included dedicated resources on separate collection, quality standards for compost and digestate and factsheets on the analysis of best practices in communication and engagement from various countries (Zero Waste Europe, n.d.).

Economic and market challenges

Economic and market-related challenges are also prominent. Although many challenges are being actively studied, **there is often a disconnect between lab research and its large-scale commercial implementation**. In addition, many solutions face **low economic returns on their end-products and limited market demand** (EEA, 2020), **or competition with conventional and often cheaper fossil-derived alternatives** (Ye et al., 2024). The existing treatment capacity is mostly focused on composting and anaerobic digestion because these are economically viable in most conditions (EEA, 2020; Alam et al., 2024; Cucina, 2023; Walk and Gambini, 2024). **Capital expenditure requirements remain high for technologies such as fermentation, biofuel production, and chemical biorefineries, and their economic feasibility is highly dependent on feedstock availability and product valorisation potential** (EEA, 2020). **Market immaturity** is particularly evident for emerging pathways such as **advanced biochemical products and insect-based feed**, which are still working to establish secure supply chains and create market demand.

Technological and Efficiency Challenges

From a technology and efficiency standpoint, **several pathways require further development or refinement to be deployed at scale**. Technologies such as **insect farming and Volatile Fatty Acids recovery from fermentation still have low to medium technology readiness levels (TRL)** and depend heavily on the quality and type of feedstock (EEA, 2020; Lopes et al., 2024). Additionally, **many of these processes exhibit reduced performance with heterogeneous or contaminated input materials**, necessitating pre-treatment steps that raise both costs and operational complexity (Ahmed et al., 2023; Marques et al., 2024; Di Mario et al., 2024; Makepa and Chihobo, 2024). Finally, while energy recovery offers consistent output, its position as a last-resort option in the circular economy hierarchy limits its prioritisation compared to solutions with higher environmental and material recovery value (Wunder et al., 2018).

Table 4. Opportunities and their limitations for each technical solution considered

Solutions	Opportunities	Limitations
Prevention	• Highest position in waste hierarchy; • Can help to avoid upstream and downstream impacts; • Can help to decrease waste collection and treatment costs; • Estimated GHG savings of 0.8-4.5 kg CO_2e per kilogram of food waste avoided (EEA, 2020).	• Difficult to enforce across the life cycle; • Low market-driven incentives; • It is necessary to improve the measurement and monitoring of the impact of food waste prevention, as well as action design (e.g., Italy established a national observatory with the objective to analyse and evaluate food surplus, recovery and food waste and how the supply chain manages these surpluses and waste and the underlying causes behind them) (EU Platform on Food Losses and Food Waste, 2019; Garcia Herrero et al., 2023); • Requires sustained behavioural change.
Composting	• Mature and widely accepted technology; • Easily adaptable solution; • Effective for garden and vegetal waste streams; • Potentially of high-quality compost for agricultural applications (e.g., high return rate of nutrients to soil) (Moretto et al., 2019); • Low investment barrier.	• Low economic value of end-product; • Contamination limits use; • The challenge of contamination by hazardous substances leads to regulatory restrictions on compost application; • Considerable greenhouse gas (GHG) emissions when done at suboptimal conditions; • Efficiency varies by technology and scale.

Solutions	Opportunities	Limitations
	• Contamination can be overcome through proper quality management from collection to treatment;	
Anaerobic Digestion	• Produces renewable energy (for electricity or heat generation or feeding into gas grids) and biofertilizer (e.g., Denmark upgrades and feeds 80% of its biogas production into the natural gas grid) (The Danish Energy Agency, 2025); • Suitable for the source-separated organic fraction of municipal solid waste and sludges; • Can pivot to other end-products, namely Volatile Fatty Acids.	• Moderate efficiency for some feedstocks; • Needs pre-treatment in some cases, reducing the economic viability; • Digestate has less applications when compared to compost; • High investment costs. • Methane losses reduce climate benefits (e.g., Denmark's average annual methane loss from biogas production is 2.5%, which has led to new regulations regarding self-monitoring programmes and inspections for methane leaks (The Danish Energy Agency, 2025)).
Animal feed (direct)	• High efficiency/nutrient recovery rate; • Viable for a limited number of products and industries; • Can help to reduce the production and import of animal feed.	• Strict EU regulation (Reg. EC No 1069/2009); • Concerns over health and safety risks; • Viable for a limited number of applications.
Animal feed through insect farming	• High efficiency/nutrient recovery rate; • Scalable protein alternative, can potentially grow to replace imports of other protein-based feed; • Increasing policy and investor interest.	• Low demand/market penetration of end-product; • Regulatory ambiguity for some feed sectors; • Efficiency depends on the source of the food (e.g., preferred homogeneous feedstock)
Advanced biochemical products	• Production of high-value Volatile Fatty Acids , can be used as base products for bioplastics, biochemicals; • Supports chemical industry defossilisation; • Strongly aligned with the EU Bioeconomy Strategy.	• Low TRL for some pathways, potentially high CAPEX and technology complexity; • Uncertain market demand, especially when compared to more cost-efficient petrochemical pathways; • Feedstock inconsistency affects yields.
Biofuel production	• Diversifies renewable energy mix and can replace fossil fuels in transport; • Compatible with existing fuel infrastructure.	• Potentially high CAPEX and technology complexity; • High energy input vs output (i.e., low efficiency) for some waste types; • Competitiveness with fossil fuels remains weak.
Energy recovery (incineration)	• Handles contaminated or non-recyclable waste, potentially being the only alternative to landfill for highly contaminated bio-waste. • Stable output and potentially higher energy efficiencies when compared to complex chemical thermal treatment processes.	• Second lowest priority in EU waste hierarchy, after landfill; • Can face strong public opposition; • Discouraged by circular economy policies.

2.1.3 Available Policy Options

This subsection focuses on potential policy options that have been employed or recommended by stakeholders across Europe. The range of documented opportunities to enhance circularity of food-related flows is significantly larger than garden and vegetal waste. This section focuses on opportunities and available policy options related to food waste, but the discussion on waste management and technology development covers the three waste types. The policy options are grouped by key objectives, namely prevention of food waste, increase quantity and quality of food, garden and vegetal waste, improve treatment and foster new technologies (Table 5).

Table 5. Summary of available policy options for food, garden and vegetal waste and their impacts

Related policy measures	Potential impacts
1. Prevention	
• **Non-binding initiatives**: Non-binding tools like voluntary actions, agreements, and awareness campaigns, which make up 82% of all national food waste prevention measures in Europe (ETC CE, 2025). • **Planning and certification**: Prevention planning, certification and labelling initiatives within the food supply chain can contribute to a better understanding and prevention of food losses and waste. • **Regulatory measures**: measures such as mandatory food donation policies, requiring stores to donate unsold but still edible food to charitable organisations, contributing to reduce food waste generation.	• Reduction of environmental impacts along the supply chain and in waste management (De Jong et al., 2023), including GHG emissions, water consumption, among other environmental impact categories. • Potentially negative economic impact in the supply chain, but significant savings by households (between 220 and 700 € per year), which can be channelled for consumption of other food items or other consumption goods.
2. Improve separate collection	
• **Collection standards**: Projects such as LIFE BIOBEST highlight the importance of establishing EU-level technical standards and operational KPI for bio-waste collection, which can complement the mandate for separate collection of bio-waste set in the Waste Framework Directive. • **Municipal solid waste collection**: Cross-cutting measures related to municipal waste collection, such as pay-as-you-throw schemes, door-to-door separate collection, among others, directly impact the quality and quantity of the food and garden waste that is collected (EEA, 2023a).	• Most significant impacts related to improved collection are measured by increasing the amount diverted from landfill and subject to treatment. Approximately 50 million tonnes of food, garden and vegetal waste remain uncollected. This has positive impacts in both the economic and environmental dimensions, as detailed below. • Serafini et al. (2025) conducted a systemic review of studies focusing on LCA of municipal bio-waste treatment and concluded that the collection process itself is not a significant contributor to the overall environmental footprint. • When bio-waste is collected in mixed waste, it cannot be effectively used as compost or digestate. An estimated 134 000 tonnes of nitrogen and 44 000 tonnes of phosphate are currently lost through the bio-waste disposed of in mixed municipal waste in Europe (EEA, 2020).
3. Improve treatment	
• **Regulatory measures**: MS have used the provisions of the Waste Framework Directive to enable the use of food waste directly or as an additive for animal feed. An EU-level strategy could help to maximise the recovery potential through use as animal feed. • **Investment Support**: The EU and MS have supported investments in composting and anaerobic digestion facilities tailored to bio-based waste flows. According to the Kohesio platform, more than 90 projects related to composting and anaerobic digestion were supported since 2020. • **Market instruments**: MS have used market instruments such as feed-in-tariffs for renewable energy, especially if the biomethane is used to displace energy at the highest possible efficiency, usually replacing natural gas in heat generation. (IEA Bioenergy, 2024). • **Treatment and quality standards**: ECN (ECN, 2025) has established quality and treatment standards to harmonize compost and digestate characteristics and foster the EU single market. Eleven countries have adopted compost quality	• The environmental benefits have been captured in many scientific studies. In a systematic review, Serafini et al. (2025) demonstrate that LCA studies tend to conclude that emissions from composting and anaerobic digestion are compensated by the avoided emissions of landfill diversion. • Composting and anaerobic digestion create more jobs per tonne of waste managed. According to De Jong, et al. (2023), composting and anaerobic digestion create around 0.5 FTE/1 000 t, whereas landfill generates 0.07 FTE/1 000 t. Compost and digestate does not have a significant market value and therefore should not be used as a proxy to the economic value generated. • Avoided environmental impacts from the substitution of manufactured products, such as animal feed, fertilisers and base chemicals from petrochemical sources. These are dependent on the technology and process. • Improved soil health and nutrient recovery • Production of renewable gases, which can substitute fossil fuels in electricity production, transport fuels, among others.

Related policy measures	Potential impacts
management and assurance schemes, mostly based on the ECN model.	
4.Foster novel technologies	
• **R&D Support**: The CORDIS database includes several projects related to food waste, bio-based waste flows and advanced treatment options. This demonstrates a continued support for R&D activities in these areas. Insect farming has also been supported in projects such as SUSINCHAIN, FarmInsect, LIFE Waste2Protein, among others. These projects not only support technology development, but also the necessary risk assessment for these technologies. This is key to ensure that the transition to a circular model is done without setbacks. • **Consistent supply from waste collection**: A key challenge that novel technologies face is the support of waste collectors, mostly municipalities, to consolidate and reach a high TRL. Cases such as the municipality of Santarém, Portugal, have committed to supply food waste collected separately to an insect farming startup and thus support it during the industrialisation stage (Municipality of Santarém, 2024). Commitment from local and regional authorities can help to de-risk technology deployment.	• Tangible impacts of R&D activities are difficult to ascertain, especially when restricting to a specific area such as circular bioeconomy. Despite a significant number of studies on the macroeconomic impacts of public R&D spending, these do not include the level of detail to provide insight. • However, focusing on successful case-studies of novel technologies, one can find reports and evidence to support that these are commonly supported by EU or national funding (IEA Bioenergy, 2023). An IEA Bioenergy report shows that several bioenergy-related projects were supported by public authorities.


Wood waste

2.2 Wood Waste

KEY MESSAGES

- An estimated 48-50 Mt of wood waste is separately collected, yet only 48% is recycled, with the rest being mostly used for energy recovery. There is a strong competition between energy recovery and recycling for this waste stream due to its high calorific value.
- Environmental benefits are maximised if wood is used in long-lasting products and when there is a cascading use of wood waste that prioritises recycling and, only after losing material properties, energy recovery applications.
- When recycling is no longer an option, recovery pathways like biorefineries might yield significant environmental benefits, if this can offset virgin materials or fossil fuels.
- The presence of hazardous substances in wood waste, such as paints or preservatives, limits the potential for high-value recycling.

2.2.1 Mapping of wood waste flows in Europe

Wood is a widely used material across the European economy, particularly in construction, packaging, and furniture. Despite its recyclability and the EU's push toward circularity, the waste market for wood remains underdeveloped (EEA, 2023b).

To assess the potential for increasing the circularity of wood waste, it is first necessary to establish a comprehensive overview of the current state of wood waste generation and management across the EU. This involves understanding how wood waste is generated, collected, treated, and reported. A critical part of this study is to estimate the quantities of wood waste currently being lost, either due to a lack of separate collection or because it is directed towards low-value and non-circular treatment routes. The findings from the detailed data analysis, presented in Annex 2, are summarised in Table 6, which aims to conciliate the best available information, starting with the generation rates where the ranges represent the lowest and highest estimates (Eurostat, 2025f; Eurostat, 2025g; EEA, 2022b).

Table 6. Data for mapping of wood waste generation in EU-27

Mass flows (Mt)	Eurostat - Waste Generation	Eurostat – Municipal waste EEA (2022)
Mixed municipal waste collection	2.39[a]	1.23
Separate municipal waste collection	10.75[b]	12.55
Separate non-municipal waste collection	37.40[c]	-

Notes: ([a]) The data published by Eurostat (2025f) for the household and similar wastes category, particularly for households and services, was considered (121 730 Mt). The percentage of wood in residual waste (1.96%) from EEA (2022) was assumed.

([b]) Wood waste data published by Eurostat (2025f) for households and services.

([c]) Wood waste published by Eurostat (2025f) for all NACE activities, except households and services.

Sources: Eurostat, 2025f. Available online

EEA, 2022b. Available online

According to Eurostat (2025f), in 2022, 46.8 million tonnes of waste generated in economic activities and households is separately collected, 37% of which originates from the manufacturing sector, mostly from the wood and cork industry (excluding furniture). Other important sectors include waste management and remediation sector (23%)[2], construction (17%), households (10%) and services (10%). Wood waste from construction and households is often more heterogeneous than manufacturing sectors and may contain hazardous substances such as paints or preservatives, limiting high-value recycling options.

Regarding municipal waste, data reported by Member States and presented in EEA (2022) was considered to estimate the weight of the wood waste fraction. According to the data, around 91% of municipal wood waste is separately collected (approximately 12.6 million tonnes)[3], while the remaining is collected in mixed waste, resulting in a loss of material value and potential for valorisation. There is no available information regarding the treatment of specific waste fractions in mixed waste, but it is typically disposed of in landfills or incinerated.

Municipal wood waste includes wood packaging waste, which accounted for around 13.3 million tonnes in the EU-27 (Eurostat, 2025i). According to Eurostat (2025i), approximately 31% of the wood packaging waste generated in the EU was recycled within the Member State where it originated, while about 3% was recycled in other EU Member States. In some Member States, including Belgium, Estonia and the Netherlands, a comparatively larger share of recycling occurs outside the country of generation, although still within the EU.

[2] Waste arising from waste management is typically an issue for statistical offices as it is possible that these are the result of double counting, but also the impact of waste treatment processed that add weight to the waste stream (e.g., cementitious stabilization, acid-base neutralisation).

[3] Denmark (DK), Hungary (HU), Latvia (LV), Luxembourg (LU), Poland (PL), Romania (RO) and Sweeden (SE) did not report information on wood waste.

Regarding recovery, around 64% of the wood packaging waste generated was recovered, indicating that there is still scope for further progress.

Wood waste statistics do not include wood byproducts, which are common in the wood industry. These include sawdust, chips, shavings, among other, that can be used directly by manufacturing industries or as an alternative fuel in industrial boilers and are often already used. These have a positive economic value and are therefore traded as products and are typically not considered waste.

From the mapping, it can be concluded that **between 26 to 28 million tonnes of wood waste are not managed in a circular model**, estimated to be over 50% of total generation, of which 1.2-2.4 million tonnes are collected through mixed municipal solid waste (estimated between 2 to 5% of total generation). Therefore, increasing separation of wood waste represents a key option to address the untapped circularity potential of wood waste to feed back into the economy. While the EU-27 already demonstrates strong performance in diverting municipal wood waste from disposal, especially compared to other biobased waste streams (e.g., food waste), significant opportunities remain to further enhance circularity. In particular, **there is significant potential to shift part of the 26-28 million tonnes of wood waste currently destined for disposal or energy recovery to high-quality material recycling**. This would extend the lifecycle of wood through cascading use (Besserer et al. 2021) until a certain number of cycles (usually a single cycle due to significant downgrade of wood fibres in the most common recycling pathways) after which the materials are no longer adequate for high-value recycling. However, this shift is limited by the strong competition between energy recovery and recycling in this stream.

In this context, the cascading principle provides a practical framework aligned with the waste hierarchy, prioritising material reuse and high-quality recycling before considering energy recovery, thereby maximising both economic and environmental value of the resource. In line with this principle, woody biomass should be used according to its highest economic and environmental added value in the following order of priorities: extending the service life of wood-based products, re-use, recycling, bioenergy and disposal. Where no other use for woody biomass is economically viable or environmentally appropriate, energy recovery helps to reduce energy generation from non-renewable sources (EC, 2025).

There is also a potential to increase circularity of wood waste from industrial activities collected with mixed waste. Eurostat (2025f) reports the generation of waste categories from mixed waste collection, namely household and similar wastes and mixed and undifferentiated materials, which include considerable bio-based waste fractions. However, there is no information concerning the weight of the bio-based waste fractions present in these waste streams, so **it is not possible to estimate the significance of the lost potential**

for its recovery. Increase separation in industrial activities would enable a better understanding of the untapped circularity potential from industrial activities and the design of targeted policies, such as the impact of mandatory separation at source.

Eurostat also provides data on the amount of wood waste exported and imported. In 2022, the data shows that a total of 1.9 million tonnes were imported (that would correspond to roughly 4% of total generation estimated), while 0.65 million tonnes of wood waste were exported (approximately 1% of total estimated generation) (Eurostat, 2025j). This significant net import of 1.2 million tonnes of wood waste suggests a strong internal demand for secondary raw materials derived from wood, likely for recycling into new materials (such as particleboard) or for energy production, but the trade statistics do not provide insight on this.

Regarding treatment, according to Eurostat (2025h), more than 99% of treated, separately collected wood waste was subject to recovery operations, with 51.4% undergoing energy recovery and 47.9% being recycled or used for backfilling. In contrast, only 0.7% was disposed of via landfill or incineration without energy recovery. The dominance of energy recovery over material recycling points to an opportunity to increase recycling rates through enhanced separation, classification and processing, particularly for streams that are currently contaminated or poorly sorted. The presence of **hazardous substances limits the potential for recycling**, but data from Eurostat (2025f) indicate that 96% of wood waste generated (approximately 45 million tonnes) is classified as non-hazardous. From a mass-balance perspective, this wood waste with hazardous substances does not imply or entail a significant problem when considering the already existing waste-to-energy capacity for this material.

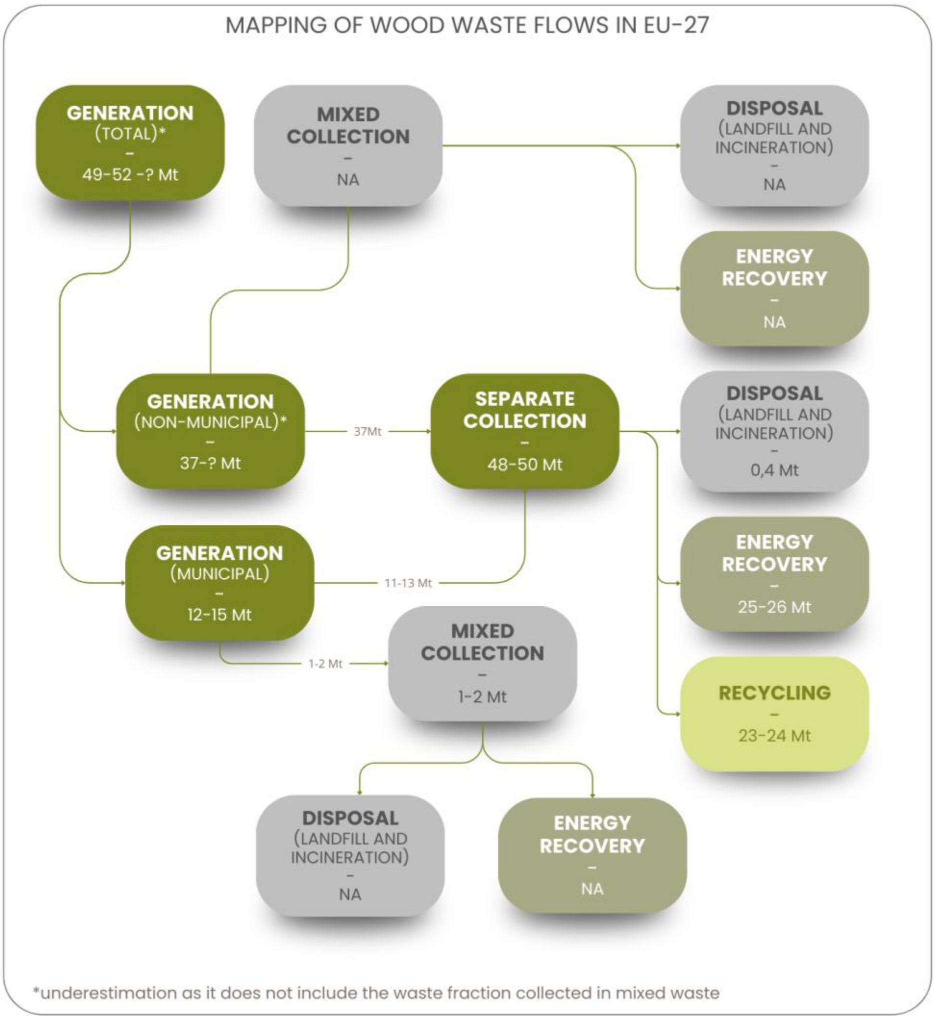

Figure 2. Mapping of wood waste flows in EU-27, 2022 (figures in the grey boxes represent the 'untapped' potential; light green boxes represent recycling)
Source: Eurostat, 2025f; Eurostat, 2025g; EEA, 2022b

2.2.2 Challenges and opportunities to enhance circularity in wood waste

These diverging scenarios underscore how future wood demand in the EU is highly sensitive **to socio-economic conditions and policy choices**. A **higher demand for wood-based products**, as projected in the middle-of-the-road path, **is expected to result in a proportional increase in wood waste generated** from both post-consumer products and industrial waste and by-products. However, despite the potential for increased wood waste recovery and recycling, significant barriers continue to hinder its full integration into the circular economy. In general, reported data highlights that **lack of data, lack of an EU common framework for wood waste and a competing market for energy recovery are among the core challenges that must be addressed to improve wood waste management and circularity** (CEPS, 2024; EEA, 2023b).

Projects promoting circularity in wood

A study conducted by Centre for European Policy Studies (CEPS) under the EU-funded Wood2Wood project, further examined these issues through interviews with experts from academia and industry. It identified three main categories of challenges for a more circular use of wood wastes. **Technological barriers** include the lack of cost-efficient systems for preparing waste wood and the need for applications that are less demanding and lower risk. **Market-related issues** stem from limited economic incentives, the absence of actors responsible for early-stage processing, and competition between material recycling and energy recovery. **Policy shortcomings** are particularly systemic, characterised by preferential support for energy use over material reuse, a lack of enabling regulations, and the absence of a harmonised EU-wide regulatory framework (CEPS, 2024). Similarly, the EEA (EEA, 2023b) has concluded that the **wood waste market is not a well-functioning market**, **lacking aspects such as an international scale, information on prices, or significant supply & demand when compared to the virgin materials**. Table 7 gives an overview the barriers identified.

Table 7. Opportunities and their limitations for each technical solution considered for wood waste

Solutions	Opportunities	Limitations
Prevention	• 50% reduction in GHG emissions when wood materials are reused or recycled in construction and demolition contexts (Shiyao Z., et al., 2024). • Improved manufacturing processes to increase resource efficiency (Bond et al., 2025). • Ecodesign with focus on reusability, repairability, standardisation and modular design (Bond et al., 2025). • Relevant for construction materials, pallets and other wood packaging, furniture.	• Requires systemic changes in design and production; • Depends on market uptake
Preparation for reuse	• Preserves material value. • Low energy input. • Applications in construction, wood packaging, furniture.	• Requires high-quality, uncontaminated wood. • Limited investment data and uncertainty about wood quality and availability (CEPS, 2024; EEA, 2023b). • Supply inconsistency by location/country prevents efficient scaling (CEPS, 2024; EEA, 2023b).
Mechanical recycling	• Faulty particleboard and residues from wood processing can be successfully recycled as raw material (Iždinský et al., 2020). • Transformation in a wide range of products (e.g., insulation panels, advanced composite materials). • Application in lower-grade applications: mulch, landscape chips, soil amendments and animal bedding. • Potential to be used for fibre-based products, such as paper and textiles. • Less demanding and lower-risk applications for lower-quality wood could enhance competition with energy recovery applications while safely and	• Contamination levels, particle size, moisture content, and potential end-use applications limit the selection of technologies. • Lack of cost-efficient technologies for sorting, analysing, cleaning, and certifying used wood (CEPS, 2024; EEA, 2023b). • Number of potential cycles limited due to the presence of resins, additives, waxes, preservatives and reduced particle and fibre size. • Market demand and the cost-effectiveness of production dictate the need to new products.

Solutions	Opportunities	Limitations
	effectively utilised (CEPS, 2024; EEA, 2023a). • Can be treated together with garden and forestry waste.	• Recycling potential reduced due to complex products (i.e., different materials attached or merged). • Little economic incentive: high processing costs, low consumer demand, and competition from virgin wood (CEPS, 2024; EEA, 2023b). • Downcycling into particleboard competes with higher-value material use (CEPS, 2024; EEA, 2023b). • Lack of clear ownership for tasks like reverse logistics, sorting, and decontamination (CEPS, 2024; EEA, 2023b). • Lack of equivalent support for reuse/recycling comparing to energy recovery (CEPS, 2024; EEA, 2023b). • Missing centralised standards, guidelines, or protocols to support sorting, verification, and certification of wood waste (CEPS, 2024; EEA, 2023b). • Fragmented regulatory framework (CEPS, 2024; EEA, 2023b): o No EU-wide (End-of-Waste) EoW criteria are established for wood o Different internal regulations that hinder a common EU market.
Thermochemical	• Converts low-quality/contaminated wood; energy/material recovery (Korba A., et al., 2025). • Commercially viable plants using thermochemical processes to wood and forestry waste. • Applications on bio-oil, syngas, biochar, chemicals (Korba A., et al., 2025).	• Higher capital/operational costs. • Emissions control needed (CEPS, 2024).
Energy recovery	• Sustainable pathway for managing low-quality or contaminated wood (Korba A., et al., 2025). • Generation of valuable by-products (e.g., bio-oil, syngas, and biochar) and contributing to resource recovery and energy production (Korba A., et al., 2025). • Renewable energy policies, including target setting and financial support, incentivise energy recovery applications from wood waste (including RED II and Red III) if sustainability criteria are met (IEA, 2024).	• Should be geared towards the material without recycling potential. • Wood waste is diverted to energy recovery due to its calorific value, reducing material recovery rates (CEPS, 2024; EEA, 2023b). • Ash must be managed, with loss of material for further cycles (except for cement, where ashes are incorporated in clinker); emission control required (CEPS, 2024; Tamanna, K., et al). • Fragmented regulatory framework (CEPS, 2024; EEA, 2023b): o No EU-wide EoW criteria are established for wood; o Different internal regulations that hinders a common EU market.
Emerging/ Innovative Technologies	• Expands recyclability. • Enables higher-value applications (Pazzaglia, A., et al., 2023b). • Conversion of wood waste into basic chemicals and then used to synthesise advanced products (e.g., biofuels).	• Enzymatic breakdown and fibre regeneration are still under development (Korba A., et al., 2025; Recycling Inside, 2025). • May require specialised infrastructure. • Little economic incentive: high processing costs, low consumer demand, and competition from virgin wood (CEPS, 2024; EEA, 2023b). • Fragmented regulatory framework (CEPS, 2024; EEA, 2023b): o No EU-wide EoW criteria are established for wood;

Solutions	Opportunities	Limitations
		○ Different internal regulations that hinder a common EU market.

EU-funded projects such as WOODCIRCLES, Wood2Wood and WoodStock play an important role in promoting circularity within the wood value chain. WOODCIRCLES aims to significantly enhance the **circular use of wood in construction** by advancing sustainable building practices and enabling the reuse of urban and demolition waste. In doing so, it contributes to a more resource-efficient and low-carbon economy (WOODCIRCLES, 2025). Wood2Wood focuses on developing and implementing advanced sorting techniques, upcycling technologies, and digital tools to **extend the lifetime of wood derived from construction**, demolition, and furniture waste. The project also seeks to establish harmonised classification schemes and provide policy recommendations to support improved circularity (Wood2Wood, 2025). WoodStock, in turn, centres on climate-smart and circular uses of underutilised wood in construction. It employs Living Labs to co-create **zero-waste building solutions**, optimise material flows, and develop robust life cycle assessment tools (WoodStock, 2025).

Chemical recycling

In parallel, projects such as NEXT-STEP, PRIMA-2 and Cepi's Forest Fibre Initiative highlight the potential growing role of chemical recycling in **unlocking new material pathways for wood waste within Europe's circular bioeconomy**. NEXT-STEP focuses on converting hardwood residues into **bio-based polyurethanes and polylactic acid copolymers**, enabling the incorporation of bio-based plastics in products such as shoe soles and insulation materials for construction. By using second-generation feedstocks and new chemical platforms, the NEXT-STEP project aims to **reduce reliance on fossil resources while promoting high-performance, renewable alternatives** (CBE-JU, 2025). PRIMA-2 tackles the challenge of medium-density fibreboard (MDF) waste through pyrolysis, recovering high-value chemicals such as phenols and methyl methacrylate. These outputs are **reintroduced into industrial applications including resins** (Unilin) **and coatings** (Baril Coatings), **closing the loop for composite wood products** (Biorizon, 2025). Complementing these technological innovations, Cepi's Forest Fibre Initiative promotes the large-scale adoption of **wood-based textiles** (e.g., lyocell) and for advancing EU infrastructure to chemically recycle blended fabrics. By leveraging existing expertise in the pulp and paper industry, this initiative aligns closely with the EU Strategy for sustainable and circular textiles (CEPI, 2022). These projects show a trend on how **chemical recycling aims to transform wood waste into high-value products, substitute non-renewable materials, and create cascading value**

across sectors. The focus on second generation feedstocks is also key to avoid constraints or backlash due to competition with food or feed production.

However, as in other bio-based waste streams, chemical-based recycling needs to **overcome significant barriers to ensure it offers a viable alternative, both economically and environmentally**. Chemical-recycling usually involves **energy-intensive processes**, which leads to a significant part of the biomass to be used as fuel for the process.

2.2.3 Available Policy Options

The potential policy options (

Table 8) have been drawn from case-studies from Member-States and from studies conducted by different organisations (CEPS, 2024; Besserer et al., 2021; EEA, 2023a). Policy options are grouped similarly to food, garden and vegetal waste, and include options related to collection and treatment. However, options related to traceability and classification and to market demand were also included. These reflect challenges and options specific for wood waste, namely the apparent trade-off between a recycling and an energy recovery model. In fact, it is argued that in a circular model, the wood material will continue to circle in products and after a few cycles, it will be subject to energy recovery. The cascade principle should be the guiding model for wood waste, which has been enhanced in several Member-States with better classification and improved pre-treatment and sorting processes.

Table 8. Summary of available policy options for wood waste and their impacts

Related policy measures	Potential impacts
1. Strengthen traceability, classification and accountability	
• **Harmonised classification standards**: Improved classification of wood waste can foster the market for wood waste. Member-States and other European countries have national guidelines or standards to help citizens and businesses (UNECE, 2022), but differences or absence in other countries limits consistency in sorting and downstream use, cross-border trade and compliance. • **EoW Criteria**: EoW criteria are established in Austria for wood materials, enabling low-risk materials to be managed directly by wood product manufacturers without a significant overhead in administrative costs.	• The impact of measures enhancing traceability, classification and accountability are typically presented qualitatively. Impact Assessment studies for the WFD have not focused on wood waste but considering the results for waste streams such as textile waste, measures related to traceability and classification have positive impact, potentially reducing costs and increasing benefits (e.g., Measures 1.1 and 2.6 in SWD(2023) 421).
2. Improve collection	
• **Extension of Extended Producer Responsibility (EPR) to cover more product types**: Wood packaging is already covered by EPR, but other relevant product types, such as furniture or construction products, can also be included in EPR systems, as is currently the case in France and Hungary (for furniture). This can help to increase the coverage of convenient collection infrastructure for households and businesses.	• Most significant impacts related to improved collection are measured by increasing the amount diverted from landfill and subject to treatment. This has positive impacts in both the economic and environmental dimensions, as detailed below.

Related policy measures	Potential impacts
• **Mandatory separate collection**: Several Member-States have mandatory separate collection schemes in place. For example, Finland (CEPS, 2024) and Portugal (EEA, 2022b) mandate that CDW must be separated by material type, including wood, to maximise the potential for recycling. The WFD already establishes mandatory separate collection for other material types and wood could be added to this list.	
3. Improve treatment	
• **Implementation of closed-loop systems:** Several projects have been undertaken to promote closed-loop recycling, especially in the construction sector, such as the EU co-funded innovation projects Woodcircles, and CIRCULess, that enable the re-use and recycling of wood materials in the sector. The projects are necessary to widen the type of materials that can be integrated in the wood recycling chain. • **Use of advanced pre-treatment and sorting technologies**: Recycling companies and technology providers have been developing and deploying automated sorting systems to ensure high-quality recycled wood streams. For example, the ASKIVIT project (2021-2024) led by the Fraunhofer Institute, integrated terahertz imaging, NIR, infrared, thermography, and AI to identify and sort wood within bulky waste. Physicochemical purification can also be used to enhance the recyclability of wood fibres, as these processes can remove harmful substances and improve final product performance (Besserer et al. 2021). • **Development of biological treatment methods:** R&D projects, such as Horizon project WoodZymes, are being developed focusing on biological approaches such as fungal-based degradation, as viable alternatives for treating contaminated or composite wood waste to produce bio-based materials.	• Diversion of wood waste from landfill has shown to have positive environmental impacts. The most challenging assessment is between the use of wood waste as a source of renewable energy or use as material for other products. For example, Hossain (2018) demonstrated that recycling wood has a negative GHG emissions footprint due to avoided virgin material extraction and processing (- 70 kg CO_2eq per tonne of wood waste), but emission savings can be maximized by using it as an alternative fuel in cement kilns by displacing coal (-1 075 kg CO_2eq per tonne of wood waste). However, LCA studies such as this tend to omit the potential cascade use, which in this case would demonstrate that the benefits of energy recovery and fossil fuel displacement can be captured in a second cycle of the particleboard, i.e. by using wood waste in cascade, you maximize the potential environmental benefits. • A study on the impacts of wood waste recycling and incineration was conducted in Sweden. Using LCC and S-LCA, it found that a small increase in wood waste recycling (thus a decrease in incineration) could contribute to improve social impact categories and has positive economic impacts through cost reduction (Elginoz et al., 2024).
4. Enable market demand for secondary raw material	
• **Minimum recycled content targets**: Specific certification schemes, such as the Nordic Swan Ecolabel, establish minimum recycled content for particleboards (e.g., a minimum of 50% of weight must consist of recycled raw material). Other certification schemes, such as EU Ecolabel for furniture, provide more flexibility since it allows recycled content to be replaced by virgin material from sustainable certified forest. Increased demand for recycled wood increases market demand and enables a sound single EU market. • **Integration of recycled wood criteria in Green Public Procurement (GPP):** Implementation of GPP policies to foster the use of recycled wood in construction projects can help to increase market demand for secondary raw material from wood waste. The EU and several national GPP criteria establish recycled content as an award criterion (e.g., EU GPP Criteria for Furniture). • **Use of economic incentives**: The use of fiscal instruments, such as reduced VAT for recycled content or landfill taxes, can contribute to a level playing field for recycled wood and other secondary raw materials, by internalising environmental costs. For example, the Czech Republic has formally proposed to the Council to lower VAT rates for products made of recycled materials and recyclates.	• Considering that a significant part of wood waste is subject to energy recovery, directly or after pre-treatment processes, market demand for secondary raw materials of wood waste can help to shift the market towards more circular solutions. However, as discussed, these might not generate the best possible environmental outcome if coal, petcoke and natural gas users are left without alternatives. There is a growing demand from intensive-energy users for biomass waste due to increasing pressure from the EU-ETS. To mitigate this risk, EU-level classification schemes can help to structure the market and tailor it according to associated health risks. • Recycled content targets might also reduce competitiveness, especially for SME in sector such as furniture, that are less likely to have access to a steady supply of high-quality wood waste that can be processed into their product lines. This can be exacerbated by competition from suppliers outside of EU, which would not be subject to same standards.


Sewage sludge

2.3 Sewage Sludge

KEY MESSAGES

- An additional 1.5 to 2.1 Mt of sewage sludge (24-27% of total generation) could potentially be recycled.
- Phosphorus and nitrogen can be recovered from sludge and reused as fertiliser, reducing reliance on synthetic fertilisers. When uncontaminated and sanitised, sludge is one of the most cost-effective soil improvers.
- Public acceptance is key for sludge reuse in agriculture and other applications, such as construction. Policies such as the ban on landfilling of sewage sludge, certification schemes and stricter legislation regarding the presence of contaminants in sewage sludge could enhance circularity.
- Thermal treatment remains a necessary option for sewage sludge which cannot be valorised through agricultural use and composting due to risks from contaminates.

2.3.1 Mapping of sewage sludge flows in Europe

To assess the potential for increasing circularity, a snapshot of the current state of sewage sludge waste management across the EU was established, where the quantities of sewage sludge currently being lost by being sent to incineration, landfill or other uses were estimated.

The main results of the analysis of available data, presented in Annex 3, are summarised in Table 9. The values are roughly consistent across the data sources, except for the 'Waste Generation' data series from Eurostat, which might be due to the difference in the waste category considered (common sludges).

Table 9. Data for mapping of sewage sludge flows (dry matter) in EU-27

Mass flows (Mt)	Eurostat - Sewage sludge production and disposal: 2022, includes estimates[a]	Eurostat – Waste Generation: 2022	Implementation of SSD report (estimates with gap-filling): 2007-2018[b]	EEA - Waterbase - UWWTD: 2020
Generation	7.69	12.01	7-8	6.31
Recycling	3.59	-	-	3.08
Composting	1.27	-	-	0
Agricultural use	2.32	-	2-3	2.35
Other recycling	0	-	-	0.73
Incineration	2.29	-	-	1.01
Landfill	0.67	-	-	0.29
Others	0.78	-	-	0.53
Other uses[c]	1.41	-	-	1.16
Not reported	-	-	-	1.39

Notes: ([a]) Data for sewage sludge production (dry matter) includes estimates for four countries: Belgium (2010), Denmark (2010), Italy (2010) and Portugal (2016); Data for agricultural use includes estimates for three countries: Denmark (2020), Italy (2010) and Portugal (2016).
([b]) As reported in the report by the European Commission (EC), the gap-filling was made through extrapolation based upon the population size of each Member State.
([c]) Based on Egle et al. (2023), "other uses" includes the amounts lost to other destinations and 50% of the sewage sludge sent to composting.
Sources: EEA – Wise Freshwater, 2025b. Available online
Eurostat, 2025m. Available online
Eurostat, 2025o. Available online
EC et al., 2022. Available online

According to (EC et al., 2022), there are "considerable data gaps and discrepancies between the Eurostat data on sewage sludge production and disposal, and Member State figures". Limited insight is given into sewage sludge disposal, with 'composting' being generally a pre-treatment technique with no information on end use. Also, regarding the 'other' disposal, Eurostat does not provide further detail on what it entails. The study report also states that there is little information in the data and literature studied on the full detail of the typical sludge management processes in each country. Having information on the volumes of sewage sludge subject to anaerobic digestion as an intermediate step is relevant as it will impact the actual volumes of sludge finally disposed of and the amount of energy recovered (EC et al., 2022).

The findings from this analysis were then consolidated in the mapping presented in Figure 21, which aims to conciliate the best available information, starting with sludge generation where the ranges represent the lowest and highest estimates (Eurostat, 2025m, 2025o; EEA - WISE Freshwater, 2025b; EC et al., 2022). Due to the lack of robust data on the quantities of sewage sludge composted and subsequently reported by Member States under the category "other use", it is assumed, based on the Egle et al. (2023) study, that composted sewage sludge is equally split between agricultural use and other purposes, with 50% allocated to each.

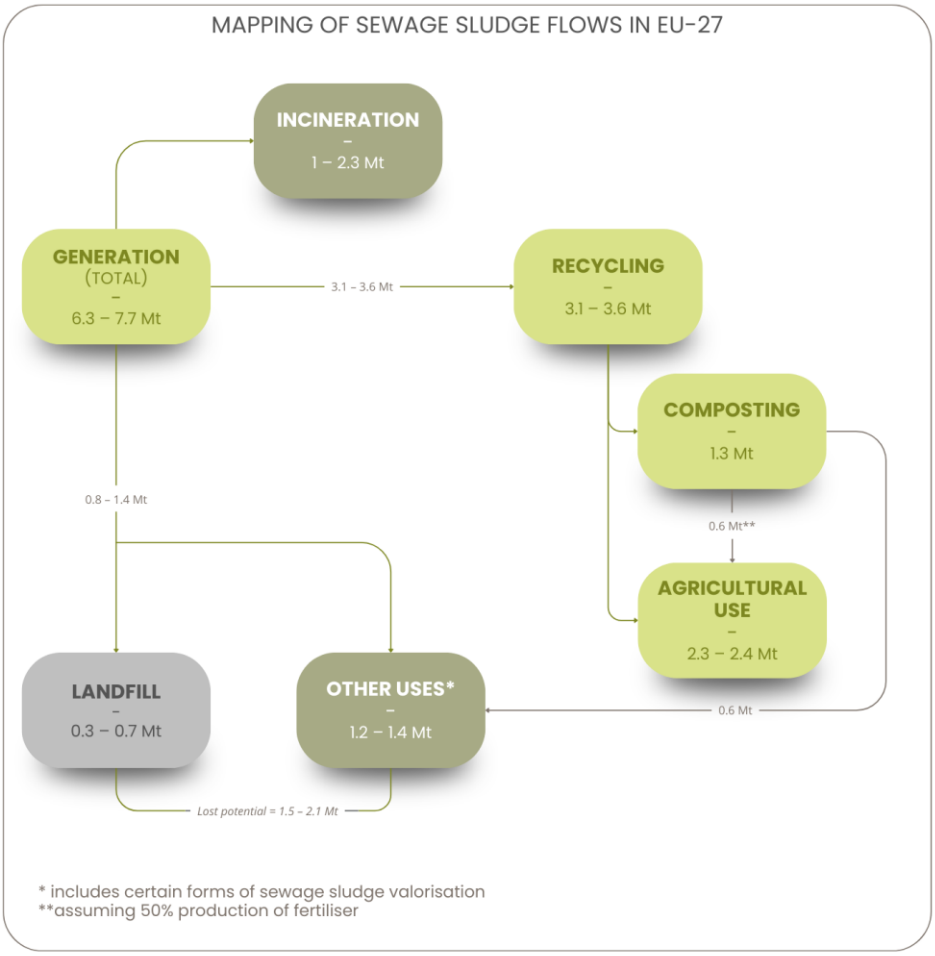

Figure 3. Mapping of sewage sludge flows (dry matter) in EU-27, 2022
Source: Eurostat, 2025m, 2025o, EC et al., 2022, EEA - WISE Freshwater, 2025b

Notes: Differences in total sludge production and total sludge disposal might be a result of sludge storage or of its shipment intra-EU or extra-EU.
The "other uses" option includes certain forms of sewage sludge valorisation (e.g., soil enrichment).
Incineration combined with phosphorus extraction from the ash still makes use of the nutrients present in sewage sludge.

The estimated total generation of sewage sludge presented in the Figure 3 ranges between 6.3 and 7.7 Mt. However, if the common sludges from sector 'Water collection, treatment and supply; sewerage; remediation activities and other waste management services' reported in the env_wasgen series are considered, this range increases to 12.01 Mt. **From the mapping, it can be concluded that between 1.5 to 2.1 million tonnes of sewage sludge are not managed in a circular model (24-27% of total generation), with an estimated 0.3 to 0.7 million tonnes being landfilled (5-9% of total generation).**

2.3.2 Challenges and opportunities to enhance circularity in sewage sludge

Based on identification and analysis of technical solutions aimed at maximising the circularity potential of sewage sludge, presented in Annex 3, the main challenges and opportunities associated with the potential to move this stream up the waste hierarchy were identified (Table 4). These aspects highlight both the barriers that need to be overcome and the strategic advantages that can be leveraged to enhance the sustainable management and valorisation of sewage sludge.

Challenges in implementing circular bio-based solutions

The implementation of circular bio-based solutions for sewage sludge faces a range of **challenges that span regulatory, economic, technological, and operational dimensions.**

The key challenge in recovering resources from waste sludge lies not in the lack of suitable technologies, but in **the high production costs of value-added products compared to their current market price from virgin materials**. For such processes to be widely adopted, they must be **economically viable, environmentally sustainable, and supported by effective supply chain strategies**. However, several factors continue to limit broader implementation, including the **lack of an economic motivation to promote circular approaches, insufficient planning tools to identify the most appropriate and sustainable solutions for specific contexts, and the generally low TRL** of bioproduct recovery technologies, typically below TRL 4–5 for industrial-scale application (EEA, 2022c; Tyagi and Lo, 2016; Capodaglio and Bolognesi, 2018).

Constraints in nutrient recovery

Regarding the wastewater-derived nutrient recovery, this process is constrained by **low yields compared to industrial fertiliser production**, which reduces its competitiveness (Kehrein et al., 2020). Additionally, **reaching the market value of fertiliser with resources recovered from wastewater remains a challenge**, considering the production costs (e.g., maintenance, chemicals, and energy) (Min & Park, 2021).

Pollutants

A major barrier to sludge circularity is the presence of pollutants. Although the SSD requires only treated and sanitised sludge to be applied to agricultural and forestry land, wastewater contamination with **hazardous chemical pollutants originating from household consumer products, urban runoff, and industrial discharges connected to wastewater treatment plants (WWTP) remains a serious problem** (Salva et al., 2025; EEA, 2022c). Wastewater treatment facilities act as central hubs where contaminants accumulate, and the resulting sewage sludge concentrates many of them, including **heavy metals, persistent organic**

pollutants (e.g., PCBs, PCDD/Fs), and microplastics (Hassan et al., 2023; Uddin et al., 2024; Achkir et al., 2022; Adjama & Dave, 2025). Microplastics are of particular concern due to their persistence, their potential to interact with and transport other pollutants, and their reported concentrations (Hassan et al., 2023; Adjama & Dave, 2025). When applied to land, these contaminants may persist, alter soil properties, and enter the food chain, posing long-term risks to environmental and human health (Hassan et al., 2023; Uddin et al., 2024; Achkir et al., 2022; Adjama & Dave, 2025). According to a JRC (2022) study, **highly toxic, persistent, and bioaccumulative pollutants like PAHs, PCDD/F+dl-PCBs, PFAS, and SCCPs/MCCPs found in sewage sludge can pose risks to human health and the environment**. Human health is still the most sensitive endpoint, even though many of these substances are already regulated under POPs and REACH Regulations. Therefore, human-focused mitigation measures will also lower risks to soil organisms and soil quality. The SSD currently mainly targets pollutants such as heavy metals, while only a few organic pollutants are regulated at the national level in some Member States (Leino et al., 2025).

Treatment of sewage sludge

The variability of the properties of the sewage sludge has an impact on the quality of its resources, and its characteristics can also vary according to the treatment process and the origin of the wastewater (K et al., 2023; Nahar et al., 2024). One of the main problems with sewage sludge is the inevitable presence of contaminants in this waste stream. Therefore, **WWTP are exploring alternative treatment methods aimed at destroying the contaminants present in sewage sludge, with non-combustive thermal treatment techniques gaining traction** (Nahar et al., 2024). Additionally, more studies on pre-treating sewage sludge before stabilization are being developed to improve the removal of emerging contaminants. Treatments such as **composting, hydrothermal, advanced oxidation, and electrochemical technologies have been widely investigated for the removal of emerging organic pollutants; however, an overview of these technologies and the associated issues is still lacking** (He et al., 2024).

Public perception and acceptance

The public perception and acceptance are also a key challenge, which is influenced by the pollutants present in sewage sludge, influencing both farmers and policymaking (EC et al., 2022; Domini et al., 2022). **Trust in treatment strategies for wastewater and sewage sludge play a crucial role in defining social acceptability of reusing these waste streams**. To **maximise public confidence in sewage sludge reuse and its products**, several critical factors must be ensured, such as: raising awareness through campaigns that highlight economic, environmental and agronomic benefits; ensuring transparency and communication about treatment technologies and sludge quality; engaging communities through open days at WWTP; providing education and training for sector professionals, as well as the general public, to improve understanding of the advantages and challenges of the by-product reuse; and demonstrating feasibility and safety through pilot projects and communication of successful case studies (Salah et al., 2025).

In this context, some Member States have established more stringent thresholds than those defined in the Directive (EEA, 2022c). Countries like Denmark, Germany, Sweden, and the Netherlands have imposed more rigorous standards to limit contaminants in sludge used in agriculture (Upadhyay et al., 2024). Some countries have found that, to maintain consumer confidence and protect the environment, they have needed to develop comprehensive assurance schemes for sludge applied to land (EEA, 2022c).

Land application challenges

Regarding its application to land, sewage sludge has a **relatively low nutrient content** that makes it **less competitive than conventional fertilisers or livestock manure**, particularly in manure-rich regions where manure is often more affordable and accessible, highlighting the need for region-specific approaches (Egle et al., 2023; Kehrein et al., 2020; EEA, 2022c). Moreover, the limited availability of agricultural land is also an additional bottleneck affecting the valorisation of this waste stream (EC et al., 2022; EEA, 2022c). Another issue that may arise is the long-term accumulation of nutrients in soils due to the landspreading of sewage sludge in excess of plant phosphorus demand, which limits its potential to effectively support plant nutrition (Egle et al., 2023) and can contribute to eutrophication.

EoW criteria limitations

The **lack of EoW criteria for this waste stream limits the alignment with the Waste Framework Directive and hinders circular economy development**, as the process is slow, **inconsistent across Member States**, and **currently restricted to a few materials** such as fertilisers (EC et al., 2022; European Sustainable Phosphorus Platform, 2024). This gap discourages investments, innovation, and expansion of the secondary materials markets, which is why the European Parliament has already highlighted the need to revise and extend EoW criteria (European Parliament, 2021; European Sustainable Phosphorus Platform, 2024).

Energy recovery challenges

In terms of **energy recovery the high moisture content of sludge makes processes inefficient and costly**, requiring innovation to reduce energy demand and improve the performance of the different options in this area. (Salva et al., 2025; Kehrein et al., 2020; EEA - Ricardo Energy and Environment, 2021; Zheng et al., 2024). Options such as

gasification, pyrolysis, and incineration, all still facing technical and financial barriers (Gusiatin et al., 2024; Capodaglio and Callegari, 2023; Kehrein et al., 2020).

Other valorisation options

Regarding other valorisation options, besides the **integration of sewage sludge ash or dried sludge as a component in the manufacturing of construction materials** shows promising mechanical properties in the short term, their long-term durability under environmental exposure still requires further research (Xia et al., 2023). **Biorefineries** show real potential for recovering materials from wastewater, but full-scale applications remain scarce. Research is needed to better connect the different products that can be recovered and to design systems that adapt to changing feedstocks and market needs while limiting environmental impacts (Capodaglio and Callegari, 2023). In the case of **polyhydroxyalkanoates (PHA) production**, issues such as inconsistent quality, high costs, small plant sizes, regulatory barriers, and limited end-use markets continue to hold back wider adoption (Kehrein et al., 2020; EC et al., 2022). **Chemical recovery** (e.g. acid-based recovery) also require adaptation. Existing methods pose environmental risks due to the generation of hazardous residues and the decline in output quality, highlighting the need for safer and more efficient alternatives (Capodaglio and Callegari, 2023).

Cost of sludge management

The costs for sludge management and disposal can account for **40-60% of the total costs for operating an entire WWTP** and they can vary according to several factors (e.g., local regulations and fertiliser limits, disposal options and ethical aspects influencing the acceptance of specific practices or technologies) (Domini et al., 2022). The **generalisation of cost regarding sewage sludge is difficult**, as it also depends on the properties of the feedstock and on operational factors (e.g. scale and available technologies) (Brandstätter et al., 2025). In Italy, between 2015 and 2018, factors such as market externalities, new regulation on sludge reuse in agriculture (introducing new limits for hydrocarbons, some organic micropollutants, and stricter limit values for some heavy metals), as well as increased sludge production due to improved performance of treatment plants, led to rising sludge management costs (Domini et al., 2022).

Variability of management approaches across Europe

Throughout Europe, there is **no common approach or consensus on the appropriate management and final destination of sewage sludge** (EEA, 2022c). While some countries promote land application within circular economy strategies, others have adopted more restrictive approaches prioritising phosphorus recovery from incineration ash. This might be partially justified by regional or local characteristics, such as sewage contamination, land availability, soil quality, among other factors, but the policy context has a significant impact on the treatment and final destination of sewage sludge.

Germany has established a national strategy to phase out the use of sewage sludge on agricultural land by 2029/2032 for WWTP serving more than 100,000/50,000 population equivalents (p.e.) (EEA, 2022c). According to the German Sewage Sludge Ordinance, beginning in 2029, phosphorus recovery will be mandatory for sludge containing ≥ 20 g of phosphorus per kg of dry solids for facilities above the thresholds. This requirement mainly targets mono-incineration plants but does not prescribe specific technologies, allowing for flexibility in implementation (The Federal Ministry for the Environment and Consumer Protection, 2025).

Austria and Switzerland follow similar trends. Switzerland, which banned land application of sludge in 2006, was the first country to legally mandate phosphorus recovery from sewage sludge and slaughterhouse waste, introducing the regulation in 2016 with a 10-year transition period. From 2026, phosphorus must be recovered from wastewater, sludge, or sludge ash, mainly for fertiliser production. Projects such as Phos4Life, Phosphor26, and ZAB aim to collectively recover over 8,800 tonnes of phosphorus annually, mainly via wet-chemical processes (European Sustainable Phosphorus Platform, n.d.-a; FOEN, n.d.).

In Austria, landfilling of materials with total organic carbon (TOC) content above 5%, including sewage sludge, is banned (Federal Ministry Republic of Austria, 2023). By 2033, phosphorus recovery will be compulsory for all WWTP with a capacity of ≥ 20,000 p.e.. These plants must either incinerate sludge with recovery or achieve phosphorus recovery targets: at least 60% from sewage inflow, or 80% if recovery occurs from ash. Alternatively, all ash must be used to produce fertilisers compliant with national regulations (European Sustainable Phosphorus Platform, n.d.b).

Sweden has adopted a different circular economy approach, supporting the safe land application of treated sludge. To ensure sludge quality and reduce chemical contamination at the source, Sweden launched the REVAQ certification scheme in 2008. The initiative, involving collaboration among farmers, regulators, and the food and water industries, restricts industrial discharge of banned substances into certified treatment plants. As a result, public trust increased and the percentage of sludge applied to land rose from 22% in 2011 to 45% in 2018 (EEA, 2022c). This example shows that when upstream mechanisms are put in place at the WWTP to ensure the safety of this waste stream, public concerns about the use of sewage sludge as fertiliser in agricultural soils can be reduced.

Table 10. Opportunities and their limitations for each technical solution considered for sewage sludge

Solutions	Opportunities	Limitations
Prevention	• Mitigates environmental and economic burdens associated with downstream sludge treatment and disposal.	• Sludge generation is expected to increase due to population growth (Mannina et al., 2024); • Prevention requires upgrades to WWTP, often involving emerging technologies with high energy demand and operational costs (Blumenthal et al., 2025; Morello et al., 2022).
Agricultural use	• When uncontaminated and sanitised, sludge is one of the most cost-effective soil improvers (Salva et al., 2025); • Enables direct recovery of nutrients (Salva et al., 2025); • Requires low technological input, with minimal need for specialised infrastructure or skilled labour (Salva et al., 2025).	• Risk of pathogen transmission to humans or animals through food chains (Salva et al., 2025); • Potential for soil contamination by pharmaceuticals, heavy metals, and microplastics present in the sludge (Salva et al., 2025); • High variability in nutrient content complicates accurate nutrient planning (Salva et al., 2025); • Limited market incentives due to lower fertiliser quality when compared with conventional mineral fertilisers (Kehrein et al., 2020).
Composting	• A mature and widely accepted treatment option; • Contributes to pathogen and pharmaceutical residues reduction (Salva et al., 2025); • When properly processed, sludge compost can serve as a fertiliser or soil improver (Salva et al., 2025).	• Sewage sludge must typically be co-composted with other organic materials (e.g. wood chips, straw, or bio-waste) (Salva et al., 2025); • Composting does not eliminate inorganic contaminants (e.g. heavy metals, microplastics), restricting its end-use applications (Salva et al., 2025); • Gas emissions (e.g. CO_2 and NH_3) are inherent to the process and often difficult to monitor effectively (Salva et al., 2025); • Since July 2022, fertilisers derived from municipal sewage sludge digestate can no longer obtain CE certification, limiting their commercialisation within the EU (Salva et al., 2025).
Struvite production	• High TRL (TRL 9) (Saerens et al., 2021); • Enables direct phosphorus recovery as struvite, reducing dependence on phosphate rock (Saerens et al., 2021); • Helps reduce operational and maintenance costs of WWTP, enhancing both operational efficiency and environmental performance (Achilleos et al., 2022); • Prevents uncontrolled precipitation that leads to pipe clogging (Sichler et al., 2022); • Applicable only to WWTP using advanced biological phosphorus removal processes (Sichler et al., 2022).	• Recovery potential is limited to 5-25% of the phosphorus present in wastewater (Saerens et al., 2021); • Operational and energy costs remain high (Ghosh et al., 2019); • Lack of market incentives, as recovered phosphorus is currently not cost-competitive with mineral sources (EEA, 2022c).
Anaerobic Digestion	• Produces renewable energy in the form of biogas, which can be used for combined heat and power or upgraded to biomethane (Salva et al., 2025); • Efficiently processes high-moisture organic waste without lowering biogas energy value (Neri et al., 2024); • Digestate often has a low pathogen content, allowing for its potential use as a soil improver (Salva et al., 2025); • Can be integrated with pyrolysis or gasification to enhance energy output (Salva et al., 2025);	• Process efficiency is generally moderate (Capodaglio and Callegari, 2023); • In many cases, pre-treatment is required, adding complexity and reducing economic feasibility; • Co-digestion with other organic materials is often necessary (Salva et al., 2025); • Anaerobic digestion is not effective in removing microplastics (Salva et al., 2025); • Digestate has less applications when compared to compost; • Since July 2022, fertilisers derived from municipal sewage sludge digestate can no longer obtain CE certification, limiting

Solutions	Opportunities	Limitations
	• Partially immobilises heavy metals and can also reduce the amount of pharmaceuticals in sewage sludge (Salva et al., 2025).	their commercialisation within the EU (Salva et al., 2025).
Advanced biochemical products	• Lipid-rich biomass in sludge can serve as a feedstock for biodiesel production (Salva et al., 2025); • PHAs are biodegradable and bio-based, offering a sustainable alternative to conventional fossil-based plastics (EEA, 2020); • New end-use markets for PHA still need to be identified and developed (EC et al., 2022); • Production of volatile fatty acids, can be used as base products for bioplastics, biochemicals and wastewater treatment processes (EEA, 2020); • PHA production from wastewater-derived feedstock is progressing towards higher TRL (TRL 5–6 or above) (ETC BE, 2025).	• Product quality consistency remains a challenge due to variability in sludge composition (EC et al., 2022); • High recovery costs (Kehrein et al., 2020); • Regulatory barriers exist, particularly for registering PHA produced from wastewater as a safe product (Interreg North-West Europe WoW!, 2020).
Pyrolysis and Gasification	• Versatile end products applications (Capodaglio and Callegari, 2023); • Pyrolysis effectively eliminates pathogens, pharmaceuticals, and some microplastics (Salva et al., 2025); • Slag produced during gasification may be repurposed as a secondary raw material in the construction sector (Salva et al., 2025); • Gasification is capable of being energy self-sufficient (Salva et al., 2025); • Biochar can be valorised in various applications such as soil improvement and environmental remediation (Gusiatin et al., 2024); • Syngas can be used for heat, electricity generation, or upgraded into fuels (Neri et al., 2024).	• Both processes require high capital investment and are energy-intensive (Salva et al., 2025); • Pyrolysis yields a carbon-rich solid residue (biochar) with low nutrient availability, limiting its use as a fertiliser (Salva et al., 2025); • The synthesis gas (syngas) produced in gasification requires cleaning before use (Salva et al., 2025); • Sludge must have low moisture content, increasing pre-treatment requirements and operational costs (Neri et al., 2024).
Incineration	• Substantially reduces waste volume and mass, facilitating transport and disposal (Salva et al., 2025; Gusiatin et al., 2024); • Achieves full stabilisation and hygienisation of the sludge, effectively destroying pathogens, pharmaceuticals, and microplastics (Salva et al., 2025; Gusiatin et al., 2024); • Allows for energy recovery in the form of heat and/or electricity (Salva et al., 2025; Gusiatin et al., 2024); • Ash can be repurposed by the cement industry as a substitute for virgin raw materials (Salva et al., 2025).	• Requires energy-intensive drying due to high moisture content in sludge (Neri et al., 2024); • Most nutrients are destroyed during combustion (only phosphorus can be recovered post-incineration) (Salva et al., 2025); • Air emissions include particulate matter, heavy metals, carbon monoxide, nitrogen oxides, sulphur dioxide, and hydrocarbons (Capodaglio and Callegari, 2023); • About 30% of the original solid content remains as ash after incineration (Salva et al., 2025); • Phosphorus-rich ash from co-incineration may be diluted, contaminated with pollutants, or lost in other by-products (Salva et al., 2025).
Metallurgical or carbonisation processes	• Can achieve phosphorus recovery rates above 80% relative to the influent (Sichler et al., 2022).	• Metallurgical processes at industrial scale face technical difficulties, as phosphorus ends up spread across various output streams (Sichler et al., 2022); • The effectiveness and safety of carbonised materials as fertilisers remains uncertain and is under scientific debate (Sichler et al., 2022);

Solutions	Opportunities	Limitations
		• Further pilot and large-scale studies are needed to address knowledge gaps (Scrinzi et al., 2023).
Input material in construction materials	• Offers an alternative to virgin raw materials and fossil fuels in cement production (Xia et al., 2023); • Potential for producing functional concrete for applications with low strength requirements (Xia et al., 2023); • Potential to reduce overall CO_2 emissions in construction materials; • Good insulation performance (Neri et al., 2024).	• Long-term durability and structural performance of sludge-based materials remain under-researched (Xia et al., 2023); • Pre-treatment requirements and high associated costs hinder the development of practical applications (Xia et al., 2023); • Sludge-based materials may exhibit inconsistent quality compared to conventional products (Chang et al., 2020); • Environmental concerns persist, such as heavy metal leaching (Chang et al., 2020).

2.3.3 Available Policy Options

The transition toward a circular economy in sewage sludge management requires both robust policy frameworks and strategic innovation. Across Europe, various countries have already implemented a range of policy instruments aimed at reducing environmental impacts and promoting resource recovery.

Sewage sludge management in the EU relies on a mix of regulatory, economic, and informational instruments. These include legal limits on pollutants and energy targets, taxes and subsidies, liability funds for agricultural reuse, market support for by-products and certification schemes that promote sustainable practices and boost the acceptance and marketability of sludge-based products (Neri et al., 2024).

A potential key area of advancement is the recovery of phosphorus, a critical raw material. Improving phosphorus recovery from sewage sludge is essential to support the direct land application of recovered nutrients, such as monoammonium phosphate and struvite (ECN, 2025). Interlinked with the establishment of EoW criteria, the potential for recovering materials (e.g., nutrients, biodiesel, fertilisers) helps avoid the environmental impacts of manufacturing new products, reduces landfill waste, and contributes to nutrient recovery.

Several national measures go beyond EU minimum requirements to enhance sewage sludge management. Countries like Germany, Switzerland and Austria have introduced comprehensive regulations mandating phosphorus recovery from sewage sludge not suitable for application on land, often with clear targets and deadlines. The promotion of advanced valorisation technologies such as pyrolysis and gasification, along with bans on landfilling untreated sludge or high TOC content (e.g. sludge), not only strengthen public acceptance of sludge reuse and recovered materials but also unlock significant energy recovery potential across the EU. At the same time, these measures contribute to reducing methane emissions from landfills, which remain a major contributor to GHG emissions in waste management. Certification schemes also play an essential role in ensuring the safety and traceability of recovered products, as seen in Sweden (REVAQ), France and Germany, thereby influencing public acceptance of the reuse of treated sewage sludge and the materials recovered from it.

Despite this progress, several gaps remain, requiring targeted policies to further support circularity. These include the creation of strong markets for recovered phosphorus and nitrogen, with legal frameworks that encourage their integration into existing fertiliser regulations. Enhanced recovery of phosphorus in marketable forms such as monoammonium phosphate or struvite can also facilitate its direct application to agricultural land, reducing reliance on virgin resources. The establishment of legal frameworks that incentivise and support innovation in the water utilities sector fosters investment in research, new technologies and solutions. In parallel, the availability of reliable and harmonised data on current sludge management practices across Europe is also essential for informed policymaking. Such harmonisation in legislative aspects and the establishment of incentives would enable competition with mineral sources and livestock manure, as well as generally increase the environmental and economic benefits of sewage sludge treatment. A revision of the SSD to incorporate updated parameters for land application, alongside improved monitoring and control mechanisms for sludge and its derivatives, could help reduce potential environmental and health risks.

In regards of the risk control and environmental safety, several Member States have introduced stricter national measures on sewage sludge use in agriculture, going beyond the requirements of the SSD. These include limitations on the timing and amounts applied (e.g., Italy), lower limits on soil and sludge contaminant (e.g., Germany, Italy, Sweden), and restrictions on application sites such as pastures, horticultural land, or raw crops. By reducing the risks associated with hazardous materials and persistent pollutants, these policies aim to ensure that the application of sludge does not contaminate soil, plants, or water in a diffuse manner. In addition, more effective phosphorus management can be supported by tying application to crop nutrient requirements within balanced fertilisation plans, which will help to protect the environment and recover resources.

This subsection focuses on potential policy options that have been employed or recommended by stakeholders across Europe. These options and their respective impacts are presented in Table 11, grouped according to key objectives: improving treatment, recovery and recycling of resources, legislative harmonisation and incentives, risk control and environmental safety, and enabling market demand.

Table 11. Summary of available policy options for sewage sludge and their impacts

Related policy measures	Potential impacts
1. Improve treatment	
• Certification schemes that assure the quality of the sewage sludge and/or by-products (e.g., Sweden, Germany and Austria) – REVAQ, QLA-System and Kompost & Biogas Verband Österreich (EurEau, 2021a); • Promotion of innovative and efficient technologies for sludge valorisation (e.g. pyrolysis and gasification); • Ban on the landfilling of materials with a TOC content above 5% (e.g. sewage sludge) (Austria); • Prohibition on landfilling untreated sewage sludge (Germany and Sweden) (EEA - Ricardo Energy and Environment, 2021).	• Supports public acceptance of the reuse of treated sewage sludge and the materials recovered from it (EEA, 2022c); • Estimated energy recovery potential from sewage sludge in EU-27: 1,800–3,200 GWh (net heat and electricity) via anaerobic digestion and 250 GWh (net electricity) via incineration of sludge currently landfilled (EEA, 2022c); • Landfilling of sewage sludge is a major source of methane emissions in waste management, contributing 4.1 Mt CH_4 or 27% of total annual EU methane emissions (Egle et al., 2023);
2. Recovery and recycling of resources	
• Comprehensive requirements for the recovery of phosphorus from sewage sludge and sludge incineration ash (e.g., Germany, Switzerland, Austria and Denmark); • Establishment of clear EoW criteria to enable marketing of by-products as fertilisers or materials (e.g., in France, sludge compost used in agriculture can exit waste status by meeting NFU 44-095 standards; traceability is no longer required, and the compost becomes a marketable finished product) (EurEau, 2021a); • Air emissions from sludge drying and co-incineration installations are subject to regulatory control (Germany) (EEA - Ricardo Energy and Environment, 2021).	• Estimated annual nutrient recovery unused potential from sewage sludge in EU-27: 6,900–63,000 tonnes of phosphorus and 12,400–87,500 tonnes of nitrogen (EEA, 2022c); • Struvite recovery from municipal sewage sludge reduces phosphorus and nitrogen emissions to water bodies while improving nutrient use efficiency (Gusiatin et al., 2024); • Biodiesel production from sewage sludge can reduce landfill waste by approximately 20–30%, depending on local sludge availability and processing capacity (D et al., 2025); • Avoided environmental impacts from the substitution of manufactured products, such as animal feed, fertilisers and base chemicals from petrochemical sources. These are dependent on the technology and process; • Production of renewable gases, which can substitute fossil fuels in electricity production, transport fuels, among others.
3. Legislative harmonisation and incentives	
• Revision of parameters for sewage sludge spreading in in the SSD (with a focus on up-to-date parameters, environmental safety and promoting circular practices) (ECN, 2025); • Inclusion of recovered phosphorus in existing fertiliser regulations (Kehrein et al., 2020a); • Improvement of data on current sludge management practices in Europe (to support evidence-based decisions and monitor circularity); • Compensation fund financed by users of sewage sludge in agriculture for damage caused by its agricultural use to people and property; contribution is annual and based on the amount of dry sludge used (Germany) (EEA - Ricardo Energy and Environment, 2021); • Adopt legal frameworks that support innovation, allowing water utilities to invest in research and apply new technologies and solutions (EurEau, 2023); • Set a minimum share of recovered P and N in all EU mineral fertilisers (EurEau, 2021b). • Enable market demand: legislation to create strong markets and demand for recovered phosphorus and nitrogen (Interreg North-West Europe WoW!, 2020)	• Enables the recovered nutrients to compete with mineral sources and livestock manure. • General increase or improvement of the environmental and economic benefits from sewage sludge treatment.

Related policy measures	Potential impacts
4. Risk control and environmental safety	

• National soil limit values are established; if exceeded, sewage sludge application is prohibited (Germany) (EEA - Ricardo Energy and Environment, 2021)
• Stricter contaminant limit values for sludge applied to agricultural land, e.g. (EEA - Ricardo Energy and Environment, 2021)
  o Germany: lower metal limits than those in the SSD;
  o Italy: stricter limits for Hg; additional limits for As, Cr, PCB, NP/NPE, PAH, and PCDD/F (not regulated under the SSD);
• Sludge stabilization treatment and application limits defined, including a maximum quantity that can be applied over a three-year period (Italy) (EEA - Ricardo Energy and Environment, 2021);
• Ban on sludge application on flooded soil, land for pasture or animal feed (five weeks before harvest), horticulture, fruit growing, or during crop growth (Italy) (EEA - Ricardo Energy and Environment, 2021);
• Use of sewage sludge is prohibited on land used for animal feed and for crops in direct contact with soil that are normally consumed raw (Sweden) (EEA - Ricardo Energy and Environment, 2021);
• Stricter metal limit values for sewage sludge used in agriculture than those set by the EU (Sweden) (EEA - Ricardo Energy and Environment, 2021).
	• Preventing contamination of sewage by persistent, hazardous pollutants enables safe land application of sewage sludge without risk of diffuse pollution to soil, plants, and water (EEA, 2022c).
	• Sewage sludge applied to fields based on crop nutrient requirements and within a balanced fertilisation plan to ensure optimal phosphorus use (European Sustainable Phosphorus Platform, n.d.-c).

A strategy to increase circularity in this waste stream can begin with the prevention of sludge production; however, this requires upgrades to WWTP, significant investment and emerging technologies. Reducing the presence of contaminants in sewage sludge appears to be a significant factor, as it opens a range of opportunities for the valorisation of this waste stream. This factor also helps change public opinion on its reuse and increases the viability of its valorisation through agricultural use and composting. Sewage sludge that cannot be valorised through options higher in the waste hierarchy, due to several factors (e.g., contamination), can still be valorised through incineration, with phosphorus recovery from the sewage sludge ash. Factors that may also help decrease the lost potential include the establishment of incentives for material recovery (e.g., nutrients), competitive markets, a ban on landfilling of sewage sludge, certification schemes and stricter legislation regarding the presence of contaminants in valorised sewage sludge.


Agricultural waste

2.4 Agricultural Waste

KEY MESSAGES

- An additional 75.3 Mt of agricultural waste, including animal faeces, urine and manure, as well as crop residues, could potentially be recovered.
- Definitions of agricultural waste vary across the literature. For this analysis, only animal faeces, urine and manure (14.4 Mt), which are published by Eurostat, and crop residues (286.4 Mt) are considered, with these two streams reported separately.
- Data on crop residues are not covered by waste statistics, as they are not classified as waste but rather as by-products of agricultural production. Their quantities are typically estimated using theoretical models, whereas data on animal faeces, urine, and manure are reported by Member States to Eurostat as part of the Waste Statistics.
- A considerable fraction of crop residues should remain in the soil to maintain its quality, estimated at 181.6 Mt (63% of total generation). The remaining fraction is primarily used for heat, power and biogas production, though circular interventions could support their use in material feedstock, animal feed and bedding, mushroom cultivation, and horticultural applications.
- There is a lack of data on residue collection practices and on the current uses of crop residues.
- The animal faeces, urine and manure stream is predominantly directed towards recycling processes such as anaerobic digestion and composting, amounting to approximately 12.6 Mt (87% of total generation). Only a limited fraction (4%) is estimated to be sent to landfill and incineration (without energy recovery).

2.4.1 Mapping of agricultural waste and by-products flows in Europe

To assess the potential for enhancing the circularity of agricultural waste, a comprehensive overview of the current state of agricultural waste management in the EU was established. The analysis of agricultural waste focuses on animal faeces, urine and manure and crop residues, as these are the two waste streams from agricultural activities that are currently the most consistently quantified. Waste streams originating from the agricultural sector, such as agricultural plastics and pesticides, are excluded from the scope of this analysis, as they are not bio-based waste. A key element of this assessment is the estimation of the quantities of agricultural crop residues that remain unrecovered. The analysis of the available data is presented in Annex 4 and summarised in *Table 12* for animal faeces, urine and manure, and in *Table 13* for crop residues.

Table 12. Data for mapping of animal faeces, urine and manure flows in EU-27 (wet basis)

	Eurostat – Waste Generation: 2022[a]	Eurostat – Waste Treatment: 2022[b]
Generation (Mt)	14.43	-
Valorisation (Mt)	-	13.90
Recycling	-	12.56
Energy recovery	-	1.34
Landfill (Mt)	-	0.02
Incineration (Mt)	-	0.47
Other (Mt)[c]	-	0.04

Notes: ([a]) It was not possible to obtain a value for generation from agriculture alone, so the figure for the combined sectors — agriculture, forestry and fishing — was assumed

([b]) The quantities reported by Eurostat were not used directly, as the treatment data cover all economic activities and households. Instead, the treatment shares provided by Eurostat for all economic activities (e.g. 87% recycling, 9% energy recovery, etc.) were applied to the generated amount of manure.

([c]) Includes disposal operations D2-D4, D6-D7

Sources: Eurostat, 2025p. Available online

Eurostat, 2025q. Available online

Table 13. Data for mapping of crop residues flows in EU-27 (dry basis)

Source: ICCT, 2021

	ICCT – 2020
Generation (Mt)	286.37
Valorisation (Mt)	30.09
Heat, power and biogas	8.48
Other uses[a]	21.61
Retained in soil (Mt)	256.28
Need for soil quality	181.55
Potentially available for other uses[b]	74.73

Notes: ([a]) Includes livestock, mushrooms and horticulture

([b]) The ICCT model assumes this quantity equals total waste generated minus the amounts recovered and left on the soil for soil quality, representing the lost potential of the stream

Sources: ICCT,2021. Available online

It is important to note that plastic film and biodegradable film mulches have not been included in the analysis, despite being discussed across EU in terms of agronomic value and environmental risks.

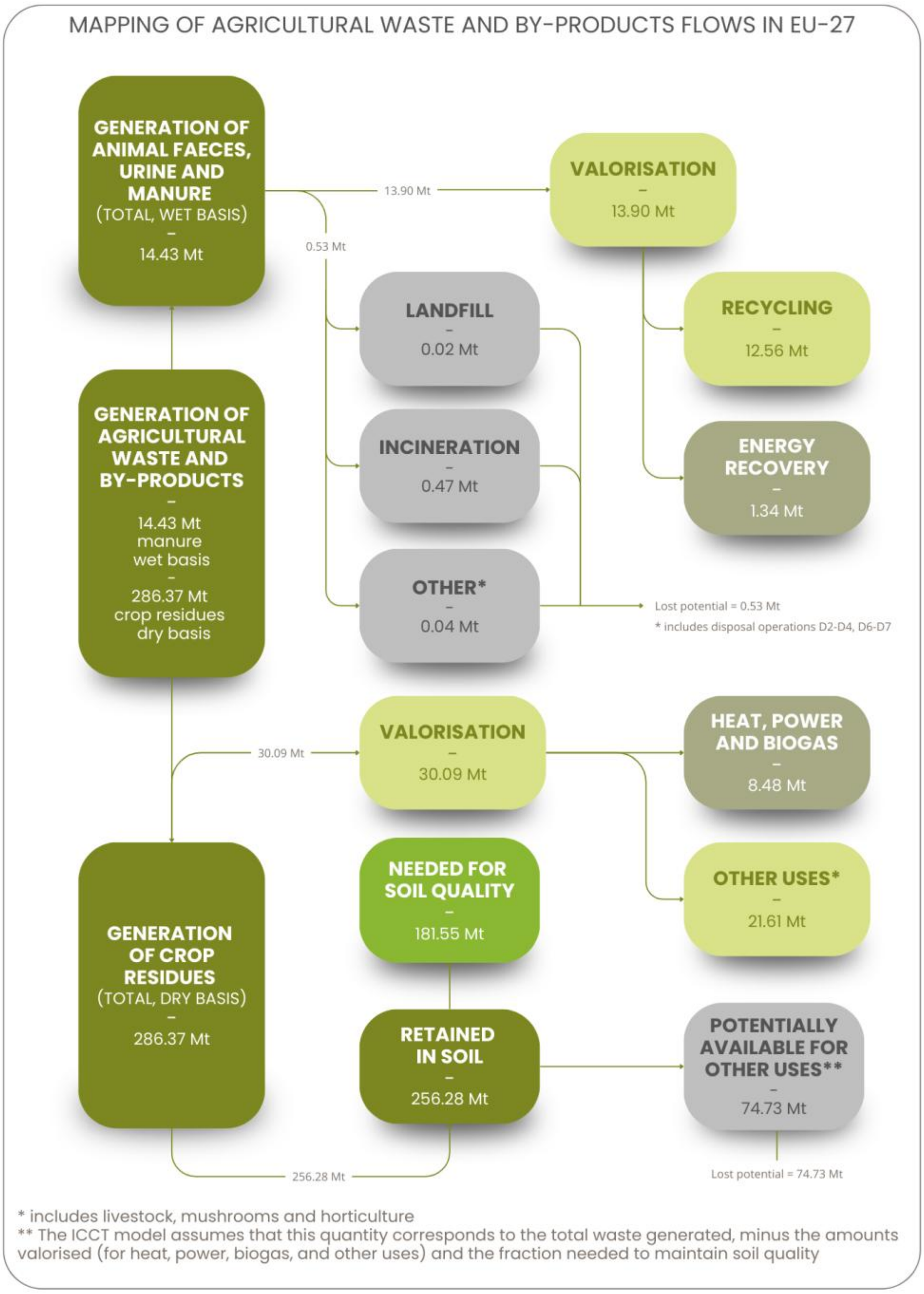

Figure 4. Mapping of flows of animal faeces, urine and manure (wet basis) and crop residues (dry matter) in the EU
Source: Eurostat, 2025p; Eurostat, 2025q; ICCT, 2021

Figure 4 provides a consolidated mapping of the best available information, starting with the generation of agricultural waste and by-products. The mapping distinguishes between animal faeces, urine and manure, and crop residues. The flow diagram for animal faeces, urine and manure is based on Eurostat data for 2022 and is presented on a wet-weight basis, while crop residues are based on the International Council on Clean Transportation (ICCT) data for 2020 and are presented on a dry-weight basis (Eurostat, 2025p; Eurostat, 2025q;

ICCT, 2021). The use of different bases reflects the inherent difficulty of converting both streams to a common basis, as this would depend on the specific material type. Notably, the former - animal faeces, urine and manure - are reported by Member States, whereas the latter - crop residues - are estimated using an empirical model.

A total of 14.4 Mt (wet basis) of animal faeces, urine and manure, and 286.4 Mt (dry basis) of crop residues were generated in the EU.

The quantity considered for the generation of animal faeces, urine and manure was that reported by Eurostat (2025p) for the agriculture, forestry and fishing sectors. It was not possible to obtain a value for generation solely from agriculture, so the figure for this combined set of sectors was assumed, as it represents the best available data. Regarding the treatment of this stream, the quantities reported by Eurostat were not used directly in the flow diagram, as Eurostat provides treatment data covering all economic activities and households. Instead, treatment shares reported by Eurostat (e.g. 87% recycling, 9% energy recovery, etc.) were applied to the generated amount of manure in order to obtain the treated quantities shown in the diagram. On this basis, a lost potential of 0.5 Mt was identified.

For crop residues, the total generation in the EU was assumed to be 286.4 Mt (dry weight basis), as reported by the ICCT. Of this amount, 30.1 Mt (11%) were directed to valorisation and 181.6 Mt (63%) were retained in the soil to maintain soil quality. On this basis, a lost potential of 74.7 Mt (26%) was identified.

The ICCT defines 'sustainable availability' as the total generation of agricultural crop residues minus the quantities already used for other purposes (heat, power, biogas and other uses) and the amounts that should remain on the soil to preserve its quality (ICCT, 2021; ICCT, 2016). In the EU, this corresponds to 74.7 Mt. Sustainable availability is understood as the fraction that is potentially available for collection and could be directed to recovery without harming soil quality, but which is currently estimated not to be collected. In this analysis, this fraction is considered the lost potential. The ICCT does not specify its fate, but it is assumed to remain on the soil as lost potential.

2.4.2 Challenges and opportunities to enhance circularity in agricultural waste

Based on the identified technical solutions aimed at maximising the potential of agricultural waste and crop residues, presented in Annex 4, Table 14 presents the main challenges, as well as the advantages and opportunities associated with making the use of agricultural waste and by-products more circular. It should be noted that all the technical solutions presented are applicable to crop residues, whereas for manure the applicable technical solutions are composting, anaerobic digestion, fertiliser production and biogas production.

This section seeks to identify the key barriers that need to be overcome and the strategic benefits associated with each solution to enhance the sustainable management and valorisation of agricultural waste and by-products.

Toxic risks

One of the challenges associated with the treatment of agricultural waste and by-products lies in the potential toxicity risks. In particular, when crop residues are **used for animal feed**, such materials may **introduce toxicity risks, for example due to the presence of insecticides or pesticides** (Koul et al., 2022). Similarly, manure applied as fertiliser may also pose toxicity risks if antibiotics were included in the animal diet, as these compounds can persist in the digestate (Köninger et al., 2021).

High costs and availability of finance

High costs are also reported as one of the main barriers to several treatment techniques. The **production of biomaterials, such as bioplastics, remains largely constrained by the high costs involved**, primarily associated with the use of pure microbial cultures. For biomaterials, an additional barrier is the fact that there are **market instruments that favour biogas production or direct energy recovery in detriment of other recovery operations** (Joó et al., 2020). As in other waste streams, there are competing objectives and it is necessary to carefully assess the comparative environmental benefits. Moreover, both **pyrolysis and gasification require substantial initial investment and entail high operational costs**, making them economically demanding (Koul et al., 2022; Sadeghpour and Afshar, 2024).

Gases and odours

The generation of gases and odours associated with some treatment processes is also a commonly reported challenge. In **composting, issues such as dust and odours, as well as GHG emissions** during the process, are frequently highlighted (Koul et al., 2022; Ufitikirezi et al., 2024). In **anaerobic digestion, methane emissions during digestate storage**, linked to incomplete degradation within the biogas facility, represent an additional challenge (Fangueiro et al., 2017).

Technical limitations

Technical limitations can also account for some of the challenges faced in implementing these solutions. In **biofuel production, for instance, several technical constraints remain** (Ufitikirezi et al., 2024). **Anaerobic digestion** is challenged by **limited efficiency due to the lignocellulosic composition** of certain agricultural crop residues (Lackner and Besharati, 2025). **Gasification** is constrained by the need to operate under very **high temperatures**

and pressures, which in turn increase operational costs (Ufitikirezi et al., 2024). **Soil mulching** also presents certain drawbacks**: in poorly drained soils, it may lead to excess moisture and reduced oxygen availability in the root zone, thereby favouring the proliferation of insects and pests**. Moreover, organic mulches such as hay and straw may contain seeds that germinate as weeds (Koul et al., 2022).

Unstable supply of materials

The unstable supply of raw materials can also pose an additional challenge for gasification, which requires a **consistent and sufficient flow of raw materials** to ensure proper operation (Ufitikirezi et al., 2024).

Table 14. Opportunities and their limitations for each technical solution considered

Solutions	Opportunities	Limitations
Prevention	• Highest position in the waste hierarchy and helps improve material efficiency.	• Growing production due to rising global food demand may lead to more waste from agricultural production (Soares et al., 2025).
Biomaterials (bioplastics)	• Strong potential as substitutes for conventional plastics reducing carbon intensity and creating local jobs (Joó et al., 2020); • Emerging technologies using mixed microbial cultures indicate rapid market growth (Joó et al., 2020); • Can be integrated with other valorisation routes (e.g., biofertilisers, bioenergy), improving cost- and material-effectiveness (Joó et al., 2020); • Investment in R&D and market analysis is key to identifying commercial niches and scaling production (Joó et al., 2020).	• High production costs, largely due to the need for pure microbial cultures (Joó et al., 2020); • Policy and market barriers, including subsidies favouring biogas production (Joó et al., 2020); • Limited suitability for biomaterial production (Joó et al., 2020).
Animal feed and bedding	• Provides an affordable and nutritious feed source (Lackner and Besharati, 2025); • Reduces reliance on cereals suitable for human consumption (Lackner and Besharati, 2025); • Lowers waste management costs (Lackner and Besharati, 2025); • Contributes to overall agricultural waste reduction (Koul et al., 2022).	• Risk of contamination in feed due to toxins from crops (naturally occurring or from pesticides/herbicides) and from moulds or fungi, which can compromise animal health and safety (Koul et al., 2022).
Composting	• Compost improves soil organic matter and fertility, boosting agricultural productivity and reducing the need for chemical fertilisers (Lackner and Besharati, 2025); • Compost enhances crop quantity and quality and water-use efficiency (Lackner and Besharati, 2025); • Reduces waste volume, eliminates pathogens and weed seeds, lowering waste management costs (Koul et al., 2022).	• Composting can release significant GHG, reducing its environmental benefits; strict process standards are required to ensure high-quality products and prevent harm (Ufitikirezi et al., 2024).
Biofuels (bioethanol)	• Renewable alternative to fossil fuels, reducing dependency and waste (Lackner and Besharati, 2025);	• Should only be used when other options have been exhausted; • RED II limits use of feedstocks from food and feed crops (OECD/FAO, 2025);

Solutions	Opportunities	Limitations
	• Produces fewer GHG emissions compared to other biofuels (e.g., biomethane, biodiesel) (Ali et al., 2022).	• Cannot use commonly used yeasts, recombinant microorganism instability, and techno-economic limitations (Ufitikirezi et al., 2024).
Anaerobic digestion (biogas)	• Can increase profitability and cost-effectiveness (Joó et al., 2020); • Can be combined with other valorisation routes (biorefinery, composting, biofertilisers) (Joó et al., 2020); • Government support through subsidies for bioenergy and biogas as part of the energy transition (Joó et al., 2020); • Abatement of odours (Fangueiro et al., 2017); • Stabilisation of manure and co-substrates (Fangueiro et al., 2017); • Reduction of the pathogens (Fangueiro et al., 2017).	• Lignocellulosic composition of agricultural waste (Lackner and Besharati, 2025); • Risks related to digestate: antibiotic-resistant genes (if manure contains antibiotics) (Köninger et al., 2021); • Biogas storage and quality issues, including H_2S content and methane losses during storage or through digester systems (Ufitikirezi et al., 2024; Fangueiro et al., 2017).
Soil mulching	• Contributes to mitigating the effects of solar radiation, reduces water evaporation, and increases soil moisture retention (Lackner and Besharati, 2025); • Prevents erosion and protects plant roots from extreme temperatures (Lackner and Besharati, 2025); • Effective in preventing surface soil washout during heavy rainfall (Lackner and Besharati, 2025); • Contributes with nutrients to the soil (Koul et al., 2022); • Low-cost valorisation route (Joó et al., 2020).	• Can keep poorly drained soils too moist, restrict oxygen in the root zone, and create breeding grounds for insects and pests (Koul et al., 2022); • Organic mulches (e.g., hay, straw) may contain seeds that can become weeds (Koul et al., 2022).
Gasification	• More efficient conversion of biomass and waste into (electrical) energy compared to traditional combustion (Lackner and Besharati, 2025); • Reduced emissions and the possibility to use solid byproducts in multiple ways (Lackner and Besharati, 2025); • High thermal efficiency and accurate combustion control (Ufitikirezi et al., 2024); • Versatile uses of the produced syngas (Ufitikirezi et al., 2024).	• Requires high-temperature and high-pressure conditions, increasing operational costs and necessitating advanced research for cost-effectiveness (Ufitikirezi et al., 2024); • Needs a consistent supply of suitable biomass to ensure stable operation (Ufitikirezi et al., 2024); • Multi-stage process with formation of tars and char (Ufitikirezi et al., 2024); • High initial investment and operating expenses, coupled with limited financial incentives, challenge economic viability and widespread adoption (Sadeghpour and Afshar, 2024).
Pyrolysis (biochar)	• Overall, pyrolysis offers high efficiency, operational flexibility, and the production of high-quality fuel (Ufitikirezi et al., 2024); • Pyrolysis produces biochar, which can reduce carbon dioxide levels in the atmosphere, and its incorporation into soil improves fertility and water retention (Lackner and Besharati, 2025); • The resulting biochar is effective for carbon sequestration, soil enhancement and water purification (Lackner and Besharati, 2025); • Biochar's high carbon content and large surface area make it an efficient adsorbent for contaminants, including in wastewater (Lackner and Besharati, 2025).	• High initial investment and operating costs, making economic viability a concern (Koul et al., 2022); • Complex process requiring high temperatures and pressures, as well as advanced research to improve cost-effectiveness (Ufitikirezi et al., 2024); • Behaviour of biochar varies with different feedstocks, affecting predictability (Koul et al., 2022); • Requires air purification systems to treat flue gases (Koul et al., 2022); • Produced ashes may contain high levels of heavy metals (Koul et al., 2022); • Lack of reliable revenue streams and limited financial incentives hinder widespread adoption (Sadeghpour and Afshar, 2024).
Mushroom production	• Cost-effective farming (Koul et al., 2022)	• Lack of available market and promotion in local level (Koul et al., 2022)

2.4.3 Available Policy Options

Overcoming the challenges identified in the previous subsection requires coordinated policy reform, improvement of collection to ensure more volume and quality, investment in innovation, and the development of robust markets for circular bio-based products.

Legislation has been identified as a key factor supporting the implementation of manure treatment processes; however, the strictness of regulations and the lack of knowledge have also been found to hinder their adoption. This highlights the importance of disseminating information and raising awareness for these issues (Köninger et al., 2021). The economic viability remains the central problem for adopting new technologies, due to the lack of reliable revenue streams and sufficient financial incentives, as well as substantial initial investments and operating costs. The implementation of new policy frameworks can facilitate the integration of new technologies for manure processing and the utilisation of manure and manure-based products. A holistic approach that merges new technologies, farmer incentives, supportive policies, market integration of manure products and advances in research and education can shift the perception of manure from a potential pollutant to a valuable resource (Sadeghpour and Afshar, 2024).

Regarding the prevention of agricultural waste, the recommended policies focus on promoting advanced technologies, improving storage, along with aligning production to demand. These policies would help cut crop losses and surplus while reducing soil degradation, water pollution and GHG emissions, including those from manure.

Policies such as standardising and monitoring manure quality, reducing livestock density and improving application practices, together with farmer education and awareness, help to reduce the presence of contaminants in the manure, such as microplastics, heavy metals and antibiotic resistance genes, thereby enhancing its overall quality. Equally important, informed farmers supported by favourable policies are more likely to adopt practices that benefit both the environment and the agricultural outcomes.

A quantification of the actual availability of waste for competitive uses is an essential step to start the improvement of agricultural waste and by-products treatment. Additionally, financial incentives for biogas production, certification schemes and manure market approaches foster more sustainable manure management. The implementation of these measures can reduce environmental risks, improve nutrient efficiency and lower GHG emissions through practices like anaerobic digestion and composting.

Concerning new technologies, further research is needed in terms of precision agriculture, automated harvesting systems, turning agricultural waste into high-value products and the feasibility and large-scale potential of producing bioenergy from agricultural waste.

Subsidies and government support are also identified as key policies for encouraging the adoption of new technologies at farm level.

This subsection focuses on potential policy options that have been employed or recommended by stakeholders across Europe. These options and their respective impacts are presented in *Table 15*, and are grouped by key objectives, namely prevention of agricultural waste and by-products, increase quantity and quality of agricultural waste, improve agricultural waste treatment and foster new technologies.

Table 15. Summary of available policy options for agricultural waste and by-products and their impacts

Related policy measures	Potential impacts
1. Prevention of agricultural waste and by-products	
• Advanced harvesting technologies (e.g., GPS, drones, IoT) and other digital agricultural technologies (e.g., crop pest infestation monitoring, aerial imaging technology, wireless sensors that warn crop-damaging weather conditions) to minimise crop losses (Lackner and Besharati, 2025; Benyam et al., 2021); • Enhanced storage solutions (e.g., controlled atmosphere, hermetic bags, smart silos) to extend product shelf life (Lackner and Besharati, 2025); • Incentives such as subsidies and tax benefits for adopting waste-reducing technologies and practices (Lackner and Besharati, 2025); • Aligning production plans and market demand regarding quantity, quality, and delivery (Perdana et al., 2023).	• Reduction of environmental impacts in waste management, including soil degradation, water pollution, and GHG emissions (Yan, 2025); • Advanced harvesting technologies reduce crop losses from overripeness and spoilage and improve efficiency and timing, lowering waste from manual errors (Lackner and Besharati, 2025); • Manure contributes with approximately 7% to the methane and nitrous oxide emissions from agriculture (Pires et al., 2025); • Aligning production with market demand helps minimize surplus and unnecessary products (Perdana et al., 2023).
2. Increase quality of agricultural waste and by-products	
• Harmonised standardisation of manure from highest to lowest quality according to its origin, treatment process, and expected effects on beneficial soil organisms (Köninger et al., 2021); • Identify the ingredients in manure (e.g., Austria classifies compost depending on the input materials, including heavy metals) (Köninger et al., 2021); • Reducing the density of animal stocks, as well as better monitoring of unprocessed manure and better manure application practices (e.g., similar to those applied to food composition and fertiliser formulations) impact the quality of the manure (Köninger et al., 2021); • Education and raising awareness to inform farmers about manure processing benefits, promote manure-based fertilisers, and support best practices in utilisation (Sadeghpour and Afshar, 2024).	• Mindful application of manure by farmers helps reduce the negative effects of low-quality manure while maximising the benefits of high-quality manure (Köninger et al., 2021); • Microplastics and antibiotic resistance genes interact to create a considerable combined source of contamination in livestock manure composting systems (Tang et al., 2025); • A smaller number of farmed animals results in lower levels of antibiotics and heavy metals in manure, which is a key factor in reducing negative environmental impacts, including those on soil biodiversity (Köninger et al., 2021); • Identifying the ingredients in manure can improve monitoring of the effects of applying specific manure types in various agricultural conditions (Köninger et al., 2021); • Farmers who are familiar and supported by favourable policies are more likely to adopt sustainable practices that contribute to wider environmental and agricultural objectives (Sadeghpour and Afshar, 2024).
3. Improve treatment of agricultural waste and by-products	
• Quantify the actual availability of waste for competitive uses; • Financial support for the use of manure for biogas consumption (e.g., Finland) (OECD, 2021); • Certification or eco-labels for products from farms applying sustainable manure management practice (Sadeghpour and Afshar, 2024);	• Integrated manure management can cut environmental risks by up to 65% and double nutrient efficiency (Köninger et al., 2021); • Several manure management strategies (e.g., anaerobic digestion, composting, solid–liquid separation, application of chemical additives) can contribute to reducing GHG emissions (Pires et al., 2025);

Related policy measures	Potential impacts
• Manure market approach: enable exports, promote sustainable practices abroad, and improve transparency on opportunities for manure use in food production (Netherlands) (Ministerie van Landbouw, Visserij, Voedselzekerhei den, 2025a; 2025b); Use of biodegradable raffia on the farms (e.g., Spain) (Duque-Acevedo et al., 2022).	• Production of renewable energy through anaerobic digestion of manure represents an opportunity to reduce methane emission from livestock (EC, 2020); • Effective treatment of pollutants and replacement of non-renewable energy sources (Yan, 2025); • The proprerties of the soil (e.g., aeration, density, porosity, pH, electrical conductivity, water retention capacity) can be improved by the structure and composition of the manure (Goldan et al., 2023); • Using biodegradable raffia instead of conventional types enables easier treatment and composting, or use as green manure, of agricultural waste (Duque-Acevedo et al., 2022).
4. Foster novel technologies	
• Provide subsidies and government support to encourage the adoption and installation of advanced farm technologies (Sadeghpour and Afshar, 2024); • Optimisation of technologies such as precision agriculture and automated harvesting systems, alternative options for upcycling agricultural waste into high-value products (e.g., bioplastics, natural dyes, fibres), and the economic viability and scalability of bioenergy production from agricultural waste remain knowledge gaps that require further research (Lackner and Besharati, 2025); • The CORDIS database includes several projects related to manure, bio-based waste flows and advanced treatment options. Projects like MANUREFINERY, NUTRITIVE, ReLeaf and NENUPHAR aim to develop bio-based fertilisers and feed, decision-making tool for sustainable manure management, and new methods, governance models, incentives, and technologies for nutrient recovery.	• Tangible impacts of R&D activities are difficult to ascertain, especially when restricting to a specific area such as circular bioeconomy. Despite a significant number of studies on the macroeconomic impacts of public R&D spending, these do not include the level of detail to provide insight.

Other biobased streams

2.5 Other bio-based streams

2.5.1 Paper and cardboard

KEY MESSAGES

- In 2022, in the EU-27, 43.9 million tonnes of paper and cardboard waste were generated from separate collection, with packaging waste making up 34 million tonnes (77%) and achieving a high recycling rate of 83%.
- In addition, 12.8 million tonnes of paper and cardboard currently end up in mixed waste, representing an untapped recycling potential.
- Paper and cardboard have strong recycling potential but face quality and material challenges: fibre degradation, coatings, and additives limit recyclability and compostability.
- Increasing complexity of packaging formats (e.g., multilayers, coatings, additives) limits efficient recycling and separation of paper and cardboard waste.
- Improved separate collection and sorting of paper and cardboard, especially composite and contaminated packaging, is essential to ensure a high-quality recycling input.

Packaging waste represents a significant share of paper and cardboard waste with high recycling rate

In 2022, the generation of paper and cardboard waste in the EU-27 reached 43.9 million tonnes, with households, services, manufacturing and water supply; sewerage, waste management and remediation activities accounting for 36.5%, 26.2%, 19.1% and 14.8%, respectively (Eurostat, 2025u). The paper and cardboard waste category includes paper and cardboard from sorting and separate collection, and excludes mechanically separated rejects from pulping of waste paper and cardboard, wastes from sorting of paper and cardboard destined for recycling and fibre, filler and coating sludges from pulp, paper and cardboard production (Eurostat, 2010). However, a significant fraction of paper and cardboard waste is present in mixed municipal solid waste. Based on the reported capture rates for recyclables in the EEA early warning assessments related to the 2025 targets for municipal waste and packaging waste (EEA, 2022d) for each Member State, an additional 12.8 million tonnes of paper and cardboard waste end up in mixed municipal waste, representing a relevant fraction with untapped circularity potential that could be separately collected and sent to recycling.

Packaging waste in particular represents a significant share of the paper and cardboard waste generation, reaching 34 million tonnes in 2022 in the EU-27, with a recycling rate of 83.2 % (Eurostat, 2025w, 2025x).

Regarding treatment, the vast majority of treated separately collected waste is recycled, with only around 1% sent to energy recovery and less than 1% sent to landfill (Eurostat, 2025v).

Paper and cardboard waste has a high recycling potential

Paper and cardboard can be recycled into resources for new products or composted through organic recycling. In accordance with EN13432, the organic recycling of food waste can occur together with paper packaging when it is certified compostable and degradable under standard controlled conditions. Due to chemicals and additives often added to packaging materials, not all materials are biodegradable or compostable, limiting their organic recycling properties (Sobhani and Palanisami, 2024).

Paper and cardboard have a high recycling potential (78-96%), and in theory these fibres can be recycled up to eight times, because the physical properties of recycled paper do not have the same quality as the paper produced from primary fibres, causing the fibres to gradually become weaker and shorter (Burggräf et al., 2023; European Environmental Bureau, 2023). On average, in 2021 in Europe, paper fibres were used 3.5 times, a value higher than the global average (2.5 times). When compared to the use of virgin fibres, the recovery of paper offers advantages such as lower costs, higher strength, lower wood pulp consumption, and the use of only a quarter of the energy required for pulp production (European Environmental Bureau, 2023).

The processes used for paper recycling have been applied for many years, relying on methods such as mechanical pulping, chemical pulping and deinking (Levin et al., 2025). It is estimated that the production of recycled paper consumes 50% less water and reduces air pollution by 74% compared to virgin paper production (European Environmental Bureau, 2023). However, these processes continue to present certain limitations, particularly with respect to water consumption, environmental impact and energy demand (Levin et al., 2025).

One of the limitations of the paper recycling industry is the complexity of existing packaging formats. For example, the development of new coatings and bio-based foils impose limitations on standard paper recycling mills, as there is a maximum limit of “non-pulpable” materials (between 3-10%) that recycling processes can tolerate. Multilayer packaging is very common in the food and beverage sector, as the use of paper alone is often insufficient due to its poor barrier properties, low heat sealability, and limited strength. For this reason, plastics, foils, and chemicals are used in the production of paper-based packaging to guarantee appropriate functional properties, which can even result in some of this packaging being classified as plastic products (European Environmental Bureau, 2023). The existence of different layers requires distinct recycling processes, which poses challenges to the circularity of these materials in three domains: material separation, contamination and economic viability (Ciawi et al., 2025). High-quality recycling and the safe production of food and beverage packaging material are much more limited compared to other materials (e.g., glass and metal food packaging), due to the requirements for separation into single materials and homogeneous waste streams (European Environmental Bureau, 2023).

The co-digestion of food waste and paper waste has been proven to improve the methane yield of anaerobic digestion. Paper packaging and tissues present in this waste stream are often contaminated, meaning they are not recyclable, and co-digestion through anaerobic digestion can enhance the nutrient balance of the two waste streams (Xu et al., 2022). Nevertheless, co-digestion should only be regarded as a secondary or complementary option, rather than a priority pathway for managing this waste stream, due to the limited recovery of material value. Paper and cardboard waste, if certified as compostable and degradable under standard controlled conditions in line with EN13432 (2000), can be added to the organic recycling stream of food waste. Industrial composting offers advantages for the paper and cardboard waste stream, as it contributes to lower energy consumption and reduced GHG emissions. However, the mixture of chemicals present in paper waste can make these materials unrecoverable and devalue the organic recycling stream (Sobhani and Palanisami, 2024).

Improving the circularity of paper and cardboard waste

It is also possible to integrate paper and cardboard waste into alternative recycling pathways, such as those for bio-based plastics, since cellulose-based bioplastic can be produced from common waste paper sources (e.g. printing paper, newspaper, straw paper and roll paper) (Barua, et al., 2025; Liu et al., 2023).

From a design for recyclability perspective, according to the Packaging and Packaging Waste Regulation (PPWR), all parts of packaging must be repurposed after use in an economically viable way, without valuable material loss. This means that all packaging must be recyclable by 2030 (EU, 2024). Minimising substances of concern in packaging is one of rules particularly relevant for this waste stream, as interfering substances in packaging materials (e.g. glue, dispersion coatings, UV inks and materials containing chlorine) hinder the recycling process (EC, 2025a; KIDV, 2020).

A well-managed collection system is considered a fundamental step towards improving the quantity and quality of paper and cardboard waste. In this context, paper and cardboard waste should be collected separately from other recyclables and, in particular, the separate collection and sorting of composite and contaminated food packaging materials should also be improved, as they contain valuable materials for recycling. By reducing contamination in this waste stream and enhancing sorting processes, a consistent and high-quality input for recycling can be ensured. In return, this could incentivise innovation and investment in recycling technologies (Cepi, 2025; European Environmental Bureau, 2023).

2.5.2 Textiles

KEY MESSAGES

- EU textile recycling capacity is low, with current high-quality fibre-to-fibre recycling estimated at around (1%).
- Textile fibre blends are a major barrier to recyclability due to complex separation and diverse material properties.
- Fully fibre-to-fibre recycling remains hindered by technical, logistical, economic and regulatory challenges, even under optimal conditions.
- Open-loop (down-cycling) pathways (e.g., integration into paper production, insulation, automotive applications) for textile waste provide favourable alternatives to landfill and incineration.
- Improving sorting systems is crucial, especially with mandatory separate collection; however, increased collection does not automatically raise recycling rates.
- In 2022, under 15% of the textile waste was separately collected, with approximately 12% being sent to landfill and 14% sent to incineration (with and without energy recovery) in EU-27 - representing a key untapped potential for increasing the circularity of textile.

Bio-based textiles represent a small but growing share of the EU market

Bio-based textiles are defined as textiles produced from "renewable biomass sources such as wood or fibre crops, but also algae, fungi, agricultural waste or end-of-life textiles that can be converted into fibres for textile applications". Bio-based fibres are divided into three main types: natural (e.g., cotton, wool, flax, hemp), semi-synthetic (e.g., viscose) and synthetic fibres (e.g., bio-PET, PLA), each with different properties, applications, value chains, and specific challenges and opportunities (JRC, 2025b).

In 2023, the fossil-based synthetic textile fibre production reached 67% of the global market in 2023. Despite the opportunities to increase the share of bio-based textiles in the market, economic constraints and biomass availability do not allow to reach fossil-based fibre production volumes (JRC, 2025c).

Recycling capacity of textile waste in Europe sits at 1.25-1.3 Mt per year

A significant proportion of textile waste generated by households still ends up in mixed municipal waste, which results in high levels of contamination in this waste stream (Zero Waste Europe, 2024), as a result of the low average capture rate of textile waste in Europe. According to the EEA (2025), the average capture rate of textile waste in the EU in 2022 was just under 15%, and approximately 12% of textile waste was sent to landfill and 14% was sent to incineration (with and without energy recovery).

Estimates indicate that there are 17 textile recycling facilities in the EU, with a total capacity to recycle between 1.25 to 1.3 million tonnes of fibres per year, of which around 1 million tonnes are processes through mechanical recycling and 250 thousand tonnes through chemical recycling (EEA, 2025b). However, high-quality recycling of waste textiles is currently still a challenge in the sector, with fibre-to-fibre recycling accounting for only 1% of recycled textile waste. Even under optimal conditions, in Europe, the maximum fibre-to-fibre recycling rate is estimated to reach only 18-26% (EEA, 2023c; Harter et al., 2025).

The recycling of textile waste usually involves a combination of two or more processes and can be classified as mechanical or chemical recycling (Juanga-Labayen et al., 2022; Ribul et al., 2021).

Mechanical recycling, a well-established method for textile recycling, involves consecutive physical and mechanical actions without altering the chemical composition of textiles (Zero Waste Europe, 2024; Ribul et al., 2021). This process can be applied to any type of textile waste and material, but to achieve high quantity and quality sorting is required, as this process cannot separate blends or filter out dyes. Fabrics should be first sorted into different fibre blends to make the feedstock input the most homogeneous possible. It also affects the quality of the fibre (i.e., reduces the length and strength), which limits their use in other processes (JRC, 2023a; Zero Waste Europe, 2024). Chemical recycling modifies the chemical composition of textile waste to different degrees (polymer or monomer level) and depending on the type of chemical recycling (i.e., for natural fibres, for synthetic fibre or for textiles with fibre mixtures), it can process textiles of a mixed fibre composition. Nevertheless, the use in fibre blends is limited (JRC, 2023a; Zero Waste Europe, 2024; Ribul et al., 2021).

When comparing the two processes, mechanical recycling is a simple, scalable and associated with lower costs. Besides the technological maturity of this process is considered high, the process degrades fibre quality and therefore requires blending with virgin material to produce new products. As a result, most of the output of mechanical recycling is recycled in textile applications outside the apparel sector (JRC, 2023a; Ribul et al., 2021). Chemical recycling has different technological maturity levels depending on the fibre's composition (i.e., natural fibres, synthetic fibres or with fibre mixtures) (JRC, 2023a). This technology is not yet considered sufficiently scaled; nevertheless, they can achieve the development of high-value fibres and enable fibre-to-fibre recycling systems. The output for the chemical recycling process of natural fibres is man-made cellulosic pulp or viscose, that can be used as yarn for woven or knitted fabrics or for paper production (JRC, 2023a; Ribul et al., 2021). From an environmental perspective, chemical recycling has high energy and water consumption, while mechanical recycling uses only 5%-20% of the energy used in virgin fibre production (Ribul et al., 2021). In general, the recycling of fibres has advantages when compared to virgin fibres production. When considering the averages across diverse recycling methods for different fabric types, virgin fibres can produce emission up to 40 kg CO_2-eq.kg^{-1}, have a significant water footprint, and consume over 140 kWh of energy per kilo of virgin fibre produced, whereas recycled fibres have lower carbon dioxide equivalent emissions (approximately 10 kg CO_2-eq.kg^{-1}), reduced water footprint and energy consumption typically below 70 kWh.kg^{-1} (Arun et al., 2025).

Regarding bio-based processes adaptable to textile recycling, they tend to have a low energy demand and use benign solvents and chemicals. However, the feedstock usually requires pretreatment that uses caustic chemicals, specific vessels and energy (Ribul et al., 2021). Composting is not considered a common method to manage textile waste and is limited to natural and semi-synthetic fibres; however, for cotton fibres it has been studied as an alternative to landfilling (Juanga-Labayen et al., 2022; Ribul et al., 2021).

Enzymatic and biological processes can be seen as an alternative to chemical recycling and can overcome issues associated with blended textiles. These options are not yet used in fibre-to-fibre recycling systems, but they have been demonstrated as an option for open-loop recycling (i.e., to produce feedstock for fermentation or to use biopolymers to make textile fabrics). However, pretreatment for these options still needs to be improved to be sustainable and economically viable, and energy and water demand remain areas for improvement (Ribul et al., 2021).

Nevertheless, the composition of textiles, typically fibre blends due to performance requirements, contributes to the complexity of the physicochemical properties of textile waste, and is a main barrier to the recycling of post-consumer textiles (Depope et al., 2025;

Ribul et al., 2021; Arun et al., 2025). A study conducted in Denmark identified 618 blends present in the textile market in 2022, illustrating the diversity of blend types. Moreover, while man-made synthetics fibres dominate global production, the availability of polyester suitable for recycling is limited due to fibre blending. The presence of disruptors (e.g., large metal findings, fabric adornments, trims, prints) also hinders the recycling process, adding further complexity by, for instance, breaking or damaging shredding equipment, disrupting the blend composition of a fibre batch, or affecting the optimization of chemical processes. The same study also revealed that, when considering high-quality recycling, only a small fraction (<2 %) of textiles in the Danish market can undergo fibre-to-fibre recycling (Logan et al., 2025).

Beyond polyester-cotton blends, a relatively well-researched combination, knowledge on innovative technologies for non-polyester/cotton blends is limited. Other blends, including synthetic-synthetic and synthetic-natural fibre combinations, have variations in thermomechanical properties, which pose barriers to their efficient separation through conventional recycling methods (Arun et al., 2025). Limiting fibre blending and the use of disruptors in garments design can enhance the recyclability of materials; however, an approach based on recycling parameters does not contribute to extending the lifecycle of existing textiles (Logan et al., 2025).

Achieving a fully fibre-to-fibre recycling systems for post-consumer textiles remains hindered by technical and logistical barriers

Despite the developments in recycling within the textile industry, there is still a number of challenges that need to be addressed which prevent the closure of the textile waste recycling loop (Abbas-Abadi et al., 2025). The transition to a large-scale implementation of close-loop recycling in this sector requires progress in regulatory frameworks, technological advancements, and broad stakeholder and consumer engagement. However, even if these issues are addressed, only a fraction of textiles would be suitable to fibre-to-fibre recycling (Harter et al., 2025).

Open-loop solutions currently being explored include the integration of cotton textiles into the paper packaging cycle as an alternative route to landfill and incineration. This option can be achieved through mechanical recycling, producing papermaking pulp that improves the mechanical properties of recycled paper (e.g., strength losses associated with fibre degradation) (Harter et al., 2025). Additionally, the physical properties of textile waste make these fibres suitable as filling materials for insulation or for use in the automotive industry (Zero Waste Europe, 2024; Biyada and Urbonavičius, 2025).

Improving the circularity of bio-based textile waste

Sorting is considered a crucial factor to enhance the potential of textile recycling, including bio-based fibres (EEA, 2023c). Driven by the mandatory separate collection of textiles at end-of-life imposed by the EU, textile waste recovery rates have been increasing (Harter et al., 2025). However, an increase in feedstock to enable the scaling of textile recycling technologies does not guarantee an increase in the recycling rates (Zero Waste Europe, 2024). Technologies for post-consumer textile recycling are not yet widely available, and the quality of collected textile waste is expected to decline due to lower quality standards and contamination from other waste streams (Harter et al., 2025). The economic viability of textile recycling is also a relevant factor to consider, as the disposal of these materials is still the cheapest option, and the price of recycled fibres is not yet competitive with virgin fibres (Zero Waste Europe, 2024).

Policies that could enhance the circularity of textile waste, including bio-based textile, include the introduction of recycled content requirements and recyclability criteria, with particular focus on fibre-to-fibre recycling (Zero Waste Europe, 2024). The newly revised Waste Framework Directive, now officially in force, establishes mandatory EPR schemes for textiles that will "finance collection schemes and the management of the collected textiles, providing for their re-use, preparing for re-use, recycling and disposal" (EC, 2025d). As a result of the waste management targets established under EPR schemes, investments in closed-loop recycling could be incentivised. Examples already in place includes the Dutch EPR system, which sets targets for textile products placed on the market to be recycled or reused, while the French EPR system sets recycling targets based on volumes collected but not reused (Zero Waste Europe, 2024). The definition of EoW criteria for recycled textiles would also promote a safe recycling system, and the JRC is currently working in this segment, consulting stakeholders and collecting data to establish harmonised EoW criteria for this waste stream (Zero Waste Europe, 2024; EURATEX, n.d.). Policies aimed at reducing the technical, regulatory, and economic barriers faced by the sector could equally improve the limited funding for scaling and innovating textile recycling technologies (Zero Waste Europe, 2024).

2.5.3 Bio-based plastics

KEY MESSAGES

- Bio-based plastics production remains relatively low (less than 1% of total plastics), but it is estimated to more than double by 2029.
- Some bio-based plastics polymers are identical to fossil-based, and can be handle in the same waste management systems. Others such as PLA are

often incompatible with existing recycling streams and require dedicated infrastructure, which is currently insufficient.

- Mechanical recycling of bio-based plastics provides better environmental outcomes than chemical recycling but is only suitable for certain polymers (e.g., bio-PE, bio-PET).
- Biodegradation pathways for bio-based plastics face significant operational and environmental limitations, including slow degradation and contamination risks. It should not be seen as a recovery pathway to either reduce plastic pollution or provide agronomic benefits.
- A transition towards second and third generation bio-based plastics, based on biomass waste and by-products, as opposed to first generation bio-based plastics, based on food crops, is necessary as to avoid potential competition with food production.
- Current data on the end-of-life fate of bio-based plastics remains limited.

Bio-based plastics circularity has increased

Bio-based plastics are defined as plastics fully or partially produced from bio-based feedstock (grown crops such as maize, or organic residuals and waste, as agricultural waste, frying oils and manure), instead of fossil raw materials. However, these polymers are not necessarily biodegradable or compostable. Biodegradable plastics are plastics that biodegrade in specific conditions at their end of life. Compostable plastics are biodegradable, and when collected, decompose in industrial composting conditions. The latter two types of polymers can be made from biological resources or fossil raw materials (EC, 2025b; Plastics Europe, 2024). Bio-based plastics, most commonly used in the packaging sector, have reached a production of around 700 thousand tonnes in 2022 in the EU-27, accounting for 1% of the total plastics produced in 2022 (JRC, 2025a). According to the latest data on global production capacity by polymer type, in 2024 bio-based biodegradable polymers accounted for 56.3% of total production capacity, with PLA having the largest share (37.1%), while bio-based non-biodegradable polymers represented 43.7%, with PA, PTT and PE being the most significant (14.4%, 13.2% and 11%, respectively) (European Bioplastics, 2024).

Currently, there are no available data on the generation of bio-based plastics waste. However, regarding the end-of-life of bio-based plastic, and depending on the properties of the polymer, mechanical recycling, chemical recycling, anaerobic digestion, and programmed biodegradation in specific open environments (when applicable), are considered relevant options for managing this type of plastic waste (EC, 2022).

Since mechanical recycling does not change the chemical structure of the material, the polymeric materials can be recycled multiple times in a closed loop (Kumar et al., 2023). The drop-in bio-based plastics are identical to their fossil-based counterparts e.g. bio-HDPE, bio-LDPE, bio-PET and bio-PP. These polymers that can be easily subjected to mechanical recycling. However, other polymers are bio-based and biodegradable and are less prone to this type of recycling (e.g., PHA and bio-PBS) due to decline in their material properties (Ritzen et al., 2023).

Although less used, chemical recycling is also an alternative to mechanical, which breaks down plastic into polymers, monomers or other valuable materials, through depolymerisation, solvent-based processes or thermal processes, recovering chemicals that would otherwise be lost (JRC, 2025a; Bakhtiari et al., 2025; Kumar et al., 2023). Processes such as hydrolysis, pyrolysis, hydrocracking, and gasification are examples of chemical recycling, and their products can be used to produce fuels, new polymers, and other chemicals (Bakhtiari et al., 2025). In comparison, mechanical recycling has lower processing costs, reduced global warming potential, lower use of non-renewable energy, and lower levels of acidification and eutrophication (Bakhtiari et al., 2025; Kumar et al., 2023).

Regarding the circularity of plastics, in 2022, around 8.4 million tonnes were converted into recyclates in the EU, of which approximately 7.3 million tonnes were used in the manufacturing of new plastics products (JRC, 2025a). In the same year, in the EU-27+ Switzerland, Norway and the United Kingdom, around 0.5 million tonnes of plastics converted into new products and components had its origin in bio-based plastics. Overall, the conversion of fossil-based plastics decreased, while the conversion of bio-based plastics into new products and components increased. The recycled content from bio-based plastics in new products represented 4.5% of plastics used in house, leisure and sports applications, 2.2% in the automotive industry, and 1.4% in packaging production (Plastics Europe, 2024).

Biodegradation of these polymers still faces challenges

Organic recovery or organic recycling is an option applicable only to biodegradable bio-based plastics and consists of biodegradation through industrial composting, anaerobic digestion, or, with industrial composting being the most widely used option (Fredi and Dorigato, 2021). However, anaerobic digestion is generally not applicable to treat these polymers due to their low hydrolysis rates, which leads to difficulties in subsequent phases. Regarding industrial composting, when these polymers tend to be treated together with the organic fraction of municipal solid waste. However, biodegradable plastics have residence times longer than those of the organic fraction of municipal solid waste, which creates challenges in achieving full degradation of the materials (Marchelli and Fiori, 2025). Additionally, there is not enough evidence that the biodegradable bio-based plastics fully degrade in nature into CO_2 and water, and if partially biodegraded plastics can become a source of micro- and nanoplastics in environment (Ritzen et al., 2023). Biodegradation of these polymers depends on several factors, such as the chemistry and microstructure of the specific bioplastic, the chosen end-of-life route, and biotic and abiotic conditions (e.g., temperature, oxygen, and moisture concentration, and population of microorganisms) (Fredi and Dorigato, 2021). For these reasons, biodegradation should not be seen as a recovery pathway to either reduce plastic pollution (Ritzen et al., 2023) or provide agronomic benefits, therefore recycling should be prioritised (EC, 2020).

Non-biodegradable bio-based polymers (e.g. bio-PET, bio-PE) can be mixed with petrochemical-based plastics and recycled in the same facilities; however, this is not always applicable to biodegradable bio-based plastics (Fredi and Dorigato, 2021). Currently, biodegradable polymers are still viewed as contaminants in conventional recycling streams, resulting in low interest in the recycling of these materials. The existence of specific recycling facilities for biodegradable plastics could help solve this problem; however, the insufficient volumes of bio-based plastics is one of the factors that also limits the mechanical and chemical recycling of these polymers (Bakhtiari et al., 2025; EC, 2022). Another factor that limits the recyclability of commercially available biodegradable plastics is the fact that they are composed of a mixture of polymers (Bakhtiari et al., 2025). Product design could improve the circularity of bio-based polymers; nevertheless, single polymers still represent certain weaknesses such as low thermal resistance, limited processability, and brittleness (Ritzen et al., 2023; Bakhtiari et al., 2025).

New EU rules will set clear conditions for using bio-based, biodegradable, and compostable plastics

Currently there are multiple policies that could potentially intersect with bio-based plastics. Nevertheless, the EC's new communication on the European Green Deal establishes EU-wide packaging regulations, including clear conditions for the use of bio-based, biodegradable and compostable plastics. Bio-based plastics must use sustainably sourced biomass, respect the cascading use of biomass (i.e. prioritising waste or by-products), and producers must avoid general claims such as "bioplastics" or "bio-based" products and specific exact percentages of bio-based content. Biodegradable plastics should be used only in specific applications that provide environmental benefits and added value to the circular economy, with clearly defined conditions and timeframes for biodegradation. For industrially compostable plastics, only specific products, such as tea bags, coffee pods, fruit and vegetable stickers, and lightweight bags, will be permitted to use this type of polymer. Additionally, these products will also need to comply with EU certification requirements (EC, 2025c).

Are bio-based plastics the more sustainable alternative?

It is estimated that the global bio-based plastics production is set to grow from 2.47 million tonnes in 2024 to approximately 5.73 million tonnes in 2029 (European Bioplastics, 2024; Plastics Europe, 2024a, 2024b). This increase may lead to the diversion of arable land for bio-based plastics production, which would otherwise be used for the production of resources needed for other economic activities, such as agriculture. It will be necessary to transition towards second and third generation biomass feedstock, such as biomass waste and by-products, as opposed to producing first generation bio-based plastics (e.g. based on corn, sugarcane), as their sustainability is not evident (Rosenboom et al., 2022).

There is a considerable body of literature associated with the environmental assessment of bio-based plastics and their comparison with conventional plastics. There are several inconsistencies which make most studies incomparable as they have different analytical boundaries, different functional units, impact categories or even significantly different products (Bishop et al., 2021). The inclusion of arable land use is considered critical in life cycle assessment studies on bio-based plastics, except in cases where the feedstock is bio-waste, in order to capture the potential impact on food production, but also to consider the potential impacts on biodiversity loss and ecosystems (Gerassimidou et al., 2020).

3 POLICY OPTIONS TO INCREASE CIRCULARITY OF BIO-BASED WASTE IN EUROPE

After analysing a set of relevant bio-based waste streams, it was possible to identify a group of policy options to unlock their circularity potential. The relevant topics identified include enhancing separate collection, improve treatment technologies, fostering new technologies, enabling market demand, increasing the quality of the waste streams and by-products, as well as harmonising legislations. These policy options were identified based on a comprehensive benchmark at the Member State level, as detailed in Annexes 1-4.

Considering the waste hierarchy, **preventing the generation** of these waste streams should be the main goal. Establishing non-binding initiatives (e.g., voluntary actions, agreements, and awareness campaigns), planning and certification along the supply chains, as well as implementing regulatory measures (e.g. mandatory food donation policies), are some examples that could be applied to food prevention. In the agricultural sector, the implementation of advanced harvesting and other digital agricultural technologies, aligning production plans with market demand, as well as enhanced storage solutions, could help prevent agricultural waste and by-products. These measures reduce environmental impacts (e.g. soil degradation, water pollution and GHG emissions), minimise surplus and unnecessary products and could potentially lead to significant savings by households. However, for some waste streams, such as sewage sludge, prevention is more difficult.

Improving separate collection, as well as treatment, can be categorised as the focus areas regarding existing policies for the waste streams analysed in this report. The improvement of separate collection appears to be particularly relevant for food waste and garden and vegetal waste, wood waste, paper and cardboard waste and bio-based textiles. The collection of these waste streams in mixed waste poses challenges regarding the capture of feedstock and contamination by hazardous substances, which impose regulatory restrictions. Establishing **collection standards** for bio-waste, extending the EPR of wood waste to cover more product types (e.g., furniture or construction products) and implementing mandatory separate collection are important steps towards a circular model. In the case of paper and cardboard waste, ensuring separate collection from other recyclables is also considered a key point to enhance the circularity of the waste stream.

Regarding treatment improvement, the use of **advanced pre-treatment and sorting technologies** by companies to recycle wood streams ensure high-quality materials and helps pave the way towards closed-loop systems. **Certification schemes or eco-labels** can also be applied to sewage sludge and agricultural waste to assure the quality of the waste streams and/or by-products, enhancing the acceptance of these feedstocks. Further support for **composting and anaerobic digestion** capacity dedicated to bio-based waste streams contributes to reducing GHG emissions from bio-waste landfilling, increasing the production of renewable gases with anaerobic digestion, which can substitute fossil fuels, avoiding environmental impacts from manufactured product substitution, and creating more jobs per tonne of waste managed compared to landfilling. For the food waste and garden and vegetal waste, treatment and **quality standards for compost and digestate** established can help to increase acceptance across Member States, and supporting cross-border trade. Additionally, the promotion of **innovative and efficient technologies** such as pyrolysis and gasification for streams with lower recovery potential, can reduce environmental risks by diverting waste from landfill. Policy options include also regulatory measures, such as the ban on the landfilling of materials with a TOC content above 5%.

The **improvement of the quality and quantity of recovered materials** is intrinsically connected to collection methods and the level of treatment. In the case of sewage sludge, the establishment of comprehensive requirements for the recovery of phosphorus from sewage sludge and sludge incineration ash, along with clear EoW criteria, can increase nutrient recovery and avoids environmental impacts from manufactured product substitution. Additionally, implementing stricter **contaminant limit values** for sludge applied to agricultural land can enable safe land application without the risk of diffuse pollution to soil, plants, and water. In the case of agricultural waste, reducing the density of animal stocks**, improving monitoring** of unprocessed manure, and adopting better manure application practices can result in lower levels of contaminants present in manure, which in turn can help to minimise the risk of soil pollution.

Facilitating market demand for these waste streams and their by-products can be achieved through several measures. For wood waste, setting minimum recycled content targets and integrating recycled wood criteria into Green Public Procurement can help shift the marked from energy recovery towards more circular solutions, reducing competition for secondary raw materials in specific sectors (e.g., furniture). Additionally, **harmonised classification** standards for wood waste can foster the market for this waste stream, improving consistency in sorting and downstream use, cross-border trade and compliance. For sewage sludge, the establishment of clear **EoW criteria** enables to marketing of by-products as fertilisers or materials. In the case of agricultural waste, a manure market approach can be explored enabling the export of manure, promoting sustainable practices abroad, and improving transparency regarding opportunities for manure use in food production. Bio-based textiles could also benefit from the introduction of **recycled content requirements** and **recyclability criteria** focused on fibre-to-fibre recycling, a defined EoW status for recycled textiles, and the promotion of a safe recycling system, thereby reducing the technical, regulatory and economic barriers present in the sector and enhance funding for scaling up and innovating textile recycling technologies.

4 CONCLUDING REMARKS

This study demonstrates that enhancing the circularity of bio-waste is a strategic opportunity for the EU to advance many of its objectives, including competitiveness and mitigation of GHG emissions. The analysis confirms that across food, garden and vegetal waste, wood waste, sewage sludge and agricultural residues, **substantial volumes remain outside circular pathways**. These untapped flows represent both an **environmental burden and a missed opportunity** to recover nutrients, materials and renewable energy.

The assessment highlights four overarching findings. First, **the scale of the opportunity is significant**: between 58–68 Mt (wet weight) of bio-waste from food, garden and vegetal sources, 26–28 Mt (wet weight) of wood waste, and 1.5–2.1 Mt (dry matter) of sewage sludge are still managed through linear routes such as landfill, mixed waste streams, or low-value recovery. Second, **data gaps**, inconsistencies in reporting, and the absence of harmonised classification frameworks remain key barriers to designing effective policy and investment strategies. Third, contamination limits the potential for high-value material recovery, requiring **improved collection systems**, quality assurance and clear regulatory thresholds. Finally, several **promising technological solutions** exist, yet many remain constrained by market immaturity, high capital costs and regulatory uncertainty.

Across the different waste streams, common issues emerged: insufficiently separate collection, particularly for bio-waste; strong competition between recycling and energy recovery, notably for wood; and inconsistent standards that hinder cross-border markets for secondary raw materials. Economic barriers also play a prominent role, as many circular pathways deliver clear environmental benefits but lack robust business cases under current market conditions.

To unlock the significant untapped value of Europe's bio-based waste streams, the analysis shows that action is required across the full value chain. Strengthening upstream measures, particularly food-waste prevention, remains essential to reduce environmental impacts. Expanding and enforcing separate collection is equally critical, as it directly determines the quality and quantity of materials available for high-value recovery. At the same time, treatment capacity must evolve: while composting and anaerobic digestion will continue to play a central role, scaling emerging solutions such as insect-based protein production, nutrient recovery from sludge, advanced biochemical pathways and chemical recycling of wood fibers is key to fully harnessing the potential of bio-based waste.

Realising this potential also depends on supportive regulatory and market environment. Harmonised EU-wide standards, including clearer classification schemes, EoW criteria, and contaminant thresholds, would reduce uncertainty and strengthen cross-border markets for secondary raw materials. In parallel, measures that stimulate demand, such as recycled-content requirements and targeted fiscal incentives, can help close the loop and improve investment conditions. Finally, reinforcing transparency, quality assurance and public trust is fundamental to ensure societal acceptance and to safeguard environmental and health outcomes. Collectively, these actions provide a coherent pathway to move bio-waste up the hierarchy, reduce losses of nutrients and materials, and advance the EU's transition toward a more circular and resilient bioeconomy.

ABBREVIATIONS

CEPS	Centre for European Policy Studies
CIRCABC	Communication and Information Resource Centre for Administrations, Businesses and Citizens
DM	Dry Matter
EC	European Commission
EEA	European Environment Agency
ETC CE	European Topic Centre on Circular Economy and Resource Use
EoW	End-of-Waste
EPR	Extended Producer Responsibility
EU	European Union
EWC-Stat	European Waste Classification for Statistics
GHG	Greenhouse Gas
ICCT	International Council on Clean Transportation
JRC	Joint Research Centre
LoW	European List of Waste
MBT	Mechanical-Biological Treatment
PHA	Polyhydroxyalkanoates
R&D	Research and Development
SSD	Sewage Sludge Directive
TOC	Total Organic Carbon
TRL	Technology Readiness Level
UWWTD	Urban Wastewater Treatment Directive
WWTP	Wastewater Treatment Plants

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ANNEX 1. FOOD, GARDEN AND VEGETAL WASTE

Current State of Food, Garden and Vegetal Waste Management in Europe

Generation, collection and treatment

Data on food, garden and vegetal waste can be found in several data sources, including from Eurostat. However, as described in the following paragraphs, a detailed analysis raises questions about consistency and representativeness.

Eurostat – Waste generation and treatment

EU Member States report data on waste generation according to the EU Waste Statistics Regulation (2150/2002/EC). Based on this reporting, Eurostat publishes data on the generation of animal and mixed food waste and vegetal wastes, whose definitions, according to Eurostat (2010), are the following[4]:

- **Animal and mixed food waste:** Animal waste of food preparation and products, including sludges from washing and cleaning and mixed wastes of food preparation and products including biodegradable kitchen / canteen wastes, and edible oils and fats. These wastes are from food preparation, agriculture and from separate collection.
- **Vegetal wastes:** Vegetal waste from food preparation and products, including sludges from washing and cleaning from agriculture and food production. It also includes green waste from separate collection.

These are broad categories that include more waste than just food waste and garden and park waste, which may not fully capture the origin, quality, or potential treatment options of the materials (Table 16).

Table 16. European List of Waste (LoW) entries for animal and mixed food waste and vegetal wastes

Source: Eurostat, 2010

09.1 Animal and mixed food waste	
02 01 02	animal-tissue waste
02 02 01	sludges from washing and cleaning
02 02 02	animal-tissue waste
02 02 03	materials unsuitable for consumption or processing
02 05 01	materials unsuitable for consumption or processing
02 03 02	wastes from preserving agents
02 06 02	wastes from preserving agents
19 08 09	grease and oil mixture from oil/water separation containing only edible oil and fats
20 01 08	biodegradable kitchen and canteen waste
20 01 25	edible oil and fat
09.2 Vegetal wastes	
02 01 07	wastes from forestry

[4] The 'animal faeces, urine and manure' category is excluded from this scope of analysis and is considered in the agricultural waste analysis.

20 02 01	biodegradable waste
02 01 01	sludges from washing and cleaning
02 01 03	plant-tissue waste
02 03 01	sludges from washing, cleaning, peeling, centrifuging and separation
02 03 03	wastes from solvent extraction
02 03 04	materials unsuitable for consumption or processing
02 06 01	materials unsuitable for consumption or processing
02 07 01	wastes from washing, cleaning and mechanical reduction of raw materials
02 07 02	wastes from spirits distillation
02 07 04	materials unsuitable for consumption or processing

Key limitations

It is important to highlight that only waste that is separately collected is reported under these two statistical categories, which means that food waste and garden and vegetal waste present in mixed waste is not being accounted for. Eurostat publishes data reported by Member States on the generation of waste categories from mixed waste collection, namely household and similar wastes and mixed and undifferentiated materials, which include considerable bio-based waste fractions. According to Eurostat (2010), these categories include:

- **Household and similar wastes:** Mixed municipal waste (20 03 01), bulky waste (20 03 07), street cleaning waste (20 03 03), kitchen waste, household equipment from private households and similar wastes from commerce which are not related directly to the production or the services (20 03 99, 20 03 02);
- **Mixed and undifferentiated materials:** Unspecific wastes and mixed waste from nearly all industries and from waste treatment.

For reference year 2022, Eurostat published data reported by Member States indicating a generation of 129.5 million tonnes and 36.8 million tonnes of household and similar wastes and mixed and undifferentiated materials, respectively, in the EU-27. Both contain considerable shares of bio-waste, however the composition of these wastes and thus the share of bio-based wastes in these waste categories are not reported. In the recently published research paper by Sund et al. (2025), the authors assumed that 43% of these waste categories corresponded to bio-waste. This means that a potentially very large fraction of the bio-based waste in the EU is present in mixed waste streams and thus is not accounted for in the analysis done in this chapter.

In 2022, the total separately collected animal and mixed food waste and vegetal wastes generated in the EU by all economic activities and households amounted to 23.59 and 50.57 million tonnes, respectively[5]. Figure 5 and Figure 6 present the share of different economic activities and of households in total waste generation for both waste streams. Households have the highest contribution in both waste categories (43% of animal and mixed food waste and 47% of vegetal wastes) (Eurostat, 2025a).

[5] Waste reported includes waste from economic activities 'Waste collection, treatment and disposal activities; materials recovery' and 'Wholesale of waste and scrap'. These sectors should be taken with reserve due to the risk of double counting.

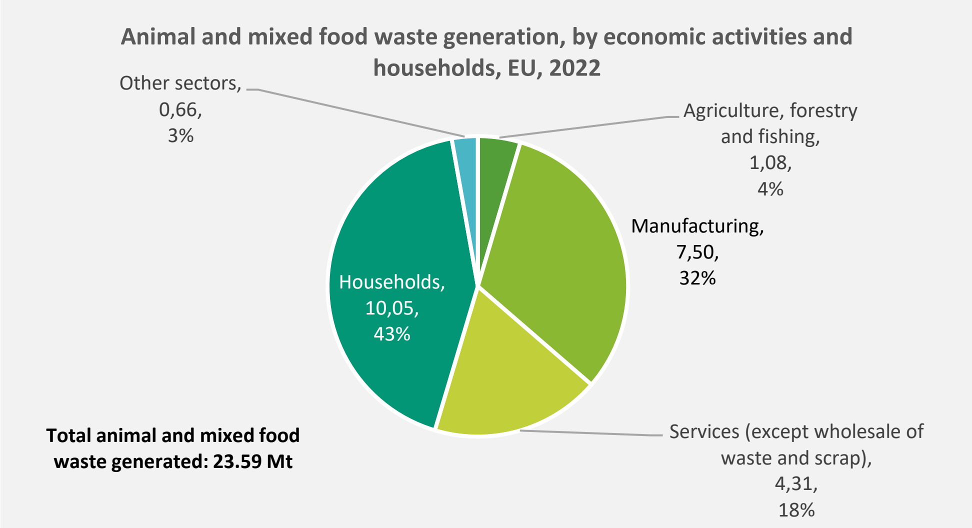

Figure 5. Animal and mixed food waste generation by economic activities and households, EU, 2022 (million tonnes and share of total animal and mixed food waste)
Source: Eurostat, 2025a

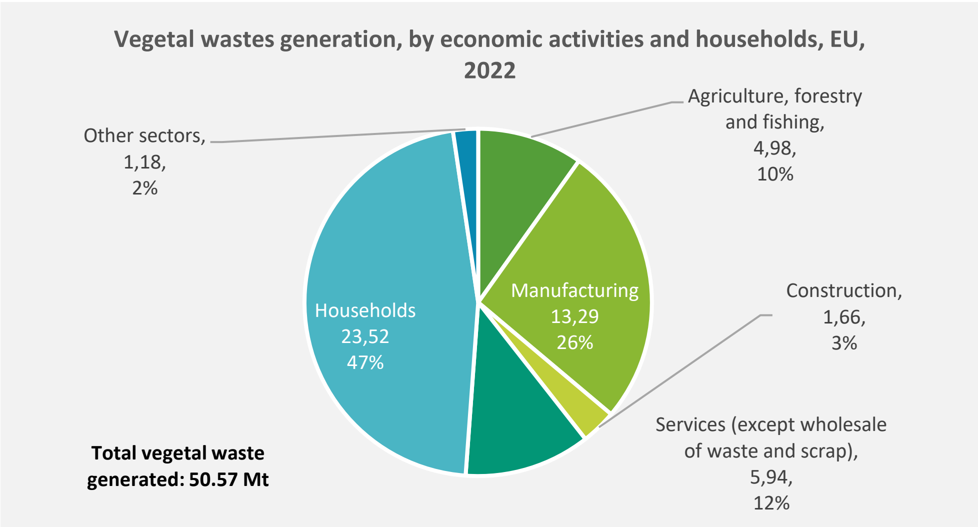

Figure 6. Vegetal wastes generation by economic activities and households, EU, 2022 (million tonnes and share of total vegetal wastes)
Source: Eurostat, 2025a

In 2022, 23.95 and 42.69 million tonnes of separately collected animal and mixed food waste and vegetal wastes were treated in the EU, respectively (Figure 7 and Figure 8) (Eurostat, 2025b). The reported amounts are not directly comparable with those on waste generation, since this does not include exported waste but includes the treatment of waste imported into the EU (Eurostat, 2025c). The waste management operation classified as "recovery - recycling" includes recovery operations from R2 to R11[6], which includes composting and anaerobic digestion.

[6] The recovery operations covered by R2 to R11 are: Solvent reclamation/regeneration (R2); Recycling/reclamation of organic substances which are not used as solvents (including composting and other

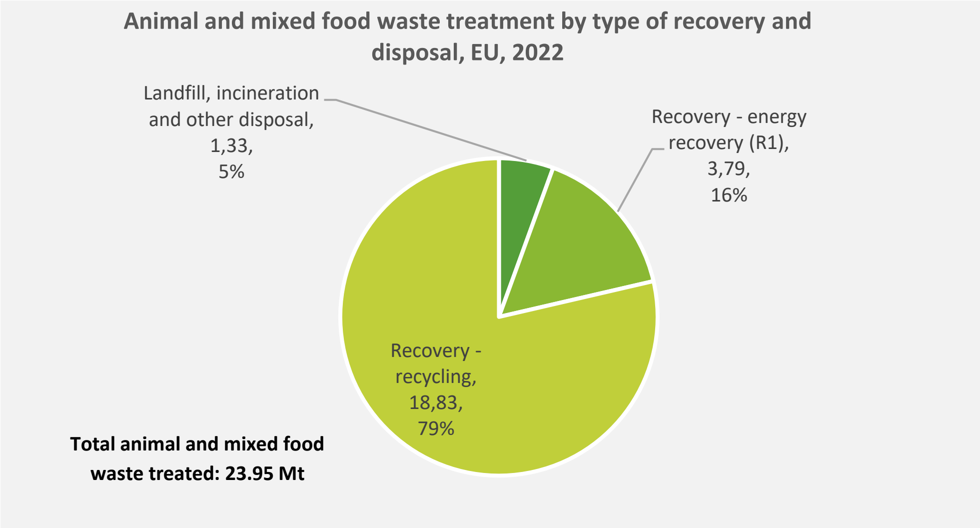

Figure 7. Animal and mixed food waste treatment by type of recovery and disposal, EU, 2022 (million tonnes and share of treated animal and mixed food waste)
Source: Eurostat, 2025b

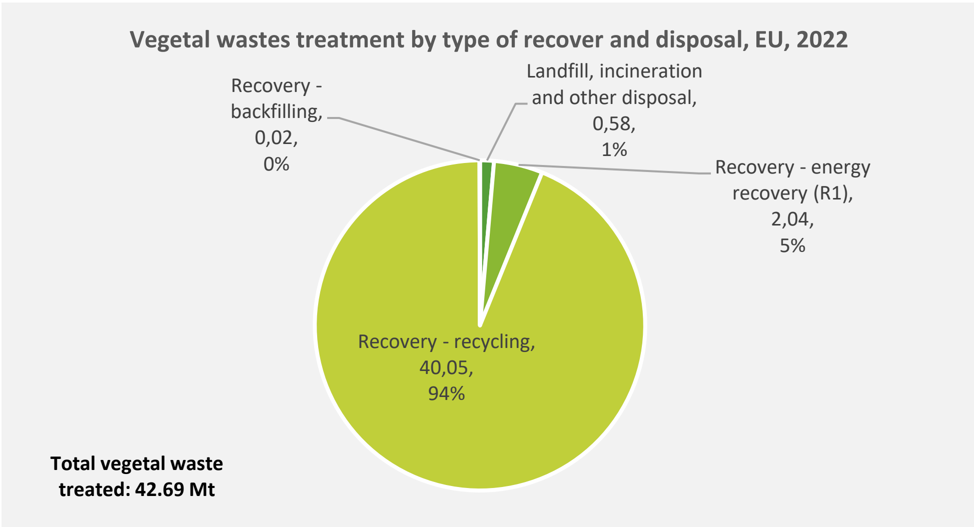

Figure 8. Vegetal wastes treatment by type of recovery and disposal, EU, 2022 (million tonnes and share of treated vegetal waste)
Source: Eurostat, 2025b

Eurostat - Food waste and food waste prevention

As mandated in the revised Waste Framework Directive (EU, 2018), Member States must monitor and report food waste at each stage of the food supply chain. In September 2025,

biological transformation processes) (R3); Recycling/reclamation of metals and metal compounds (R4); Recycling/reclamation of other inorganic materials (R5); Regeneration of acids or bases (R6); Recovery of components used for pollution abatement (R7); Recovery of components from catalysts (R8); Oil re-refining or other reuses of oil (R9); Land treatment resulting in benefit to agriculture or ecological improvement (R10); and Use of wastes obtained from any of the operations numbered R1 to R10 (R11) (Eurostat, 2024).

the Waste Framework Directive was amended, setting legally binding food waste reduction targets to be achieved by Member States by 2030 (EU, 2025).

At EU level, a total food waste generation of around 57.7 million tonnes of fresh mass was reported in 2022 (Figure 9), which includes the food waste disposed as part of the mixed waste, with household food waste representing 53% of the total (food losses, i.e. food not harvested or food not authorised to be marketed for safety reasons, are excluded) (Eurostat, 2025d). It is important to note that the results for the EU-27 are estimates derived by Eurostat, as some Member States have not yet provided complete or consistent direct measurement.

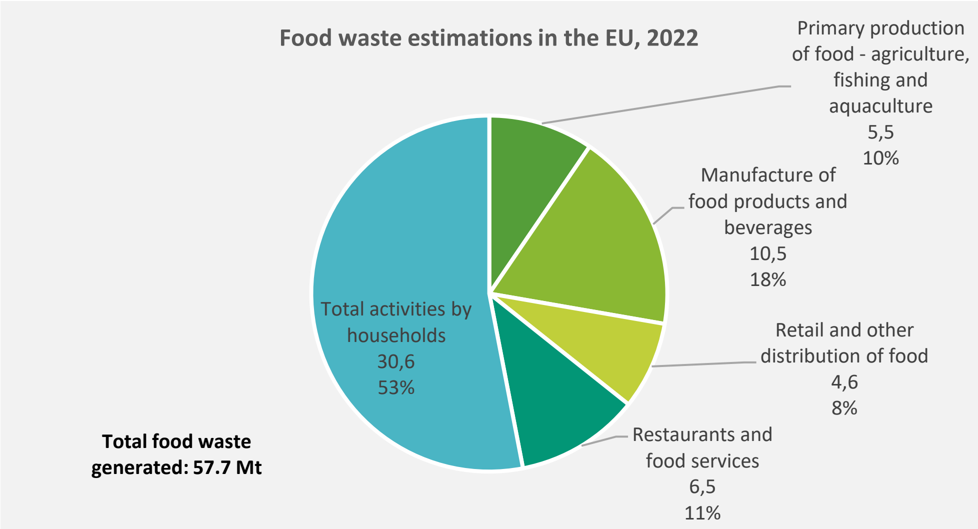

Figure 9. Food waste estimations in the European Union, 2022 (million tonnes and share of generated food waste)
Source: Eurostat, 2025d

Eurostat – Municipal waste management operations

Focusing on municipal waste, food and garden waste are key streams comprising the bio-waste fraction. Due to its considerable volume, it is considered a critical waste stream for meeting the EU target to recycle 65% of municipal waste by 2035, established in the Waste Framework Directive. The implementation of separate bio-waste collection systems is key to achieve this target. The Waste Framework Directive also establishes that from 2024 onwards, bio-waste must either be separated and recycled at source (home composting) or collected separately and not mixed with other types of waste (EU, 2018).

According to Eurostat (2025e), the EU generated 230 million tonnes of municipal solid waste in 2022. There is no consolidated statistical information available on the generation of bio-waste in municipal waste by Eurostat, i.e. the fraction food and garden waste in municipal solid waste. The EEA (2023) estimated that, on average, bio-waste accounted for 37% of the municipal solid waste generated, amounting to around 85 million tonnes in 2022 in the EU-27. A similar figure was provided in a paper by the JRC (Albizzati et al., 2024), which estimated that 89 million tonnes of bio-waste are generated, with only 42.5 million being collected separately (collection/capture rate of 48%), and that 5.2 million are treated through home composting, for reference year 2020.

Information at Member State level has been compiled by the European Topic Centre on Circular Economy and Resource Use (ETC CE) based on the EEA early warning assessments related to the 2025 targets for municipal waste and packaging waste (EEA, 2022a). It largely builds on the answers provided by the responsible authorities from Member States in 2021 to a questionnaire developed by the EEA and ETC/WMGE. Based on the country profile reports, the *per capita* bio-waste generation waste was estimated for each Member State (Figure 10). Based on the reported information, the weighted average capture rate of bio-waste in the EU-27 was 45%.

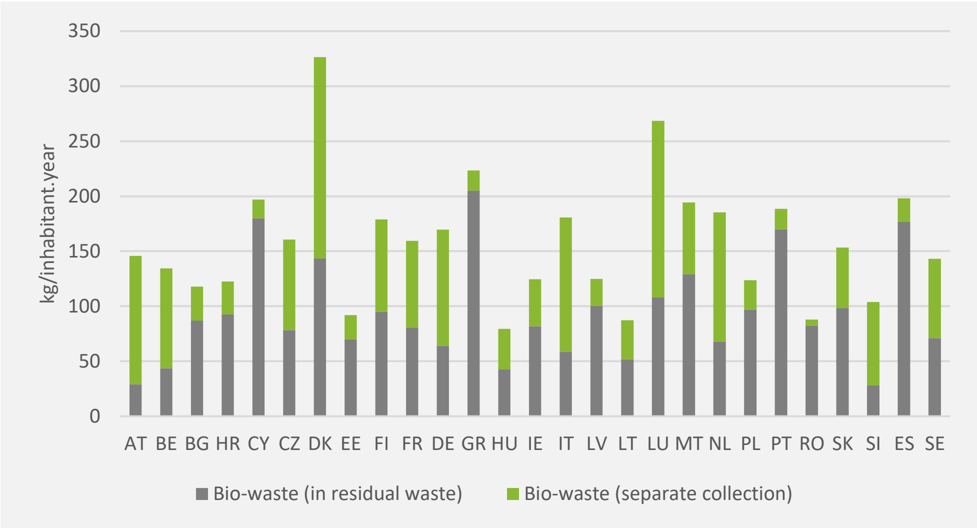

Figure 10. Generation of bio-waste in residual waste and separately collected by Member State (kg/inhabitant.year). Data refer to different reference years, mostly to 2019 and 2020, but partly to previous years
Source: EEA, 2022a

While there is no specific consolidated data for bio-waste treatment in Europe, the data on municipal waste treatment can be used to provide a general picture. According to Eurostat (2025c), 43.6 million tonnes of municipal solid waste were sent to recycling – composting and digestion (19% of treated municipal waste) (Figure 11). This quantity includes a fraction of the mixed municipal waste treated in MBT plants.

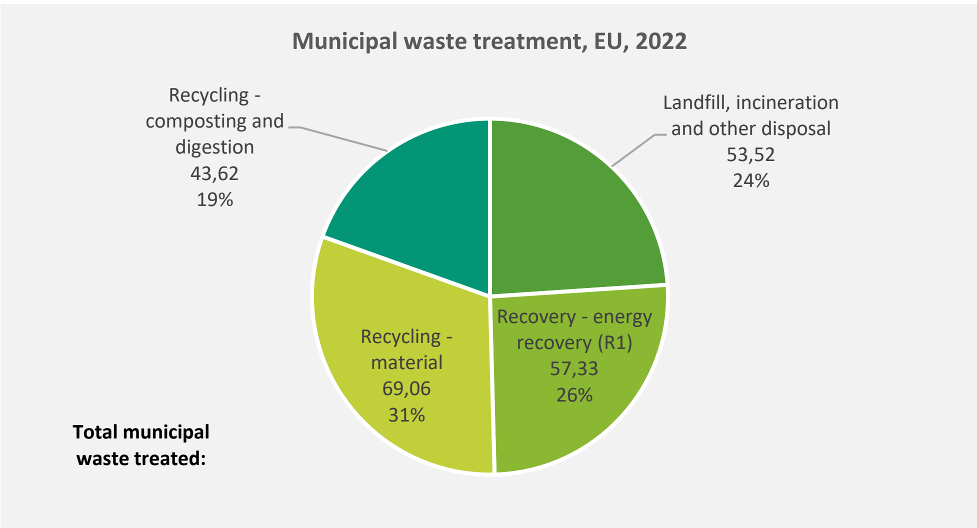

Figure 11. Municipal waste treatment, EU, 2022 (million tonnes and share of treated waste)
Source: Eurostat, 2025e

In the case of municipal waste, a significant fraction of bio-waste still ends up in the mixed waste that is landfilled, incinerated or sent to MBT, however, there is no reported consolidated information at EU level about the amounts sent to MBT as it counts as a pre-treatment operation. MBT is a widely used waste management technology in some Member States for mixed municipal waste. The process begins with mechanical sorting, where a share of recyclable materials is recovered. The remaining organic waste, including food and garden waste, is then subjected to biological treatment methods such as composting or anaerobic digestion, or it can be dried and stabilized to be integrated in refuse-derived fuel.

Bio-waste easily gets contaminated during mixed waste collection with contaminants such as plastics, and metals, which results in a significant reduction in its quality and suitability for recycling or composting. This analysis is grounded in the experience of southern European countries, such as Spain and Portugal, that have employed MBT followed by anaerobic digestion to recover value from bio-waste within mixed municipal solid waste streams. Evidence suggests that biogas generation from source separated organic fraction of municipal solid waste is significantly higher when compared with mechanically sorted organic fraction, i.e. from mixed waste collection. Le Pera et. al (2021) suggests that mechanically separated yields a third of the source separated, but evidence from a small number of plants in Portugal (Ambirumo, 2021) suggests that the difference might be smaller (210 m^3/t from source separated versus 120 m^3/t from mechanically separated).

The primary challenge lies in the operational sustainability of organic recovery following MBT, which require between 30 to 40% of bio-waste content in unsorted municipal solid waste to remain economically feasible. As separate bio-waste collection systems become more widespread, this proportion will inevitably decrease, thereby diminishing the effectiveness of MBT plants for handling unsorted waste. Consequently, these facilities may increasingly become relegated to serving as a transitional stage for waste that ultimately ends up in landfill or incineration, rather than contributing meaningfully to resource recovery.

It is important to note that the Waste Framework Directive has established an obligation for separate collection of bio-waste to be applied after December 31st, 2023, and that from 2027 onward, municipal bio-waste entering aerobic or anaerobic treatment may only be counted as recycled if it has been separately collected or separated at source. This implies that bio-waste treated in MBT plants will no longer count towards the municipal waste recycling targets (EU, 2018).

Although comprehensive data on the proportion of unsorted waste directed to MBT plants is scarce, existing evidence from Member States such as Portugal and Spain, that heavily rely on this technology, provides valuable insights (Table 17). In these countries, the performance of MBT systems has shown that they often produce outputs of relatively low quality. This raises concerns about the compatibility of MBT+anaerobic digestion with separate bio-waste collection strategies, as the integration of both approaches may undermine the quality and effectiveness of the recycling process. Therefore, while MBT+anaerobic digestion may serve as a short-term solution in certain contexts, the evidence suggests it is not a viable long-term strategy in the face of increasing separate bio-waste collection and stricter recycling regulations.

Table 17. Municipal waste sent to MBT in selected Member States

Source: ADEME, 2023; MITECO, 2022; ISPRA, 2024; Destatis, 2024

	France	Spain	Italy	Germany	Portugal
Input MBT (t)	1 539 000	4 807 128	8 638 452	3 331 000	1 339 243
% municipal waste generated	4.2%	20.9%	30.1%	6.6%	25.2%

There is a lack of comprehensive analysis of the quantities of mixed waste treated in MBT plants, but analysis of data from selected Member-States that reportedly rely on MBT for mixed waste treatment suggests that capacity should be above 20 million tonnes per year (Table 17), which translates into 8-10 million tonnes of food, garden and other bio-waste categories in mixed waste.

European Compost Network – Generation, collection and treatment

The European Compost Network provides data and insights on the treatment of bio-waste (food and garden waste) in Europe, particularly in relation to composting and anaerobic digestion. However, like many sector-specific data sources, European Compost Network data comes with limitations that should be considered in this study. The data presented by the European Compost Network is based on voluntary reporting from composting and biogas plant operators, national associations, and member organisations. It is also important to highlight that data from the European Compost Network primarily reflects what is being treated in composting and digestion facilities that are members of the Network, and not necessarily on how much bio-waste is generated or collected, which results in only a partial view of the overall bio-waste management chain. Nevertheless, the data provided European Compost Network plays a key role in attempting to consolidate and harmonise available information at the European level.

According to the European Compost Network (2022), a total of 59 million tonnes[7] of bio-waste were separately collected and treated in 2019 in EU-27, of which 38 million tonnes originated from municipal sources and 21 million tonnes from non-municipal sources (commercial and industrial sources). It is important to highlight that European Compost Network data refers only to separately collected bio-waste, and exclude mixed waste treatment, sewage sludges and agricultural wastes. Another key consideration is that the values published by the European Compost Network are underestimates, as they do not include data from Romania, Bulgaria, and Croatia, since the European Compost Network has no members in these countries, and they only report quantities treated in their member organisations' facilities.

In their 2022 report, the European Compost Network estimates that bio-waste accounts for 34% of the total municipal solid waste, which is equivalent to 76 million tonnes of municipal bio-waste generated. The assumption would then be that 50% of the generated municipal bio-waste is collected with mixed municipal solid waste.

[7] It should be noted that the ECN data presents a small inconsistency, possibly a rounding discrepancy. While it reports that 59 million tonnes of bio-waste were selectively collected and treated, it also states that 36 million tonnes were sent to composting and 24 million tonnes to anaerobic digestion , resulting in a discrepancy of 1 million tonnes.

Regarding treatment, according to the European Compost Network, a total of 60 million tonnes of bio-waste was treated in the EU-27 in 2019 through composting and anaerobic digestion, including both municipal and commercial/industrial waste (Figure 12).

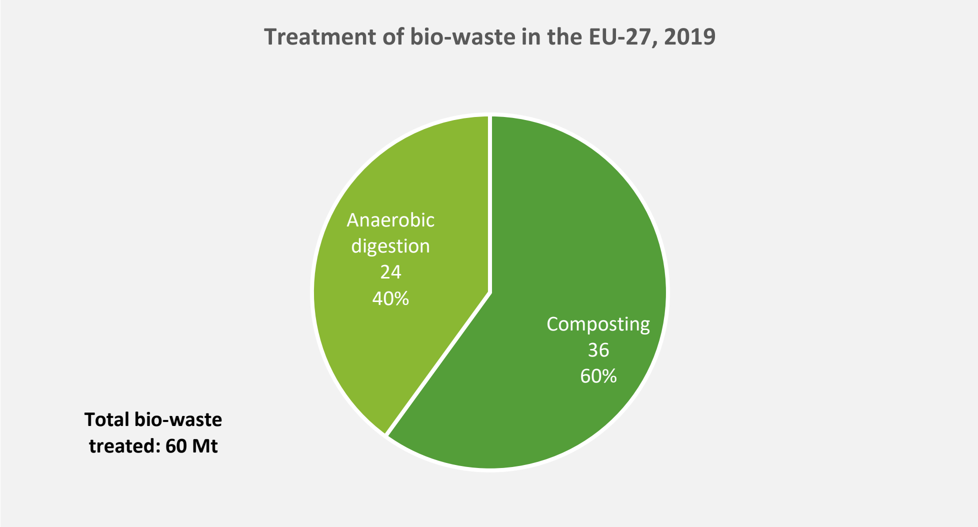

Figure 12. Treatment of bio-waste in the EU-27, 2019 (million tonnes and share of treated waste, excluding home-composting)
Source: ECN, 2022

According to the European Compost Network, composting facilities process mainly household waste whereas anaerobic digestion facilities process household and commercial and industrial waste in similar quantities (Figure 13).

Despite potential issues on representativeness for all EU-27, these results are aligned with the best estimations from generation and collection.

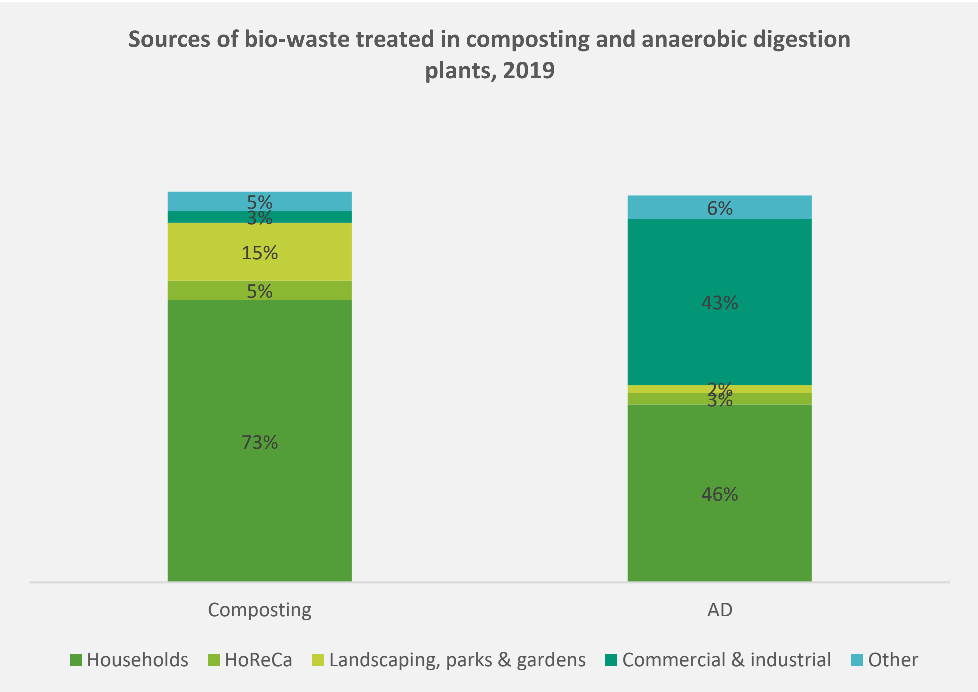

Figure 13. Sources of bio-waste treated in composting and anaerobic digestion plants, 2019
Source: ECN, 2022

Other data sources

JRC – Food waste generation: The JRC (De Laurentiis et al., 2024b) has developed a food waste model based on material flow analysis, which produces annual estimates of food waste generation by food category and by stage of the food supply chain. The model has been used to assess and support the validation of data reported by Member State. The latest update of the model estimated that 73 million tonnes of solid food waste (in fresh mass) were generated along the EU food supply chain in 2021. The report also underscores the importance of clearly defining the scope of food waste flows, particularly when comparing results across different projects and reports. One challenge identified is that some studies report only edible food waste, which limits their comparability with total food waste figures that must be reported to the EC in accordance with regulatory requirements.

EC - EU Bioeconomy Monitoring System: The EU Bioeconomy Monitoring System from the EC (2025a) offers an overview of European trends in indicators related to the EU Bioeconomy, including the generation of bio-waste from the industry, agriculture and households. According to this reported indicator, which resorts to data from the JRC, 16.8 and 21.7 million tonnes of animal and mixed food waste and vegetal wastes, respectively, were generated in 2022 (70% and 51% from households, respectively). These values are not directly comparable to the values discussed before since the EU Bieconomy Monitoring System reports on a dry matter basis.

EC – CIRCABC: The EC's platform CIRCABC (Communication and Information Resource Centre for Administrations, Businesses and Citizens) provides information from the reporting of data on municipal waste from Member States in accordance with Annex V to Commission Implementing Decision (EU) 2019/1004. This dataset captures information on municipal waste broken down by material, encompassing waste generation, separate collection, preparing for reuse, recycling, energy recovery, and other recovery operations (CIRCABC, 2025). Even though the currently available data is still under validation to be published at a later stage by Eurostat, this reporting will be a relevant data source in the future for the analysis of bio-waste generation.

Zero Waste Europe - Bio-waste generation in the EU: Current capture levels and future potential: In 2024, Zero Waste Europe presented a study which aimed to estimate the current and future availability of bio-waste in the EU-27, besides UK and Norway, with a particular focus on food waste. The assessment was based on public information and national data from these countries for bio-waste generation and relied on assumptions to calculate the current capture of bio-waste in the EU-27+ and the theoretical potential. The report estimates that the current capture of food waste is 15 million tonnes per year in the EU-27+, less than 26% of the theoretical potential, which is estimated at 60 million tonnes (Zero Waste Europe, 2024).

Summary

Table 18 summarises the obtained results of the analysis of the aforementioned datasets, in which it is possible to conclude that the differences are considerably significant due to different methodologies and scope of reporting.

Table 18. Analysis of bio-waste generation, 2022 (million tonnes)

Source: Eurostat, 2025a, 2025d, 2025e; EEA, 2022a; ECN, 2022, Sund et al., 2025

	Eurostat - Waste Generation	Eurostat – Municipal waste EEA (2022)	ECN, 2022	Eurostat - Food waste and food waste prevention	Eurostat – Mixed and undifferentiated waste Sund et al., 2025
Waste categories	Animal and mixed food waste Vegetal wastes	Bio-waste in municipal solid waste	Bio-waste	Food waste	Bio-waste
MUNICIPAL WASTE					
Scope	Services (except wholesale of waste and scrap) Households	Municipal	Municipal	Households, services, retail	-
Mixed waste collection	-	47	38	-	-
Separate collection	44	38[8]	38	-	-
Total generated	-	85	76	42	-
NON-MUNICIPAL WASTE					
Scope	Agriculture, forestry and fishing, mining and quarrying, manufacturing, electricity, gas, steam and air conditioning supply, water supply; sewerage, waste management and remediation activities, construction, wholesale of waste and scrap	-	Non-municipal (commercial and industrial)	Primary production of food - agriculture, fishing and aquaculture, manufacture of food products and beverages	All NACE activities, except households
Mixed waste collection	-	-	-	-	13[9]
Separate collection	30	-	21	-	-
Total generated	-	-	-	16	-

Applications

Data for waste treatment is reported in several data sources, however, there is no consistent information on the quality, contamination levels, or end uses of compost and digestate, which limits the assessment on the potential for increasing circularity of these waste streams.

The main output of composting processes is compost, while the principal output of anaerobic digestion is digestate, alongside the production of biogas (mainly methane and carbon dioxide). There are also instances where the digestate is composted to increase the range of applications of the output. Compost is a nutrient-rich, solid particulate material

[8] Considered weighted average capture rate of bio-waste in the EU-27 of 45% (EEA, 2022a).

[9] In order to provide an estimate on the bio-waste produced from industrial and commercial sources that is not separately collected, data on the quantity of mixed and undifferentiated materials generated from all NACE activities, except households, from Eurostat (2025a) was considered (30.3 million tonnes). It was assumed that 43% of this fraction consists of bio-waste (Sund et al., 2025).

that results from the controlled decomposition of biodegradable organic matter and has been sanitised and stabilised. Digestate, a nutrient-rich solid or liquid material, is the result of the anaerobic digestion of biodegradable organic matter by microorganisms. Depending on the anaerobic digestion technology used, digestate can be liquid, pasty, or solid (LIFE BIOBEST, 2024).

According to the latest report from the European Compost Network, published in 2022 (covering data from 2019), approximately 19 million tonnes of compost were produced (conversion of bio-waste to compost was assumed by European Compost Network to be 50% for the EU-27). To provide an indicative estimate of digestate production in Europe, a conversion rate of 33% - as used in the European Compost Network's previous report (ECN, 2019) - was applied, yielding an estimated 8 million tonnes of digestate produced in 2019. Biogas production is not addressed in the European Compost Network report, as it falls outside the scope of its analysis (ECN, 2022).

The separate collection of bio-waste is a prerequisite for the production of high-quality compost and digestate, as high-quality feedstock, together with effective pre-treatment and post-treatment processes that precede and follow biological treatment, contributes to improving the quality of the final product. According to LIFE BIOBEST (2024), similar products can be obtained using different types of biological treatment technologies; however, more advanced processes are capable of handling lower-quality feedstock. Demand for such quality products is high and continues to grow, driven by the fact that these biologically treated outputs provide locally sourced organic matter and nutrients (ECN, 2022).

It is important to highlight the important role of the EU Fertilising Products Regulation (EU 2019/1009) (EU, 2019) as it lays down harmonised rules for compost and digestate as component materials in EU fertilising products. This Regulation establishes clear standards for the cross-border marketing and use of organic fertilising products, ensuring that compost and digestate produced from bio-waste are safe, effective, and compliant with EU environmental and health regulations. However, for national use of compost and digestate, national quality standards may apply which may or may not be aligned with the Fertilising Products Regulation.

Agriculture is the dominant market segment for the use of both compost and digestate. In the case of compost, agriculture accounts for 50% of the market share, followed by landscapers (9%), general public (9%), topsoil blenders (9%), with the remaining market divided among sectors such as parks and roads, commercial horticulture, nurseries, retail, landfill cover, and others (ECN, 2022). For digestate, agriculture constitutes the predominant market segment, accounting for approximately 93% of the total market, with the remainder distributed across markets including the general public, commercial horticulture, landfill cover, and others. Despite agriculture being the primary outlet, the ECN reports that sales prices remain well below their theoretical value. The weighted average price for compost was reported at just 10.1 euros per tonne (fresh mass), while digestate typically has a zero or even negative market value (ECN, 2022). These values are expected to vary based on many variables, but as a rule of thumb, these should not be considered a source of revenue for waste managers.

Identification and assessment of the viable technical solutions to promote circularity

A wide range of technological options is available to manage food, garden and vegetal waste streams in Europe, each with different levels of maturity, environmental performance, and alignment with circular economy principles. Selecting the most appropriate solution requires considering both the characteristics of the waste (e.g. moisture content, homogeneity, contamination levels) and the most relevant environmental goals, such as nutrient recovery and GHG mitigation. However, it should be noted that most options listed require high-quality inputs, and therefore, bio-based waste flows must be collected and managed separately to avoid contamination and maximise yields.

Food waste prevention as a priority

In 2024, the JRC presented an updated version of the 'food use hierarchy' (Figure 14) which aims to prioritise prevention and support the alignment of bioeconomy policies with the use of surplus food and the valorisation of food waste, helping to minimise the environmental, economic and social impacts associated with food waste (De Laurentiis et al., 2024b). **Prevention remains the most environmentally beneficial and cost-effective strategy.** Avoiding food waste through behavioural change and improved manufacturing and logistics, among other strategies, prevents the environmental burdens associated with both waste treatment and food production. Studies consistently show that preventing food waste offers significantly greater life-cycle emission savings. According to Scherhaufer (2018), cited in EEA (2020), food waste contributes approximately 15–16% of the total environmental impact of the entire food value chain, particularly in terms of climate change, acidification, and eutrophication. While modern treatment methods such as anaerobic digestion can reduce GHG emissions through nutrient and energy recovery, studies consistently show that preventing food waste offers significantly greater life-cycle emission savings (EEA, 2020). Avoiding food waste also represents an economic benefit. According to the EC, the economic loss from food waste is approximately 2.2 € per kilogram of food waste (EC, 2023).

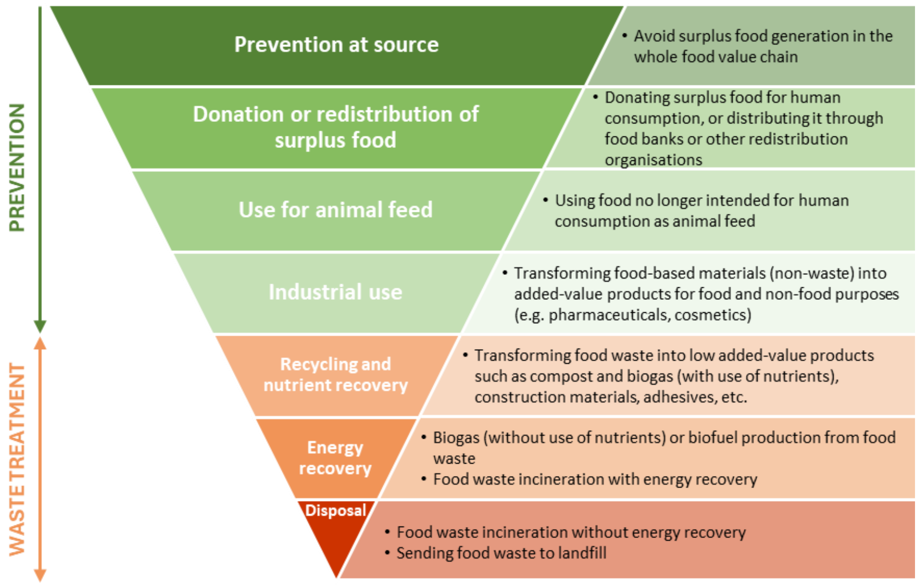

Figure 14. Hierarchy for the prioritisation of options to manage food surplus, by-products from food processing and food waste – 2024 update
Source: De Laurentiis et al., 2024

Reducing food waste involves not only savings from avoided food purchases but also costs related to implementation, such as increased labour or investment in improved storage. Additionally, food waste reduction may lead to lower food prices, potentially increasing the consumption of agricultural products and offsetting some of the intended environmental gains (EEA, 2020).

The recently amended Waste Framework Directive establishes legally binding targets for each EU Member State to be achieved by 2030: 10% food waste reduction in food processing and manufacturing and 30% per capita reduction in retail, restaurants, food services and households compared to the average levels in 2021-2023 (EU,2025).

Composting and anaerobic digestion

For the waste that does occur, composting is the most widespread biological treatment option in Europe. It is especially effective for managing garden and vegetal waste, as well as food waste with low contamination. Composting is relatively low-tech and low-cost, and it returns organic matter and nutrients to soils. However, it requires high-quality input material and is sensitive to contamination, which can limit the end uses of the resulting compost. Anaerobic digestion offers a more technologically advanced alternative, allowing for the simultaneous recovery of energy and nutrients. Anaerobic digestion is particularly suitable for food waste or mixtures of food and garden waste with appropriate pre-treatment. Although capital costs are higher than for composting, the environmental benefits can be significant if the biogas produced replaces fossil fuels. However, the quality and marketability of the digestate can vary, and anaerobic digestion facilities must be carefully operated to prevent methane leakage and ensure process efficiency.

As of recent estimates, approximately 5 800 bio-waste treatment facilities operate across the EU-27, plus Switzerland, Norway, and the United Kingdom, of which about 66% is dedicated to composting and 34% to anaerobic digestion. On average, each composting facility processes around 8 000 tonnes of bio-waste per year, while anaerobic digestion facilities handled on average approximately 13 000 tonnes annually. Composting plants served about 120 000 people each, compared to 225 000 people served by each anaerobic digestion facility. In terms of feedstock, 88% of composting facilities treated only bio-waste, whereas just 48% of anaerobic digestion facilities operated exclusively with bio-waste (ECN, 2022). Data from 20 countries reported in 2019, representing around 59% of municipal bio-waste generation in EEA member and cooperating states, show an installed annual treatment capacity of roughly 38 million tonnes, with 21 million tonnes for composting and 17 million tonnes for anaerobic digestion. However, actual capacity is likely higher, as some countries have not reported infrastructure data, and many facilities co-treat municipal bio-waste with other waste streams such as manure or food industry waste. The Waste Framework Directive mandates separate collection or home composting by December 2023, a measure expected to boost the use and expansion of both composting and anaerobic digestion (EEA, 2020). The EEA's country profiles on municipal and packaging waste management (EEA, 2025a) provide a status of separate collection systems for bio-waste across Europe.

Despite being the most common recovery options for bio-waste, including food, garden and vegetal waste, composting and anaerobic digestion have their limitations. The slow biodegradability of lignin, present in tree leaves and branches, means that the anaerobic digestion of garden waste alone achieves only about 10% of its theoretically expected methane production (Suarez et al., 2022). When food waste and garden waste is anaerobic co-digested, besides the garden waste favourable C/N ratio, its high lignocellulose content slows degradation and reduces methane output; however, food waste degrades rapidly and produces more methane but risks acidification due to volatile fatty acid accumulation and its relatively low C/N ratio. Achieving the right balance between these two waste streams is therefore essential to enhance performance. (Song et al., 2021).

Valorisation through animal feed and insect farming

In specific contexts, processing food waste into animal feed presents a highly efficient valorisation pathway for food waste, especially when using by-products from food processing such as spent grains or vegetable trimmings. Examples include the use of brewery by-products, such as spent grains and yeast, or surplus bakery items, which are regularly incorporated into livestock diets in several European countries. Fruit and vegetable trimmings from markets and food processing facilities can also serve as feed for animals or be integrated into on-farm feed mixes. EU regulations, however, impose strict limitations on the use of food waste as feed, particularly if it includes animal-derived materials. The direct use of commercial and household food waste is strictly regulated in the European Union. Under Regulation (EC) No 1069/2009, catering waste and food scraps of animal origin is classified as Category 3 animal by-products, and their use in feed is banned due to the risk of transmitting diseases. In other regions of the world, such as Japan, there are regulated systems to allow for the reintegration of treated food waste into animal nutrition.

A growing alternative is insect farming, which uses food waste as feedstock to produce insect protein and fertiliser. Insect-based systems are gaining traction, but they remain in early stages of development, and regulatory and market uncertainties persist. Solutions have been studied in R&D projects like LIFE Waste2Protein, such as the cultivation of Black Soldier Fly larvae using bio-waste streams, including discarded vegetables, food scraps, or fishery by-products. These larvae efficiently convert organic waste into high-protein biomass suitable for aquaculture, poultry, or pig feed, while also generating frass that can be used as an organic fertiliser. The larvae are rich in nutrients, containing 32–58% protein and 15–39% fat, making them a viable raw material for animal feed. There are pilot and commercial plants operating across the world which demonstrate the viability of integrating insect farming into waste management systems. These solutions offer an alternative to traditional protein sources like soy and fishmeal while diverting bio-waste from landfills or incineration. Given that around 5 million EU farmers raise livestock for food—requiring about 450 million tonnes of animal feed annually—and that there are around 70 million pet-owning households consuming approximately 10 million tonnes of pet food each year, solutions aiming to substitute part of conventional animal feed offer a sustainable and effective way to tackle food waste and food security issues while supporting the transition to a circular economy (EC, 2025c; Aleisa & Alsaleh, 2024).

Both strategies offer a compelling argument in the efficiency of nutrient recovery and the overall market demand. Animal feed consumption (excluding forages) in the EU-27 amounted to 250 million tonnes in 2022. This figure suggests that the animal feed solution has the necessary scale to warrant dedicated policies. Notably, 18 million tonnes are met with byproducts of food & bioethanol industries (FEFAC, 2023), which are, by definition, excluded of the waste statistics. As more material is used as animal feed, these can be reclassified as byproducts and ultimately contribute to waste prevention.

Emerging bio-based chemical and fuel pathways

More advanced options include the fermentation of food waste into volatile fatty acids, which serve as precursors for bioplastics, solvents and other high-value bio-based chemicals. Through anaerobic acidogenic processes, food waste and other bio-based wastes can be converted into Volatile Fatty Acids such as acetic, butyric, and propionic acids. These compounds are valuable not only for their role in bioplastic production, particularly in synthesising PHA, but also as precursors for solvents, lubricants, and chemical intermediates in various industrial applications. These emerging technologies offer significant potential for circular bioeconomy applications, as demonstrated by the large number of R&D and pilot projects in the EU-27, but they currently face barriers related to feedstock quality, technical complexity, and market uptake. These barriers, combined with high capital costs and competition from traditional production pathways, suggest that in the short term these will not represent a significant share of the recovery options available.

Biofuel production is viable at the commercial scale for some energy dense fractions but requires large and reliable bio-based waste flows. Conversion into bioethanol or biodiesel supports renewable energy goals but may compete with higher-value recovery options and does not align with the fundamental principles of circular economy. Technologies like pyrolysis and gasification are also being explored, though their application to bio-waste is still limited and largely confined to pilot projects. Oils produced from these processes have shown promise in the development of new materials and energy sources, further broadening their potential utility and market applications. The potential demand for biofuel production can be relevant, but the lack of consistent quality and quantities will be a limiting factor and other bio-based waste streams can be more competitive.

Recovery from mixed waste

Recovery from mixed municipal waste should be seen as a last resort solution. MBT with composting or anaerobic digestion has been used in several Member States to recover value from mixed municipal waste. While it can extract some energy and material from residual waste streams, MBT is increasingly considered a transitional solution. It suffers from high contamination rates, lower biogas yields, and will no longer count towards recycling targets under EU rules after 2027 unless input waste is separately collected. As separate collection systems expand, the economic and environmental rationale for MBT is expected to weaken.

All options represent different levels of risk to the environment and human health that need to be assessed and considered to move forward. Further studies, especially for the less established solutions, will help to maximise confidence and, consequently, the adoption rate.

ANNEX 2. WOOD WASTE

Current State of Wood Waste Management in Europe

Generation, collection and treatment

Eurostat - Waste Generation and Treatment

In accordance with Regulation (EC) No 2150/2002 on waste statistics, Member States are required to report data on waste generation and treatment using the European Waste Classification for Statistics (EWC-Stat) nomenclature. This regulation provides a harmonised statistical framework for monitoring waste flows across the EU.

Regarding wood waste, the regulation establishes a dedicated category under code 07.5, ensuring clarity in scope and classification. This category covers both hazardous and non-hazardous wood waste and is defined by its type, origin, and potential hazardous content. Specifically, it includes wooden packaging, sawdust, shavings, bark, cork, and wood waste from pulp and paper production, as well as wood from construction and demolition activities and separately collected wood waste. The category explicitly excludes mixed wastes containing wood and wood containing polychlorinated biphenyls (Eurostat, 2010). The source branches identified include:

- Wood processing and panel/furniture production;
- Pulp, paper and cardboard production;
- Construction and demolition;
- Mechanical waste treatment;
- Waste collection of separately collected fractions.

The correspondence between the EWC-Stat classification for wood waste (Category 07.5) and the relevant LoW codes is presented in Table 19.

Table 19. Comparison on the EWC-Stat classification for wood waste with the corresponding LoW codes

Source: Eurostat, 2010

EWC-Stat Code	EWC-Stat Description	Corresponding LoW Code	LoW Description	Origin
07.51	Wood packaging	**15 01 03**	Wooden packaging	Packaging (including separately collected municipal packaging waste)
07.52	Sawdust and shavings	**03 01 05**	Sawdust, shavings, cuttings, wood, particle board and veneer other than those mentioned in 03 01 04	Wastes from wood processing and the production of panels and furniture
		03 01 04*	Sawdust, shavings, cuttings, wood, particle board and veneer containing hazardous substances	
07.53	Other wood wastes	**03 01 01**	Waste bark and cork	
		03 03 01	Waste bark and wood from pulp/paper industry	Wastes from pulp, paper and cardboard production and processing
		17 02 01	Wood	Construction and demolition wastes
		19 12 06*	Wood containing hazardous substances	Wastes from the mechanical treatment of waste
		19 12 07	Wood	
		20 01 37*	Wood containing hazardous substances	Separately collected fractions of municipal wastes (household waste and similar commercial, industrial and institutional wastes)
		20 01 38	Wood	

An analysis based on Eurostat data for the year 2022, focusing on this category (W075. Wood Wastes) under the EWC-Stat classification, reveals key insights into the generation and treatment of wood waste across the EU-27 (Eurostat, 2025a; Eurostat 2025b).

In 2022, the total amount of wood waste generated in the EU-27 by all economic activities and households was approximately 46.8 million tonnes (Figure 15). The manufacturing sector is the largest contributor, responsible for 37% of the total wood waste generation, with 58% of that specifically from the manufacturing of wood and of products of wood and cork (excluding furniture)[10]. Additionally, 23% of wood waste comes from the waste

[10] According to the EC, the sector 'manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials', with NACE category C16, includes the manufacture of

management sector. Other relevant contributors include construction (17%), households (10%), and services (10%). These figures suggest that a substantial share of wood waste originates from industrial processes, which are generally more homogeneous and easier to recycle. In contrast, wood waste from construction and households is often more heterogeneous and may contain hazardous substances such as paints or preservatives, making recycling more complex.

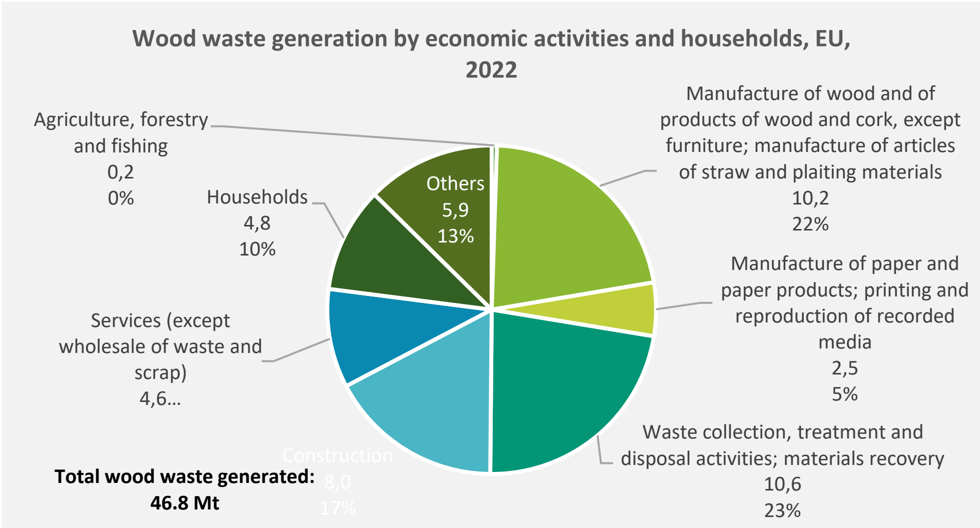

Figure 15. Wood waste generation by economic activities and households, EU, 2022 (million tonnes and % share of total wood waste)
Source: Eurostat, 2025a

It is important to highlight that only waste that is separately collected is reported, which means that wood waste present in mixed waste is not being accounted for. Eurostat publishes data reported by Member States on the generation of waste categories from mixed waste collection, namely household and similar wastes and mixed and undifferentiated materials, which include considerable bio-based waste fractions. According to Eurostat (2010), these categories include:

- **Household and similar wastes:** Mixed municipal waste (20 03 01), bulky waste (20 03 07), street cleaning waste (20 03 03), kitchen waste, household equipment from private households and similar wastes from commerce which are not related directly to the production or the services (20 03 99, 20 03 02);
- **Mixed and undifferentiated materials:** Unspecific wastes and mixed waste from nearly all industries and from waste treatment.

In 2022, Eurostat published data reported by Member States indicating a generation of around 130 million tonnes and 37 million tonnes of household and similar wastes and mixed and undifferentiated materials, respectively, in the EU-27 (Eurostat, 2025a). These are relevant waste streams, however, Eurostat does not report information concerning the composition of these waste streams.

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wood products, such as lumber, plywood, veneers, wood containers, wood flooring, wood trusses, and prefabricated wood buildings. The production processes include sawing, planing, shaping, laminating, and assembling of wood products starting from logs that are cut into bolts, or lumber that may then be cut further, or shaped by lathes or other shaping tools. The lumber or other transformed wood shapes may also be subsequently planed or smoothed, and assembled into finished products, such as wood containers.

Regarding treatment (Figure 16), more than 99% of treated wood waste was subject to recovery operations, with 51.3% undergoing energy recovery (R1) and 47.9% being recycled or used for backfilling (R2–R11). In contrast, only 0.8% was disposed of via landfill or incineration without energy recovery (D1-D7, D10, D12).

The dominance of energy recovery over material recycling points to an opportunity to increase recycling rates through enhanced separation, classification, and processing, particularly for streams that are currently contaminated or poorly sorted. While contamination with hazardous substances remains a significant barrier to higher recycling, data from Eurostat indicate that 96% of separately collected wood waste (approximately 45 million tonnes) is classified as non-hazardous. Only around 1.8 million tonnes (4%) are considered hazardous, highlighting a substantial potential for expanding recycling efforts, especially within the non-hazardous fraction.

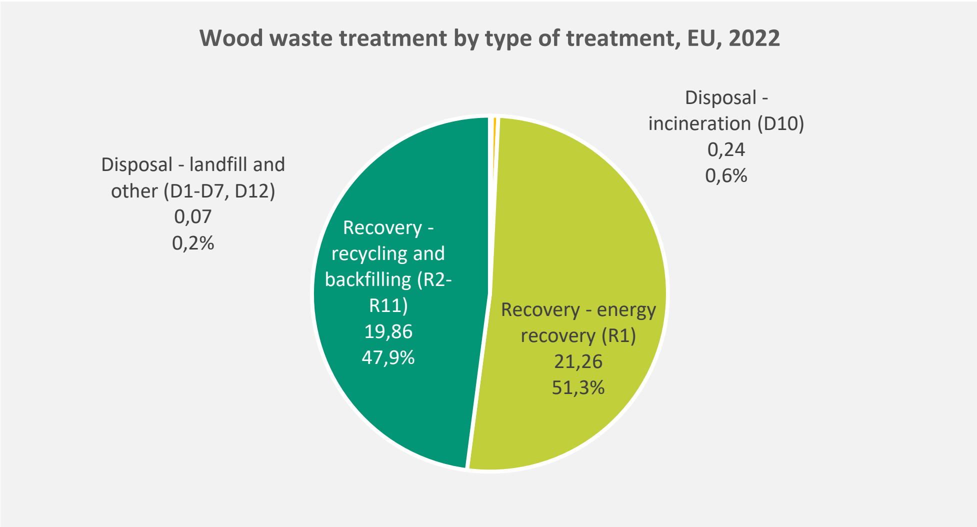

Figure 16. Wood waste treatment by type of treatment, EU, 2022 (million tonnes and % share of treated wood waste)
Source: Eurostat, 2025b

A detailed analysis of Eurostat data on wood waste treatment at Member State level is presented in Figure 17, where it is possible to observe that recycling and energy recovery are the preponderant treatment options for this waste stream. However, it is important to note that Austria and Sweden do not report data for energy recovery, as it is marked as confidential. In the case of Sweden, data reported in 2020 shows that 98% of wood waste is sent to energy recovery.

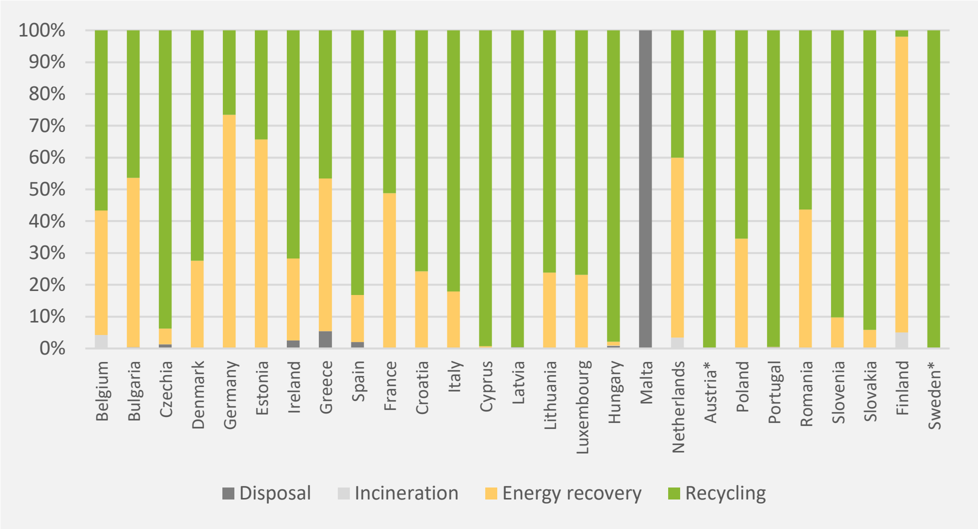

Figure 17. Percentage Wood waste treatment by type of treatment, EU, 2022 (million tonnes and % share of treated wood waste) (Member States with asterisk do not report all the data related to treatment)
Source: Eurostat, 2025b

Eurostat – Trade in waste

Wood waste is a waste type that is frequently traded between countries. In 2022, the data from Eurostat shows that around 1.9 million tonnes were imported, while around 0.64 million tonnes of wood waste were exported (Eurostat, 2025c). This significant net import of wood waste suggests a strong internal demand for secondary raw materials derived from wood, likely for recycling into new materials (such as particleboard) or for energy production. Figure 17, which presents data related to treatment within each country, including imported and excluding exported wastes, is therefore influenced both by policies, trade and industry structure.

Eurostat – Municipal waste management operations

Regarding municipal waste, Eurostat published data reported by Member States showing that that approximately 230 million tonnes of municipal waste were generated in the EU-27 in 2022 (Eurostat, 2025e), however, consolidated statistical information on its composition is not available.

The EEA early warning assessments related to the 2025 targets for municipal waste and packaging waste (EEA, 2022a) provide data concerning these waste streams at Member State level, particularly the capture rate of different waste fractions. According to this data, wood waste represents around 8% of the generated municipal waste and the weighted average capture rate of wood waste in the EU-27 was around 90%.

Figure 18 shows the amount of wood waste generated in municipal waste per capita at the EU level, along with the breakdown of wood waste by collection type. It is important to highlight that data related to wood waste in municipal waste is missing for several countries in the EEA’s early warning assessments, namely Denmark, Hungary, Latvia, Luxembourg, Poland, Romania and Sweden. A detailed analysis of country-level data reveals that Germany stands out as the country with the highest generation of wood waste in municipal waste, at approximately 105 kg/inhabitant/year, the majority of which is selectively collected (98%). In contrast, countries such as Greece, Spain, Cyprus, and Bulgaria exhibit separate collection capture rates for wood waste below 30%, highlighting a significant potential for improving separate collection and in turn enhancing circular management of this material stream. It should be stressed that this data relies on waste composition analysis which is not harmonised across countries and thus is likely to contain considerable uncertainty. More recent data on wood and other materials (in municipal waste has been reported by most EU Member States but not yet published by Eurostat.

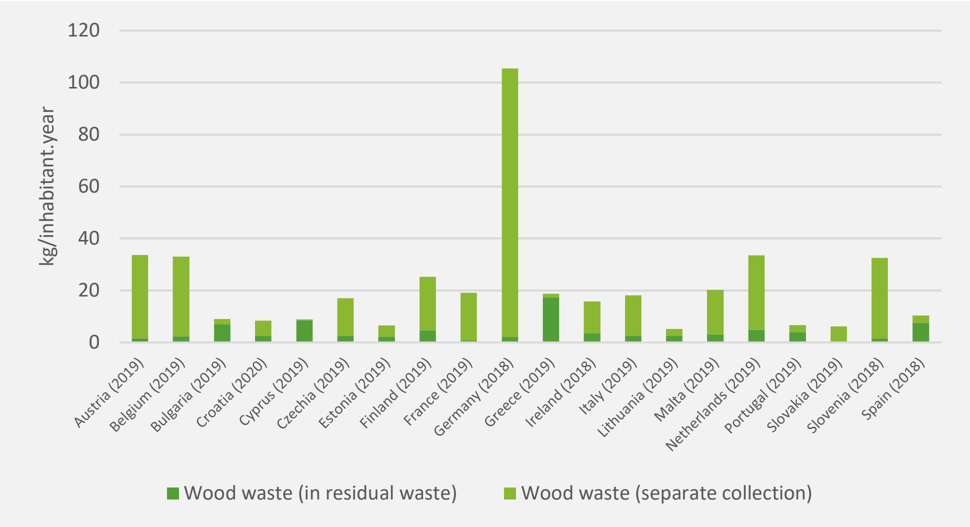

Figure 18. Generation of wood waste in municipal waste and separately collected by selected Member State (kg/inhabitant.year)
Source: EEA, 2022b

Eurostat - Wood packaging

Eurostat also provides detailed data on specific waste streams, including packaging waste (Figure 19). In 2022, the amount of wood packaging waste generated across the EU was approximately 13.4 million tonnes (Eurostat, 2025d). This includes items such as pallets, crates, and boxes. Of this total, around 34% (~4.6 million tonnes) was recycled within the Member State where it was generated. The majority of wood packaging waste (approximately 64%) was subject to recovery, with around 30% undergoing energy recovery. These figures highlight the relevance of wood packaging as a significant component of the wood waste stream, as well as the importance of improving recycling rates to enhance circularity in this sector.

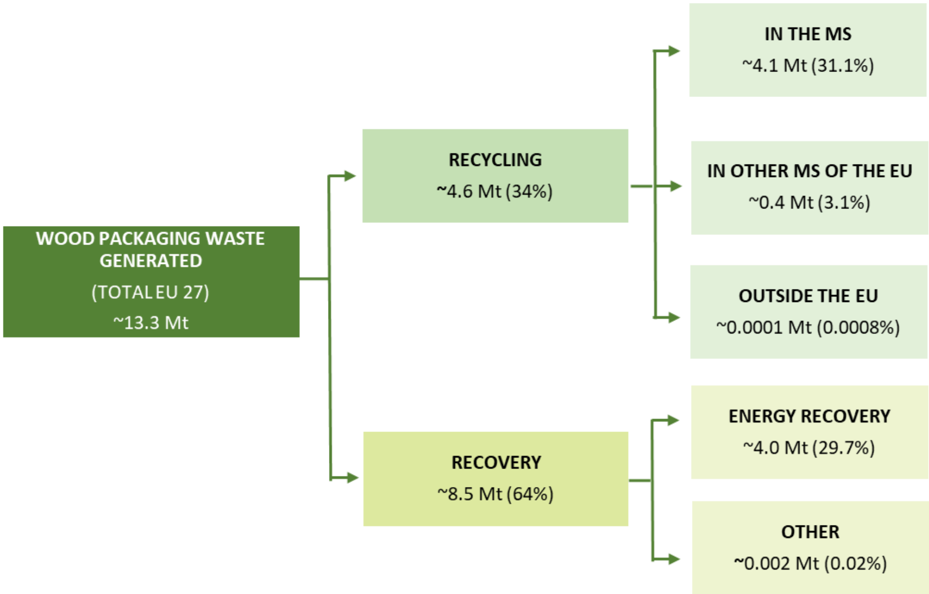

Figure 19. Wood packaging generation and recovery, EU, 2022
Source: Eurostat, 2025d

The EU Regulation on packaging and packaging waste establishes different recycling targets depending on the packaging material. For wood packaging specifically, the recycling targets are set at 25% by 2025 and 30% by 2030 (EU, 2024). According to Eurostat data, only eight Member States have not met the 2025 target ahead of schedule in 2022 (Figure 20) (Eurostat, 2025f).

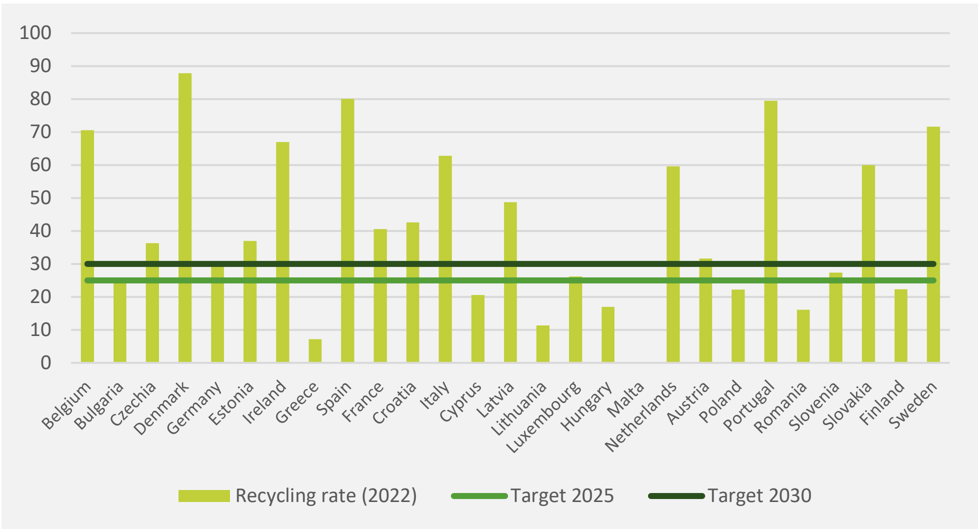

Figure 20. Recycling rate of wood packaging waste in Member States (%), 2022
Source: Eurostat, 2025f

Applications

Wood waste can hold substantial economic and environmental value when effectively managed and utilised. Its value is influenced by factors such as type, quality, processing methods, and potential end-use applications, offering benefits that range from direct economic returns to wider environmental gains.

According to Eurostat data (Section 2.3.1), approximately 51% of treated wood waste is recovered for energy generation purposes, while around 48% is subjected to recycling processes. In addition, an unknown amount of wood waste in mixed waste fractions is sent to landfill or incineration, which are the main treatment routes for mixed wastes. The dataset, however, does not provide specific information regarding the end-use applications of the recycled material. Nevertheless, existing literature offers insights that enable preliminary conclusions to be drawn regarding the potential material valorisation pathways for recycled wood waste.

The quality of wood waste plays a pivotal role in determining appropriate recycling or reuse strategies. Factors such as the wood's source, type, and quality grade are essential for assessing its suitability for various recovery pathways. This assessment should consider the presence of physical and chemical contaminants, including heavy metals, polycyclic aromatic hydrocarbons, pentachlorophenol, phenols, and polychlorinated biphenyls. A study conducted by (Pazzaglia, A. et al., 2023a) classifies wood waste into four distinct quality categories, each associated with specific potential uses, as detailed in Table 20.

Table 20. Wood waste categorisation and potential uses according to its quality grade

Source: Pazzaglia, A. et al., 2023a

Quality grade	Chemical composition	Potential uses
Grade A 'Clean' recycled wood	Untreated wood	Recycling
Grade B Industrial feedstock	Glued, painted, coated, lacquered wood	Recycling
Grade C Fuel	Wood with halogenated organic compounds in the coating	Biomass fuel
Grade D Hazardous waste	Wood treated with creosote, chromate copper arsenate (CCA), PCP	Incineration or landfill

Another study, conducted by the CEPS, identifies several valorisation pathways for waste wood, emphasising its potential as a secondary raw material in various industrial processes (CEPS, 2024). One such pathway involves the co-processing of waste wood with polymers to manufacture insulation panels for use in the construction sector (Grigoriadis, K. et al., 2019). Despite this, the predominant material recovery route reported within the European Union remains its reprocessing into particleboard. Additional applications include the conversion of wood waste into pulp for industrial use, its integration into cementitious materials such as concrete and cement, as well as its utilisation in chemical synthesis and biological remediation processes (Bertoldo, N. et al., 2024). While these material applications present significant opportunities to support decarbonisation objectives across multiple sectors, the study notes that the exploitation of waste wood for such purposes remains limited in scale and largely untapped.

Identification and assessment of the viable technical solutions to promote circularity

Identifying technically viable solutions for increasing the circularity of wood products is essential to maximise resource efficiency, reduce environmental impact, and promote sustainable material cycles.

Prevention

Prevention remains at the top of the priorities, but preparation for reuse and recycling are also central to wood waste circularity, with significant environmental benefits such as over 50% reduction in GHG emissions when wood materials are reused or recycled in construction and demolition contexts (Shiyao Z., et al., 2024).

Regarding prevention, there are several options to minimise wood waste generation and its contamination levels, which include improved manufacturing processes to increase resource efficiency, switching from traditional site-building construction practices to building construction components in a controlled factory environment, among others. Ecodesign can also help to minimise wood waste generation through a larger focus on reusability, repairability, standardisation and modular design, as seen on wood pallets. The standards of the wood pallets market provide a potential blueprint for enhancing reuse and repairability in other products. Beyond construction and packaging, many other sectors that manufacture wood-based products (e.g., furniture) or use wood as a raw material (e.g., pulp and paper) have specific prevention measures that contribute to a circular model, usually related to ecoefficiency and ecodesign.

Since 2023, Member States are required to report data on reuse of certain product groups to the EEA, in accordance with Implementing Decision (EU) 2021/19. According to the data reported for 2023, approximately 2 million tonnes of furniture were reused across the EU (EEA, 2024), with a considerable share of wood although composition data is not available. This data highlights that, while reuse is occurring, the amount of reused wood in furniture remains relatively small when compared to the quantities of wood waste managed through recycling and energy recovery. This suggests that reuse remains an underutilised strategy in the overall circular management of wood products.

Mechanical recycling

A range of technical options for mechanical recycling is currently available or under development, depending on wood waste types and quality grades. The selection of appropriate technologies depends on several factors, including contamination levels, particle size, moisture content, and potential end-use applications.

The most established and technically mature pathway is recycling wood waste into particleboard and other engineered panels. The recycling process usually involves the collection, sorting and shredding of the wood waste; particles are then dried and blended with a resin and, finally, hot-pressed at high temperatures and pressure. Studies have demonstrated that even materials such as faulty particleboard and residues from wood processing can be successfully recycled as raw material (Iždinský et al., 2020). However, the presence of resins, additives, waxes, preservatives and other materials, as well as the reduced particle and fibre size, reduces the potential number of cycles after the wood waste is transformed. Beyond particleboards, the same pathway can result in a wide range of products, such as insulation panels and advanced composite materials, which ultimately depend on market demand and the existence of more cost-effective products. However, the use of more complex products where different materials become attached or merged, significantly reduces the potential for recycling.

When other higher-grade options are no longer possible, industrial wood waste can also serve as a versatile and increasingly valuable feedstock for a range of lower-grade applications, including mulch, landscape chips, soil amendments and animal bedding. These uses are especially relevant in small-scale sites and in regions where there is low demand for the manufacturing of particleboard and other engineering wood. This wood waste can be treated together with garden and forestry waste to take advantage of synergies in the treatment stage.

A small fraction of wood waste can also be used for fibre-based products, such as paper and textiles. Specific pre-consumer wood residues (e.g. from sawmills or furniture manufacturing) can be incorporated into pulping streams, especially for lower-grade paper or packaging products. As pulping is also a first step in the production of some textile fibres, wood waste can also be used, albeit with low economic and technical added values as it replaces easily available materials.

Organic recovery

Biochemical methods, such as enzymatic treatment and bioremediation, rely on the action of biological agents and controlled chemical reactions to facilitate the breakdown and valorisation of wood waste into useful materials. This pathway is commonly associated with the biorefineries concept. Together with other ligno-cellulosic materials, wood waste can be converted into basic chemicals and then used to synthesise advanced products, including biofuels. Processes such as anaerobic digestion are not well-suited for wood waste or similar bio-based waste streams, due to the stability of the fibres and the time it would take for decomposition.

Energy recovery

Thermochemical processes (including pyrolysis, gasification, and torrefaction) involve the application of high temperatures to transform wood waste into energy-dense products (Korba A., et al., 2025). These methods not only offer a sustainable pathway for managing low-quality or contaminated wood waste but can also generate valuable by-products such as bio-oil, syngas, and biochar, contributing to both resource recovery and energy production (Korba A., et al., 2025). Contrary to other bio-based waste streams, there are several large-scale, commercially viable plants using thermochemical processes to wood and forestry waste.

As discussed, **a significant part of wood waste is subject to energy recovery due to its high calorific value.** The use of wood waste as biofuel is actively promoted under renewable energy policies, including the Renewable Energy Directive (RED II and RED III), if sustainability criteria are met. In fact, with increased scrutiny of the sustainability of biomass, increased carbon prices and increased application of climate neutrality targets, the demand for bioenergy from wood waste and other biomass waste is expected to significantly increase (IEA, 2024). This legal framework has increased scrutiny of the origin of the wood waste to minimize the risk of the presence of primary wood for energy.

The energy use of wood waste takes place at all scales. From large-scale facilities, such as waste-dedicated incineration plants, cement plants, thermal power plants, down to small-scale activities, such as biomass boilers for building heating. The different treatment processes, such as shredding and pelletisation, are key to enable an economically and technically viable energy recovery process, but careful sorting is also key to minimise the environmental and health risks associated with wood waste. Countries have enacted different regulations and guidelines to ensure that contaminated and hazardous materials are adequately treated. In sum, energy recovery represents an important contribution to carbon neutrality goals, but it should be geared towards the material without recycling potential. This will be increasingly hard as energy-intensive industries will find in wood waste a key decarbonisation vector.

ANNEX 3. SEWAGE SLUDGE

Current State of Sewage Sludge Management in Europe

Generation

Eurostat - Sewage sludge production and disposal (env_ww_spd)
Eurostat is the main source of data about sewage sludge management in Europe. The data on sewage sludge production and disposal is reported under the joint OECD/Eurostat questionnaire and is not mandated under the SSD. Therefore, data collection methods are not fully harmonised. The data is collected on an annual basis, being the National Statistical Institute or delegated administrations (e.g. environment agencies) the default operational source of the data. National Statistical Institutes obtain data from multiple sources, such as regional and local authorities, environmental agencies, and industry, and, when appropriate, they complement this information with their own surveys and statistical estimation methods (Eurostat, 2025a).

Some countries have not reported data on sewage sludge in the recent years (Belgium, Denmark, Italy, Portugal), and Eurostat therefore does not publish an estimate for sewage sludge for the EU-27 as a whole. Adding up the generation of sewage sludge for the 23 countries for which data is available in 2022 leads to 6.2 million tonnes of sewage sludge generated in urban WWTP[11]. A gap-filling approach was followed for the missing countries with data reported for earlier years[12], which resulted in a total amount of sewage sludge generated for the EU-27 of 7.7 million tonnes.

The variation of the yearly per capita sewage sludge production in the Member States of the EU-27, is presented in Figure 21.

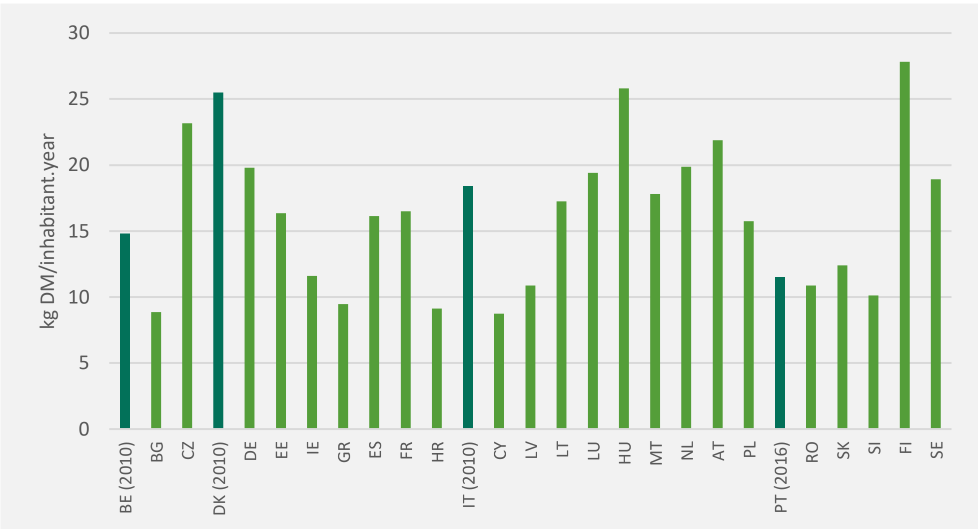

Figure 21. Sewage sludge production (kg DM/inhabitant.year) in the EU-27 in urban WWTP, 2022

[11] At the time of this report, data for 2023 is being published by Eurostat. However, in addition to the aforementioned Member States, Bulgaria, Greece, Spain do not report data for this year, and the Netherlands reports a provisional value. For this reason, the analysis focuses on the year 2022.
[12] Belgium (2010); Denmark (2010); Italy (2010); Portugal (2016).

Source: Eurostat, 2025b

Note: Member States marked in darker green have not reported data in recent years. The data gaps were filled using the most recent data available for each Member State with the indication of the reporting year.

Given that sewage sludge is a residue resulting from the treatment of wastewater treatment processes, a correlation is expected between production and the percentage of population covered by WWTP (Figure 22). In 2022, 81% of the EU-27 population was connected to at least secondary wastewater treatment.[13]

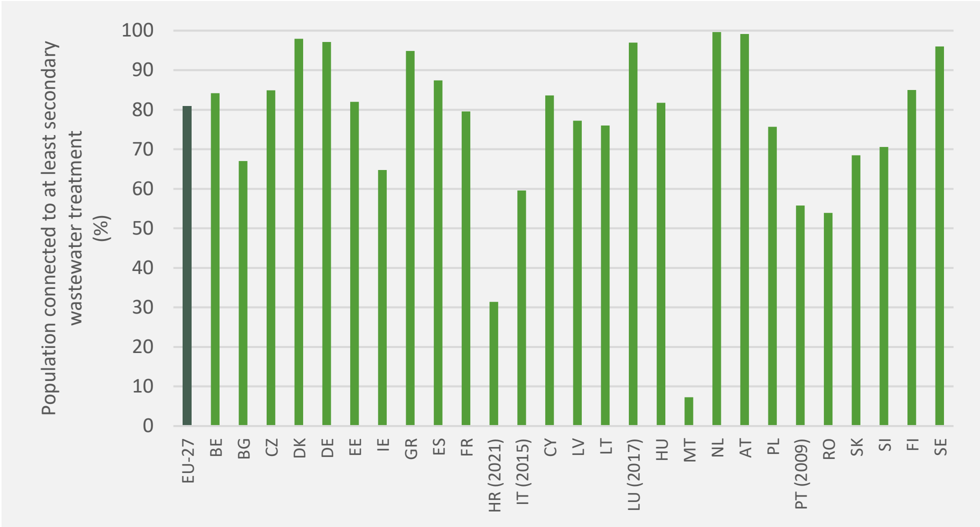

Figure 22. Population connected to wastewater treatment at least at the secondary level in the EU-27 Member States, 2022
Source: Eurostat, 2025c

In the case of Malta, even though the entire population is connected to WWTP, the share of wastewater receiving at least secondary treatment according to EU requirements is only at around 6% (EEA - WISE Freshwater, 2025a).

One potential reason for part of the differences observed between Member States (Figure 21) might be related to the fact that data is reported as dry matter (DM), and the methodology for this calculation might vary between Member States, and even between years. Even though data on sewage sludge production and disposal route refers to DM, there is no definition of DM in the SSD (EC et al., 2022). For example, a production of 242 tonnes DM of sewage sludge was reported by Lithuania in 2001 and 51 tonnes dry matter in 2010. This significant reduction could be explained by a correction in the DM evaluation methodology (Bianchini et al., 2016).

The data series on production and disposal of sewage sludge (Eurostat, 2025b) also provides information on the generated sludge in other WWTP. According to the Data Collection Manual for the OECD-Eurostat Joint Questionnaire on Inland Waters and Eurostat Regional Water Questionnaire, these include any non-public treatment plants, such as industrial

[13] Process generally involving biological treatment with a secondary settlement or other process that removes organic material and reduces its biochemical oxygen demand (BOD) by at least 70% and chemical oxygen demand (COD) by at least 75% (Eurostat, 2025c)

WWTP or treatment facilities of hotels, army camps, among others (Eurostat, 2023). However, for other WWTP, only nine Member States have reported sewage sludge quantities in any given year. In 2022, eight Member States reported a production of 1.6 million tonnes dry matter, including Malta and Slovenia, which reported a value of zero that year (Figure 23).

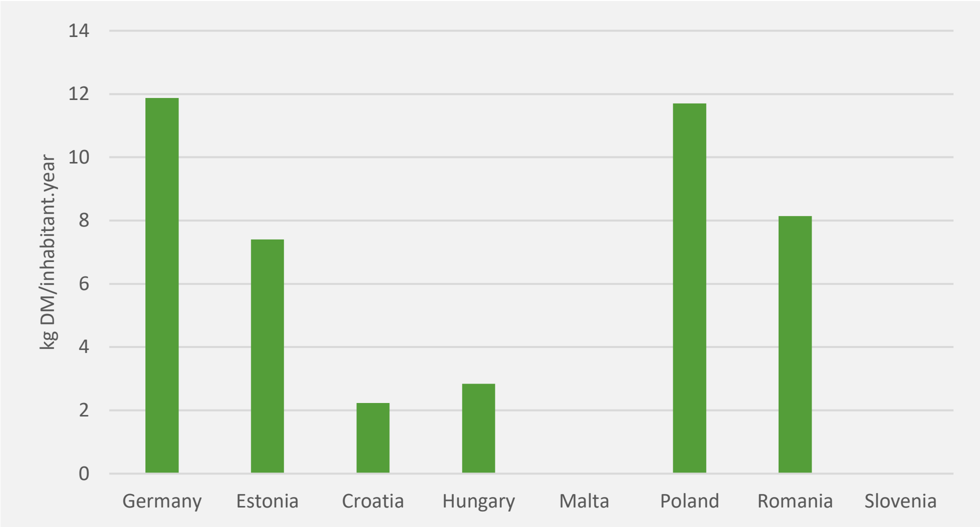

Figure 23. Sewage sludge production (kg DM/inhabitant.year) reported by selected Member State from non-public WWTP, 2022
Source: Eurostat, 2025b

It is possible to observe a significant variation in the per capita production values, which are close to the production values in urban WWTP for some Member States.

Eurostat – Waste Generation (env_wasgen)

Eurostat also publishes data on the generation of common sludges in the dataset 'Generation of waste by waste category, hazardousness and NACE Rev. 2 activity' (Figure 24), which are defined as wastewater treatment sludges from municipal sewerage water as well as organic sludges from food preparation and processing from households, municipal and industrial WWTP (Eurostat, 2010). Regarding the industrial sewage sludge, from on-site effluent treatment, the most intensive sectors typically include manufacture of paper and paper products, manufacture of chemicals and chemical products and manufacture of sugar (Eurostat, 2023). Regarding households, the sludge is associated with cesspit contents, namely septic tank sludge (LoW 20 03 04) and waste from sewage cleaning (LoW 20 03 06). However, the manual on waste statistics refers that regarding common sludges comparability between countries can be problematic, due to "different statistical units as they will not assign the waste to the same economic sector" (Eurostat, 2013).

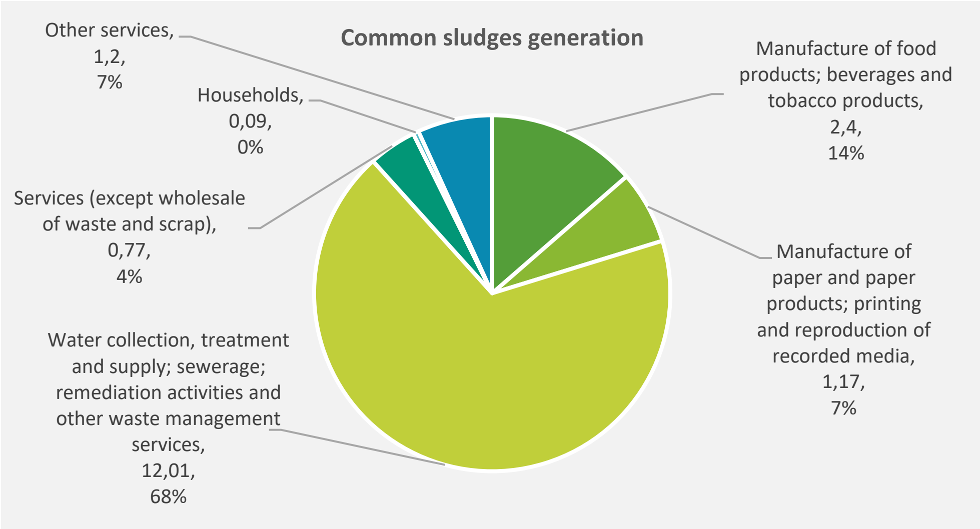

Figure 24. Common sludges generation (in million tonnes and share of total sewage sludge generation) in the EU, 2022
Source: Eurostat, 2025d

The quantity of sludge produced in the sector 'Water collection, treatment and supply: sewerage; remediation activities and other waste management services' (12.01 million tonnes DM) should be comparable to the sludge production in urban WWTP (7.7 million tonnes DM) from Eurostat (2025b). The differences between the two series could result from large-scale industrial remediation activities, such as cleaning contaminated soils which also can generate sludge.

In 2022, the yearly per capita sludge production from this sector in the six Member States with the largest total production of waste in the sector in 2022, namely, Belgium, Italy, Poland, Spain, France and Germany, is presented in Figure 25.

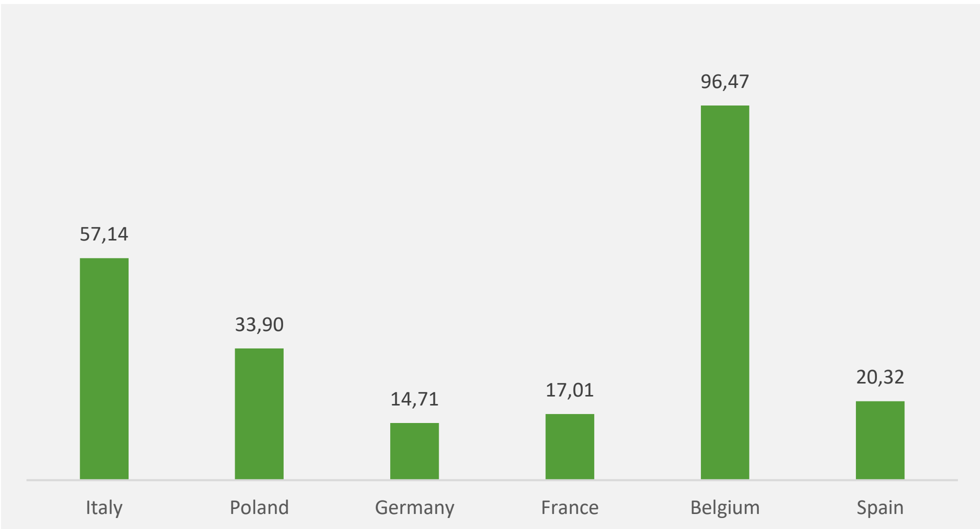

Figure 25. Sludge production from water collection, treatment and supply; sewerage; remediation activities and other waste management services (kg DM/inhabitant.year) for the Member States with the highest production, 2022
Source: Eurostat, 2025d

When comparing the different data series at Member State level (env_ww_spd and env_wasgen), around half showed a significant difference in the reported sludge production, i.e., a difference greater than ±30% (Figure 26). Considering that the env_ww_spd series does not provide values for all 27 Member States in 2022, for Belgium, Denmark, Italy and Portugal, the most recent data from this series was compared with the corresponding values from the same year in the env_wasgen series. The largest differences were observed in Hungary, Denmark, Belgium, Ireland and Bulgaria, where the difference between the values of common sludges (env_wasgen) and sludge production (env_ww_spd_urban) exceeded 70%.

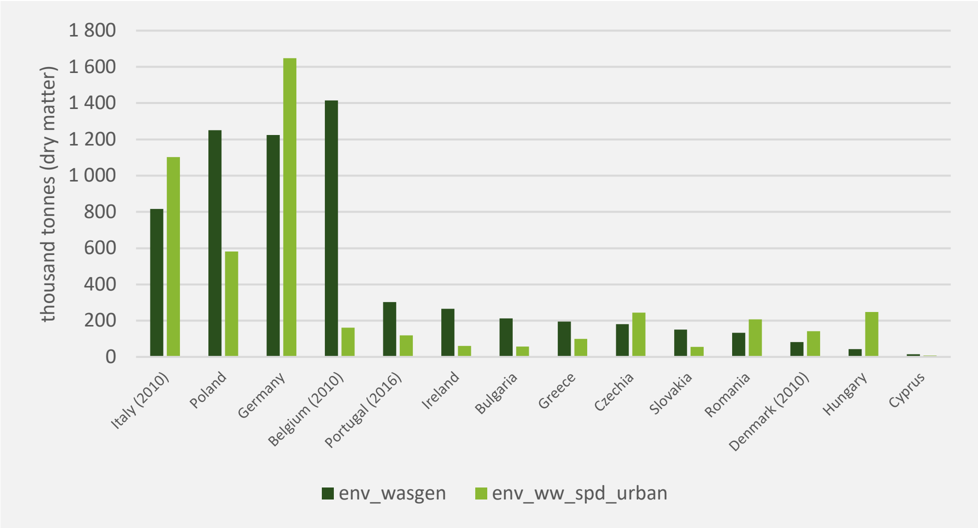

Figure 26. Comparison of sludge production data from different Eurostat series (only Member States with differences larger than 30%)
Source: Eurostat, 2025b, 2025d

Note: In the env_wasgen series, only common sludges from the sector 'Water collection, treatment and supply; sewerage; remediation activities and other waste management services' was considered.

In the env_ww_spd_urban series, in the absence of data for 2022, the most recent data available were used for the following Member States: Belgium (2010); Denmark (2010); Italy (2010); Portugal (2016).

In the case of Belgium, the third most significant difference between the two data series was observed, only surpassed by Hungary and Denmark.

Implementation of SSD

Member States are required by the SSD to report to the EC on the implementation of the Directive, whose findings are presented in a biennial implementation report (EC et al., 2022). As mentioned in the report regarding the evaluation of the SSD, there were several gaps in the data reported by Member States regarding both the total sludge produced and its use in agriculture, mostly associated with missing data. To avoid distortions in the representation of data, the EC filled the gaps through data extrapolation. Based on this approach, the estimated amount of sludge produced in the period 2007-2018 has remained relatively stable, with a reported production typically averaging between 7 and 8 million tonnes DM. This estimate is consistent with the value observed in the Eurostat series on sewage sludge production and disposal, which is around 7.7 million tonnes after gap filling.

EEA - Waterbase - UWWTD: reported data

Under the Urban Wastewater Treatment Directive (UWWTD), Member States are obligated to report a series of indicators related to their effluents, to ensure they meet emission control standards (The European Parliament and the Council, 2024). This information is consolidated in EEA's dataset 'Waterbase - UWWTD: Urban Wastewater Treatment Directive – reported data'. Information on sludge from this dataset is available in the EU's WISE Freshwater (EEA - WISE Freshwater, 2025b) for 2020, where a production of around 6.3 million tonnes of wastewater sludge at the EU is reported. As of the date of this report, this is the most recent data available; however, data referring to 2022 is expected to be released by the end of 2025.

Disposal and use

Eurostat - Sewage sludge production and disposal

The same approach to fill the data gaps in Member States' reporting used for sewage sludge generation was implemented for analysing the disposal (Figure 27), to avoid the distortion of results. According to (Eurostat, 2023) sewage sludge can be sent to:

- Agricultural use: all use of sewage sludge as fertiliser on arable land or pastures, irrespective of the method of application.
- Compost and other applications: all use of sewage sludge after mixing it with other organic material and composting, e.g. in parks or for gardens.
- Landfill: all sludge that is disposed of in tips, landfill areas or special depot sites and that serves no useful function.
- Incineration: all sludge that is disposed of by direct incineration or by incineration after mixing with other waste.
- Other disposal.

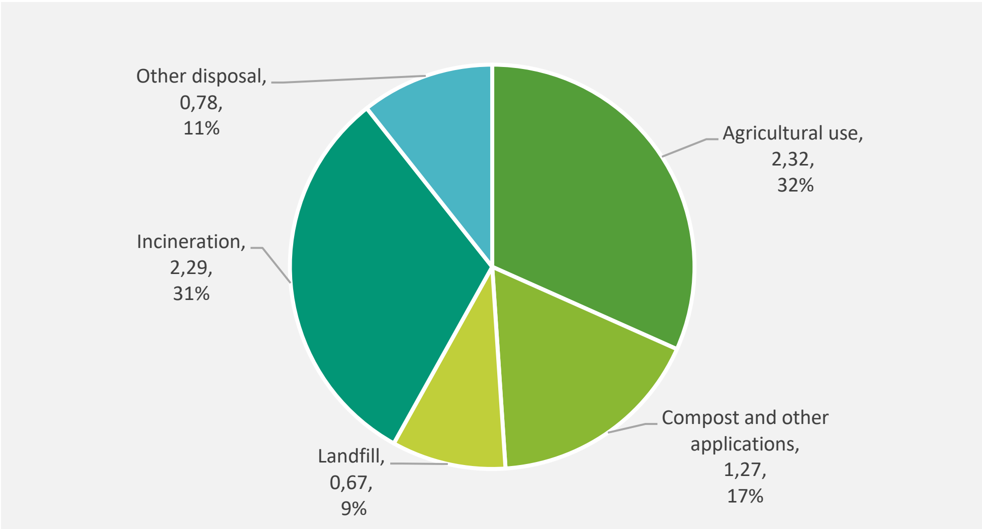

Figure 27. Sewage sludge disposal (in million tonnes and share of disposal) in the EU-27
Source: Eurostat, 2025b

It is important to note that in several Member States the total sludge production and total sludge disposal differ. This might be a result of sludge remaining in the treatment centre or other facilities at the beginning or end of a specific reporting year, or of its shipment intra-EU or extra-EU.

The analysis of sludge disposal at Member State level is presented in Figure 28.

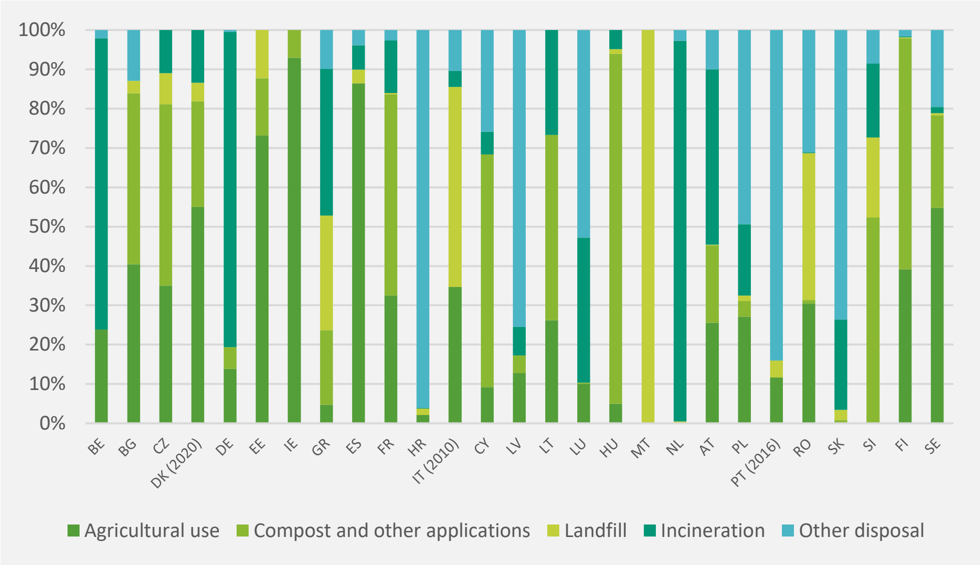

Figure 28. Sewage sludge disposal by Member State, 2022
Source: Eurostat, 2025b

In many Member States, the category "other" in sewage sludge management seems to cover a wide range of unclear, temporary, or non-standard practices. In some cases, such as Bulgaria and Croatia, the destination is unknown or limited to temporary storage within WWTP premises. While Italy mentions blending and repackaging sludge for unclear purposes, other countries report ambiguous uses like soil enrichment (Cyprus) or re-use within the plant site (Greece). The term "other" can refer to a variety of uses, including forestry, land reclamation, or landscaping (e.g., Latvia, Romania, Sweden), temporary or landfill storage (Slovakia), and even exporting to other countries (Slovenia). Notably, in Portugal, half of the sludge had no identified destination. Overall, the "other" category often reflects a lack of transparency, inconsistent reporting, or the application of sludge in ways that fall outside standard classifications (EEA - Ricardo Energy and Environment, 2021).

Implementation of SSD

According to EC (EC et al., 2022), the amount of sludge used in agriculture has remained rather stable in the period 2007-2018, between 2 and 3 million tonnes.

EEA - Waterbase - UWWTD: reported data

According to the information presented in (EEA - WISE Freshwater, 2025b), the wastewater sludge management in the EU in 2020 is presented in Figure 29.

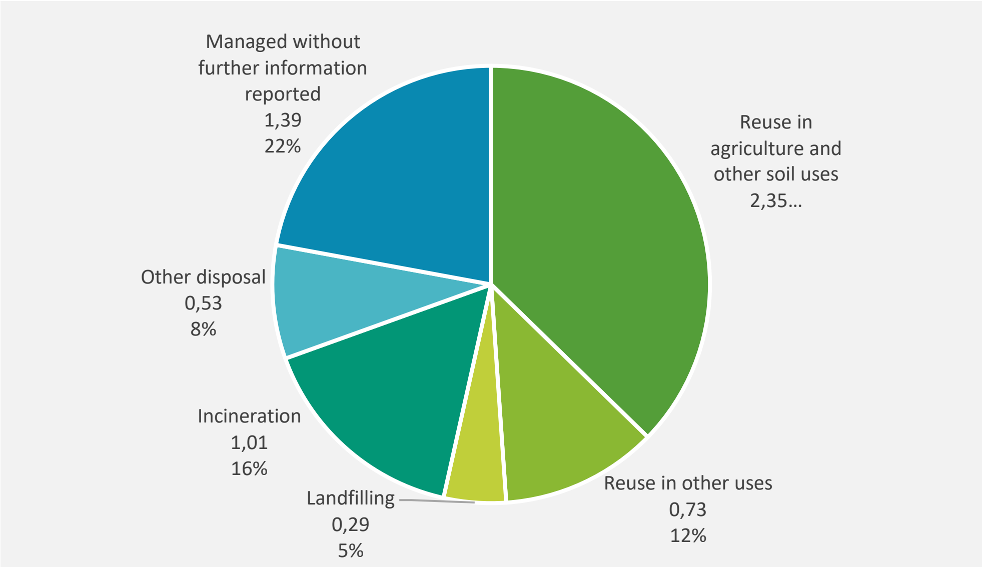

Figure 29. Waste water sludge management (in million tonnes and share of treated sludge) in the EU, 2020
Source: EEA - WISE Freshwater, 2025b

Identification and assessment of the viable technical solutions to promote circularity

The treatment of wastewater inevitably results in sewage sludge, and its generation is expected to rise as the population continues to grow (Mannina et al., 2024). Given that the revised UWWTD requires WWTP to carry out energy audits every four years, this could lead to the implementation of additional anaerobic digestion systems, a certain decrease in sludge volume is anticipated. Nutrient levels may increase, sewage sludge volumes are unlikely to decrease, and current challenges are expected to persist. Therefore, in the years to come, efficient sewage sludge management will continue to be crucial (Egle et al., 2023).

Despite current wastewater and sewage sludge treatment procedures partially eliminating some pollutants, many hazardous materials still enter effluents or sludge (Leino et al, 2025). For this reason, there are some effective upstream prevention strategies that can reduce contamination of wastewater with pollutants. Although rarely implemented, examples include replacing pollutant-generating chemicals and materials in production processes, enforcing legislation to limit atmospheric emissions of pollutants found in sludge, and installing sustainable urban drainage systems to remove contaminants from runoff before entering sewers (e.g., green roofs, permeable pavements, bioretention areas) (EEA – Ricardo Energy and Environment, 2021). In Sweden, upstream work is typically led by municipal water utilities through engagement with enterprises, public awareness campaigns, and source mapping. Under the REVAQ certification scheme, this includes monitoring influent water at WWTP, prioritising pollutants for detailed investigation, and screening chemicals used by connected enterprises (Fältström & Gustafsson, 2021).

Sewage sludge is mostly produced by biological processes, particularly the conventional activated sludge system, leading to research focused on advanced technologies to reduce it. The use of biofilm systems, long solid retention times systems to encourage cell lysis and cryptic growth, and coupling conventional activated sludge with anoxic/anaerobic reactors or ozonation to initiate sludge reduction mechanisms are some solutions (Morello et al., 2022). Nevertheless, certain approaches can be energy-demanding and may hinder the potential for complete recovery of energy and materials downstream (Blumenthal et al., 2025).

Traditional methods for disposing of municipal sewage sludge, such as agricultural use, composting, incineration, and landfilling, face limitations due to regulatory restrictions and growing environmental and public concerns in various Member States (Gusiatin et al., 2024).

According to the analysed data, the recycling of sewage sludge on land is the most common disposal technique in Europe, regulated by the SSD. Incineration is the second most common disposal method, with countries like Belgium, Germany and Netherlands preferring this option. It is worth mentioning that the application of sewage sludge on land has been banned in Switzerland, and Germany has established a national strategy to phase it out by 2029/2032 (European Sustainable Phosphorus Platform, n.d.-a; EEA, 2022c). However, applying sewage sludge to agricultural land is considered a key disposal option, offering a way to recover valuable plant nutrients (Salva et al., 2025). It contains macronutrients and organic carbon beneficial to plants and can be used in both agriculture and bioremediation. Its application improves the soil's physical properties, particularly by enhancing its capacity to retain water and nutrients (Neczaj et al., 2021). A study developed by EEA - Ricardo Energy and Environment, (2021) estimated that the management of sewage sludge in the EU-27 at that time meant that landspreading had the potential to enable the recovery of up to 69,300 tonnes of phosphorus and 96,300 tonnes of nitrogen. These amounts correspond to approximately 6.3% of the phosphorus fertilisers and 0.9% of the nitrogen fertilisers used in the EU in 2018.

Regarding composting, when properly processed, sludge compost can serve as a fertiliser or soil conditioner, enhancing soil quality and structure. This approach is considered technologically simple, requires lower investment and operational costs and is easy to implement compared to other treatment methods (e.g., thermal treatment, biodiesel production) (Salva et al., 2025). Additionally, when applied to soils contaminated with heavy metals, compost derived from municipal sewage sludge has shown potential for soil remediation, by acting as an organic amendment that contributes to the immobilisation of metals (Gusiatin et al., 2024).

The EU encourages exploring alternative methods to reuse municipal sewage sludge, focusing on thermal treatment for energy recovery and its conversion into new products, particularly for use in agriculture (Gusiatin et al., 2024). In this context, the circular economy prioritises nutrient recovery and the use of secondary raw materials, while safeguarding environmental and human health, and subsequently, the recovery of energy (EEA - Ricardo Energy and Environment, 2021).

Despite the presence of contaminants, sewage sludge contains valuable resources such as nitrogen, phosphorus, heavy metals, proteins, and enzymes, offering agricultural, environmental, and industrial potential beyond that of conventional sources (Tyagi and Lo, 2016; Gusiatin et al., 2024).

Phosphorus is essential for agriculture and food security, with rising global demand and finite phosphate rock reserves raising concerns over scarcity and supply risks. In 2020, the EU classified it as a critical raw material due to its economic importance and vulnerability to supply disruptions, guiding current efforts to focus primarily on phosphorus recovery (Kelly, 2025; Gusiatin et al., 2024). The updated UWWTD reinforces this priority by setting stricter phosphorus discharge limits for large treatment plants and promoting its sustainable recovery and reuse. This aligns with broader EU goals to reduce sludge disposal and improve the environmental and energy performance of wastewater treatment (Blumenthal et al., 2025). Phosphorus recovery from sewage sludge generally follows three main approaches. The first involves precipitation from P-rich side streams during wastewater treatment, producing struvite or calcium phosphates suitable for agriculture, with recovery rates up to 35% (or 50% with acid leaching). The second approach uses thermal methods like metallurgical or carbonisation processes, achieving over 80% recovery but facing technical and fertilising limitations. The third targets phosphorus in sewage sludge ash, using wet or thermochemical treatments to convert it into bioavailable forms or phosphoric acid, also reaching recovery rates above 80% (Sichler et al., 2022).

Emerging technologies for extracting valuable compounds from wastewater sludge are increasingly directed toward high-value products such as volatile fatty acids and polyhydroxyalkanoates (PHA) (Domini et al., 2022). Research interest in volatile fatty acids recovery has grown, with advances in two-stage anaerobic digestion, nutrient removal, and bioelectrochemical systems, while bibliometric analyses highlight it as an emerging field that requires further collaboration (Sanchez-Ledesma et al., 2023). Volatile fatty acids, generated during anaerobic digestion, have applications beyond energy, serving as feedstocks for bioplastics, biofuels, and wastewater treatment chemicals (EEA, 2020). The production of PHA, biodegradable plastics with properties similar to conventional ones, from wastewater has reached TRL 5–6 or higher, with industrial-scale feasibility and associated environmental benefits already demonstrated, including lower emissions from feedstock sourcing and waste disposal (ETC BE, 2025). Its production is gaining momentum, driven by demand for sustainable plastics and circular economy strategies, highlighting activated sludge as a cost-effective feedstock with strong potential for industrial-scale production despite requiring further development (Lorini et al., 2022; Coelho et al., 2025; Zhang et al., 2024).

Energy recovery from sewage sludge is a key strategy to manage increasing volumes, reduce waste, eliminate organic pollutants, and recover nutrients and metals (Salva et al., 2025). Technologies include anaerobic digestion, incineration, co-digestion, pyrolysis, gasification, hydrothermal liquefaction, and supercritical wet oxidation. These processes can generate heat, electricity, biofuels (e.g., hydrogen, syngas, bio-oil), and even construction materials (Tyagi and Lo, 2016).

Among these, anaerobic digestion is the most widely used, producing biogas that can be used for heat and power or upgraded to biomethane for injection into gas grids or as vehicle fuel (Domini et al., 2022; Corsino et al., 2023; Kehrein et al., 2020). In 2022, the EurObserv'ER Biogas Barometer reported that biogas production from wastewater treatment plant sludge reached 1.15 Mtoe in the European Union (EU-27). Thermochemical methods have some advantages, such as reducing sludge volume, eliminating pathogens, while still recovering energy, and can serve as an effective complement to anaerobic digestion. These processes provide improvements in process economics through proper design and reduced energy requirements. Pyrolysis and gasification enable faster sludge processing and offer versatile applications for end products (Gusiatin et al., 2024; Capodaglio and Callegari, 2023).

Incineration is another common method, reducing sludge volume by over 90% and enabling energy recovery. However, it releases all carbon and nitrogen to the atmosphere, leaving behind only phosphorus concentrated in the sewage sludge ash (Blumenthal et al., 2025). Sewage sludge ash (from mono-incineration) contains 5–11% phosphorus and recovery efficiencies can reach 90%. A key advantage is that phosphorus can be recovered at the end of the treatment chain, ensuring that it does not interfere with other measures implemented in the WWTP (Michellin Kiruba N et al., 2024; Kehrein et al., 2020). When agricultural application is not possible because soils are already full of nitrogen and phosphorus, where there are national bans on land application, if the sludge does not meet quality standards, heavy metals build up in soils that make it unsafe to use, or when phosphorus recovered from ashes is better for crops than direct land application (EurEau, 2021a), incineration is an adequate option for managing sludge.

In addition to energy recovery, sludge and its ash can be used as building materials in construction. Dried sludge or sewage sludge ash is utilised as an additive in cement-based products or as a component in the production of cement, bricks, ceramics, and lightweight aggregates (Tyagi and Lo, 2016; Chang et al., 2020).

Thermochemical processes such as liquefaction, pyrolysis, combustion, and gasification can simultaneously recover energy and concentrate metals in ash or biochar. These approaches are particularly promising when combined with recovery techniques already applied in sectors such as e-waste treatment or mining (e.g., ion exchange, alternative solvents, supercritical CO_2), offering potential pathways for resource recovery from sludge (Capodaglio and Callegari, 2023).

EU-funded projects such as SYSTEMIC, ENERCOM, LIFE ENRICH, SUPREMAS, ReLeaf, FlashPhos, CINDERELA, S2H2, RES URBIS, SMART-Plant, AshCycle and Fuels-C play an important role in promoting circularity within the sewage sludge value chain. These projects collectively aim to promote circular economy principles by developing innovative and sustainable solutions for the recovery and reuse of resources from various waste streams, particularly sewage sludge and other organic or urban wastes. Their goals include producing renewable energy (e.g., syngas and hydrogen), extracting nutrients and minerals for fertilisers, recovering valuable raw materials like white phosphorus, and creating construction materials from secondary raw materials. They also emphasise modular and scalable technologies, digital support tools, and integrated platforms to facilitate decision-making, market access, and knowledge sharing across sectors and stakeholders.

ANNEX 4. AGRICULTURAL WASTE

Current State of Agricultural Waste Management in Europe

Generation

Data on agricultural waste is available from different sources. However, a detailed analysis raises questions about their consistency and representativeness, mainly because there is no common definition of this waste stream across datasets. The EEA defines agricultural waste as “unusable materials, liquid or solid, that result from agricultural practices, such as fertilisers, pesticides, crop residues (such as orchard prunings) and cattle manure” (EEA, n.d.). Yet, there are no data sources that report agricultural waste as this consolidated set of streams. In this report, the analysis of agricultural waste focuses on manure and crop residues, as these are the two waste streams from agricultural activities that are currently the most consistently quantified. Waste streams originating from the agricultural sector, such as agricultural plastics and pesticides, are excluded from the scope of this analysis, as they are not bio-based waste.

For the purposes of this report, the term agricultural waste refers collectively to the two streams under analysis (manure and crop residues), while the term agricultural crop residues specifically designates the by-products generated during crop harvesting that are not considered the main product. Residue, when used in relation to crops, refers to material that is not the intended end-product of the production process. Residues are by-products that occur naturally, as the process is not primarily designed or deliberately modified to produce them (EC, n.d.).

It is also important to define the scope of the present analysis, which in this case is limited to the production phase (harvesting and farming/cultivation), while excluding processing and consumption. Accordingly, the analysis focuses on primary production, namely the activities of growing crops and raising livestock, without extending to the broader food system, which also encompasses food preparation and sales (Eurostat, 2020). It is important to note a potential overlap with the data considered in the assessment of food, garden and vegetal waste. Specifically, when analysing Eurostat data on animal and mixed food waste generation, as well as vegetal waste generation by economic activities and households in the EU in 2022, references were made to 1 Mt of animal and mixed food waste and 5 Mt of vegetal waste separately collected from the agriculture, forestry, and fishing sectors (Eurostat, 2025a). These sectors generate waste streams such as animal and vegetal waste, including slurry and manure, as well as various green wastes, including biodegradable fractions (Eurostat, 2020). It can therefore be inferred that part of this waste may originate from the primary production stage. However, it is not possible to obtain a disaggregated figure solely for the agricultural sector, as the data are aggregated across the three sectors in the EU Waste Statistics published by Eurostat.

The publicly available data on the generation of agricultural waste (manure and crop residues) are presented below. For crop residues, it should be noted that the quantities used in this report are based on models developed by the JRC and the ICCT, rather than on data reported by Member States.

Animal faeces, urine and manure

Eurostat – Waste generation

According to Eurostat (2010), the generation of animal faeces, urine and manure refers to slurry and manure of agricultural origin, including spoiled straw, as well as effluents that are collected separately and treated off-site.

In 2022, the total generation of animal faeces, urine and manure in the EU, from all economic activities and households, amounted to 16.2 million tonnes. Figure 30 illustrates the distribution of waste generation across the different economic activities and households, showing that agriculture, forestry and fishing represented the largest share (approximately 89%) (Eurostat, 2025a).

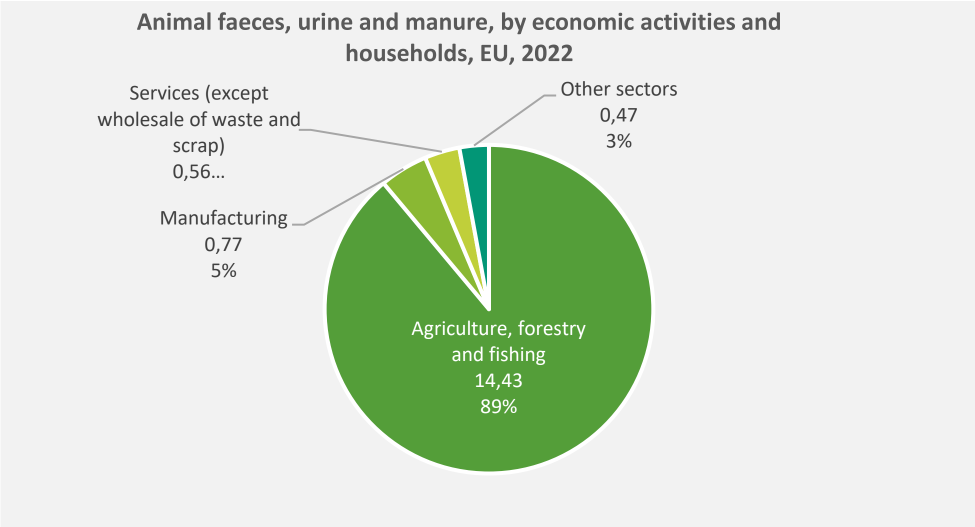

Figure 30. Animal faeces, urine and manure waste generation by economic activities and households, EU, 2022 (million tonnes and share of total waste)
Source: Eurostat, 2025a

It should be noted that the sector agricultural waste from “Agriculture, forestry and fishing” also includes horticulture, aquaculture and hunting. Within manufacturing, this waste is originated from the manufacture of food products, beverages and tobacco products, as well as the manufacture of chemical, pharmaceutical, rubber and plastic products. Other contributing sectors include electricity, gas, steam and air conditioning supply; water supply, sewerage, waste management and remediation activities; construction; services activities (except wholesale of waste and scrap); and households. For the purposes of this report, the focus is on the 14.4 million tonnes of animal faeces, urine and manure generated in 2022 by agriculture, forestry and fishing within the EU (LoW code 02 01 06). It should be emphasised that it is not possible to isolate the quantity produced solely by agriculture as the available Eurostat data combine these three sectors. Although this slightly exceeds the scope of agricultural waste considered in this analysis, these figures represent the most reliable data currently available.

EC – EU Bioeconomy Monitoring System

The EU Bioeconomy Monitoring System of the EC (2025a) provides an overview of European trends in indicators related to the EU Bioeconomy, including the generation of animal faeces, urine and manure from industry and agriculture. According to this indicator, approximately 3.2 million tonnes were generated in 2022. This figure is not directly comparable with the Eurostat values, as the EU Bioeconomy Monitoring System reports on a dry matter basis while Eurostat's data are refer to wet weight.

Crop residues

JRC – Residue generation

In 2025, the JRC published the report 'EU Biomass Supply, Uses, Governance and Regenerative Actions', which includes considerations on agricultural residue production (such as leaves, stems, and husks). It is emphasised that there are no systematic statistical data on residue production; as such, the values presented are the result of estimates derived from crop production figures using empirical models. According to the JRC, for the reference period 2018–2022, the annual production of agricultural crop residues in the EU was estimated at 423.7 Mt in dry matter. It is further noted that a decreasing trend was observed over these years, resulting from adverse weather conditions. The source also provides an estimate of the residue production of major crops (Figure 31), with 311 Mt of cereal residues (73.4%), 71 Mt of oil-bearing crops (16.8%), 22 Mt of permanent crops (5.3%), 12 Mt of sugar and starchy crops (2.7%), 7 Mt of pulses (1.6%), and 1 Mt of industrial crops (0.2%). It also provides a quantitative breakdown of each crop group by specific crop (JRC, 2025d).

Figure 31. Average annual production in the EU of agricultural crop residues by crop category for the period 2018-2022 (share of total crop residues, dry matter)
Source: JRC,2025

The source further highlights that 70% of the crop residues are produced by six Member States, namely: France, Germany, Italy, Poland, Spain, and Romania (JRC,2025).

The JRC has been developing work on this topic over several years and, as a result, already has substantial information available on crop residues. In 2023, the JRC published 'Biomass Supply and Uses in the EU – Summary for Policymakers', which provides an assessment of agricultural biomass production, sources and uses. The report presents an overview of the annual average residue production from agriculture in the EU-27 for the reference period

2016–2020, estimating a total of 424.1 Mt (dry matter) (JRCb, 2023). Figure 32 illustrates the distribution of this generation across the different categories of crop residues.

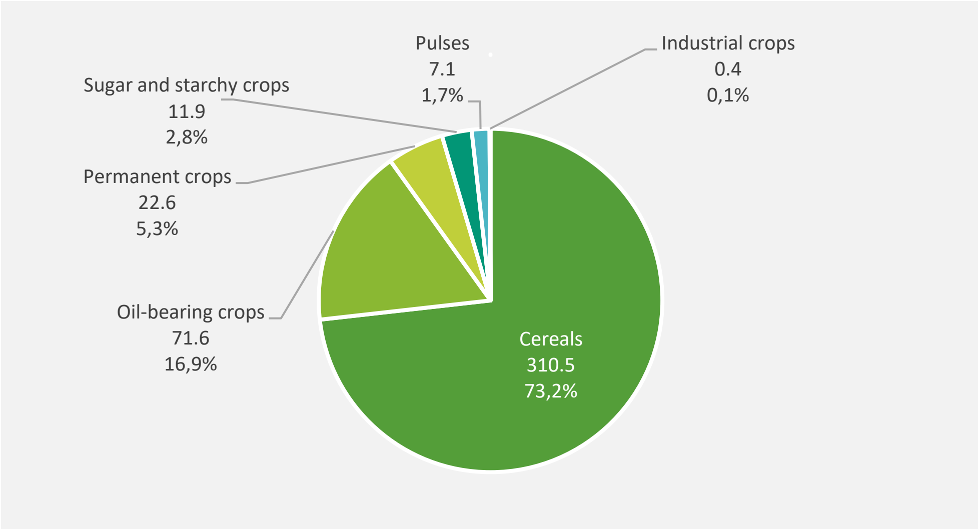

Figure 32. Average annual production of agricultural crop residues in the EU, by crop category, for the period 2016–2020 (million tonnes, dry matter, and share of total crop residues)
Source: JRC, 2023b

In 2018, the EC Knowledge Centre for Bioeconomy prepared a brief on agricultural biomass production, which estimated the average annual production of agricultural crop residues in the EU-28 for the period 2006–2015 at 442 Mt per year (dry matter) (JRC, 2018). The source further highlights the uncertainties associated with the estimates, noting that there are no systematic agricultural statistics on residue production. Instead, estimates are deduced from crop production figures using empirical models established from extensive datasets of observations for each individual crop. These models do not account for differences linked to genetic factors (varietal differences), agro-climatic conditions, or agro-management practices (e.g. irrigation, fertilisation). It is also emphasised that there is a lack of data on residue collection practices and on the current uses of crop residues. Moreover, to quantify the actual availability of crop residues for competitive uses, environmental sustainability requirements (e.g. soil conservation, biodiversity and the full range of ecosystem services in the agricultural sector) should be considered. To date, there is no agreed methodology to assess the quantity of residue needed to satisfy such requirements (JRC, 2018).

In 2019, the JRC published a study providing estimates of agricultural crop residues available at the European level. This study complemented earlier research by expanding the geographical scope to 36 European countries (presenting results both for the EU and Europe) and improving the underlying methodology. It assessed the amount of residues potentially obtainable from the main crops cultivated in Europe, namely wheat, rye, barley, oats, maize, rice, rapeseed, and sunflower. Four types of potential were considered: theoretical (total production of biomass residues without any harvesting, environmental and/or economic constraints), technical (amount that could be technically removed from the field), environmental (amount removable without harming soil), and sustainable (collection limited by both technical and environmental constraints, that is, by technical limitations related to harvesting and collection, as well as by environmental restrictions associated with soil impacts). The study estimated an average annual theoretical potential of 291 Mt (dry matter) in the EU, considering average values for the period 2000-2015. It highlighted an annual variability in crop residue production, ranging from 209 to 365 Mt (dry matter) per year, directly linked to fluctuations in agricultural production across all EU countries. This substantial variation in crop residue production between countries over the 15-year period helps to explain, at least in part, the differences observed in the estimates of crop residue potential reported in various studies. The technical potential was estimated at 168 Mt (dry matter) per year in the EU, while the average sustainable potential - which represents the amount that can be removed, taking into account technical and environmental constraints - was estimated at 124 Mt (dry matter) per year in the EU. This means that 124 Mt of crop residues can be mobilised in the EU to exploit its potential (JRC, 2019).

It is also worth noting that, as early as 2010, the JRC published a study presenting an earlier iteration of the estimation of agricultural crop residue production in the EU-27, covering the main crops: wheat, barley, oats, rye, rice, maize, sunflower and rapeseed. The analysis considered crop production, yields and cultivated areas. The study also considered sustainable removal rates to ensure the protection of soil fertility, as appropriate crop residue removal rates should be based on the minimum level of crop residues that should be kept on land to preserve soil quality, maintain soil organic matter, and reduce the risk of erosion. The study used sustainable removal rates of 40% for wheat, rye, barley and oats, and 50% for maize, rice, rapeseed and sunflower, with these values based on expert estimates and data reported in the literature on sustainable rates. Based on these rates, the yield and moisture content, it was also possible to estimate the amount of collectable crop residues. The study estimated that, on average, 258 Mt of agricultural crop residues (dry matter) were produced annually in the EU-27 over a ten-year period (1998–2007). Furthermore, it provided figures for the amount of collectable crop residues, with an annual average of 111 Mt (dry matter) across the EU-27, ranging from 86 to 133 Mt depending on yearly crop residue production (JRC, 2010).

International Council on Clean Transportation – Waste generation

The ICCT is an independent, non-profit research organisation that provides technical and scientific analyses to environmental regulators, enabling policymakers and other stakeholders to improve the environmental performance of road, maritime, and air transportation (ICCT, n.d.). The ICCT analyses the availability of agricultural crop residues for advanced biofuels, a key component of clean transportation strategies. In this context, the ICCT provides data on the generation of agricultural crop residues across the EU-27. These residues include the following crops: barley, maize, oats, olives, rapeseed, rice (paddy), rye, soybeans, sunflower, triticale, and wheat, which together represent the most significant crops within the EU (ICCT, 2021). Total residue production is calculated by multiplying the production of the main crop by a residue ratio, which indicates the amount of agricultural residue generated per unit of crop. Crop production and yield data are obtained from the FAOSTAT Database (Food and Agriculture Organisation Statistics), while residue ratios are taken from literature. Residue production is further adjusted for moisture content, with all estimates expressed in oven dry tonnes (ICCT, 2016).

According to the ICCT, a total of 286.4 million tonnes of agricultural crop residues were generated in the EU-27 in 2020. Country-level data also indicate that France, Germany, and Romania are the largest producers of agricultural crop residues, with 59.8, 39.1, and 30.9 million tonnes respectively. This is largely attributed to the scale of the agricultural sector in these countries (ICCT, 2021).

The data provided by the ICCT present certain limitations that should be considered. While the ICCT figures capture not only the quantities of agricultural crop residues generated, but also the quantities allocated to different applications and the share retained for maintaining soil quality, the report does not provide information on collection. However, it is assumed that the quantity of crop residues collected corresponds to the total used in applications such as heat, power, biogas, and other uses (livestock, mushrooms, and horticulture), amounting to 30.1 Mt. Nevertheless, the data compiled by the ICCT play an important role in consolidating and harmonising the information available at the European level.

Summary

Table 21 summarises the results obtained from the analysis of the aforementioned datasets on agricultural residue generation, indicating that the differences are considerable, primarily due to the scope covered by each dataset and the methodologies applied.

Table 21. Analysis of agricultural waste generation in the EU

Source: Eurostat, 2025a; EC, 2025a; JRC, 2025d; JRC, 2023; JRC, 2018; JRC, 2019; ICCT, 2021

	Eurostat – Waste generation	EC - EU Bioeconomy Monitoring System	JRC – Residue generation	JRC – Residue generation	JRC – Residue generation	JRC – Residue generation	ICCT - Waste generation
Waste categories	Animal faeces, urine and manure	Animal faeces, urine and manure	Agricultural crop residues	Agricultural crop residues	Agricultural crop residues	Agricultural crop residues	Agricultural crop residues
Time period	2022	2022	2018-2022*	2016-2020*	2006–2015*	2000-2015*	2020
Scope	Agriculture, forestry and fishing	Industry and agriculture	Wheat, maize, barley, rapeseed, sunflower, olive trees, vineyards, sugar beet, potatoes, field peas, broad and field beans, tobacco, fibre flax and cotton fibre	Cereals, oil-bearing crops, permanent crops, sugar and starchy crops, pulses and industrial crops	Wheat, maize, barley, rapeseed, sunflower, olive trees, vineyards, sugar beet, potatoes, field peas, broad and field beans, tobacco, fibre flax and cotton fibre	Wheat, rye, barley, oats, maize, rice, rapeseed, and sunflower	Barley, maize, oats, olives, rapeseed, rice (paddy), rye, soybeans, sunflower, triticale, and wheat
Generation dry basis (Mt)	-	3	424	424	442	291	286
Generation wet basis (Mt)	14	-	-	-	-	-	-

*Annual average in selected time period.

The analysis of sources reporting data on waste generation highlights significant discrepancies between them, not only because they cover different temporal periods, but also because, in the case of crop residues, they rely on empirical models to estimate quantities generated rather than on official reports from Member States. It should also be noted that the JRC has been the primary institution attempting to address this data gap in the quantification of agricultural crop residues.

Treatment and applications

Data on the treatment and use of agricultural waste and by-products are limited. For manure, such information is published exclusively by Eurostat, while for crop residues it is only available from the ICCT. It should be noted that the latter is based on a modelled estimation derived from main crop production and residue ratios, rather than on data directly reported by Member States.

Animal faeces, urine and manure

Eurostat – Waste treatment

In 2022, an estimated 12.3 million tonnes of animal faeces, urine and manure were treated within the EU (Figure 33) (Eurostat, 2025b). The reported data are not directly comparable with waste generation statistics, as they exclude exported waste while including the treatment of waste imported into the EU (Eurostat, 2025c). The waste management category "recovery - recycling" encompasses recovery operations R2 to R11, which comprise, among others, composting and anaerobic digestion.

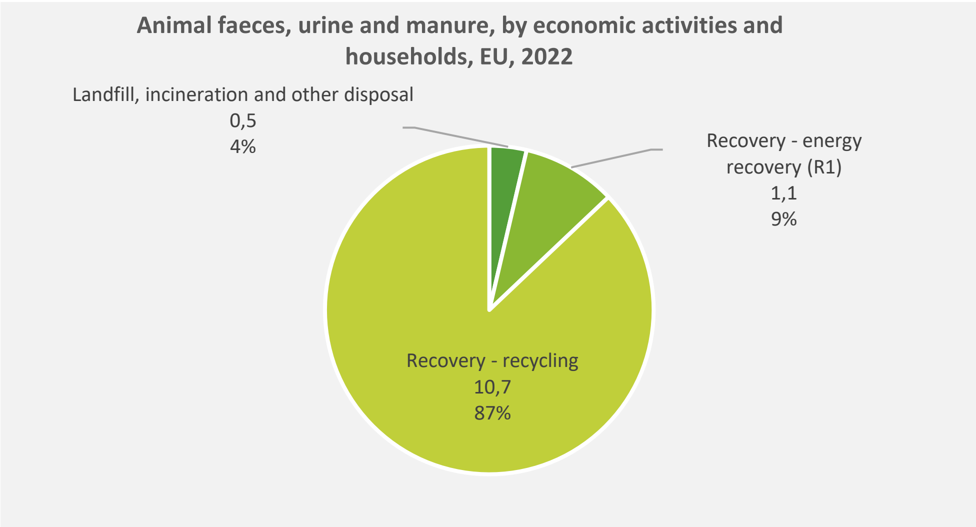

Figure 33. Animal faeces, urine and manure waste treatment by type of recovery and disposal, EU, 2022 (million tonnes and share of treated waste)
Source: Eurostat, 2025b

It is important to note that the reported amount of animal faeces, urine and manure treated in the EU in 2022 does not refer exclusively to the agricultural sector, as the Eurostat dataset does not provide a sectoral breakdown of this data. Consequently, the reported figures correspond to the total amount of this stream treated across all economic activities and households, which may include: agriculture, forestry and fishing; mining and quarrying; manufacturing; electricity, gas, steam and air conditioning supply; water supply, sewerage, waste management and remediation activities; construction; services activities; and households. Nevertheless, this represents the best publicly available data and provides an overall view of the treatment of this specific stream.

It should also be highlighted that a certain share of animal faeces, urine and manure is likely to be treated on-site and not entering the waste management system, meaning that this quantity is not captured in the waste treatment statistics. This share could in fact be significant. Considering only the bovine livestock population in the EU in 2024, estimated at 72 million head, and assuming that a typical cow produces approximately 5-6% of its body weight in manure per day - equivalent to a dry mass of around 5.5 kg per animal per day - the total manure generated by EU bovines can be estimated at approximately 144.5 Mt per year (Eurostat, 2025e; ScienceDirect, n.d.a). Although this figure is expressed in dry weight and is therefore not directly comparable with Eurostat data (which are reported in wet weight), it nonetheless highlights that, even when other types of livestock are excluded and only cattle are considered, the estimated quantity is considerably higher than the amounts reported by Eurostat as generated and treated within the EU. It should be noted that Eurostat only reports quantities treated off-site, while waste recycled internally is excluded from the reporting of both waste generation and waste treatment (Eurostat, 2024). This means that certain quantities of manure are generated and managed in situ. The quantity of manure potentially treated on-site at farms would be represented in Figure 33, according to the type of treatment applied. However, as no statistics are available to accurately capture these amounts, this treatment option is not included in the figure above.

Crop residues

International Council on Clean Transportation – Waste applications

Current uses of agricultural crop residues include heat, power and biogas generation, and other applications such as livestock feed and bedding, mushroom cultivation, and horticulture. Nevertheless, a certain share of crop residues must be left on-site to preserve soil quality (ICCT, 2021). According to the ICCT, in the EU-27 in 2020 approximately 8.5 Mt (dry matter) were utilised for heat, power and biogas, 21.6 Mt (dry matter) for other applications (including livestock, mushroom cultivation and horticulture), and 181.6 Mt (dry matter) were retained to maintain soil quality (ICCT, 2021) (Figure 34).

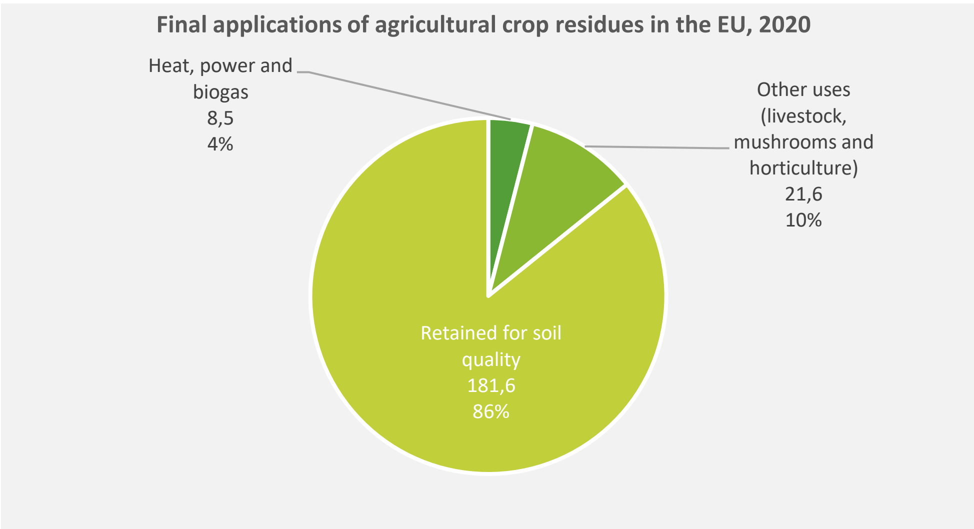

Figure 34. Agricultural crop residues applications by type of use, EU, 2020 (million tonnes and share of utilised residues)
Source: ICCT, 2021

According to the ICCT (2016), the quantities of agricultural crop residues allocated to heat, power and biogas were estimated using Eurostat data, specifically the category reported as “other vegetal materials and residues” under feedstock in total primary energy production.

ICCT assumes that half of this category corresponds to agricultural crop residues used for heat, power and biogas, resulting in an estimated 8.5 Mt. It should be noted, however, that this category is outdated and is no longer reported by Eurostat (Eurostat, 2025d). Regarding residue consumption for livestock feeding and bedding, ICCT (2016) estimates these values based on per animal rates and livestock numbers in each country. For mushroom cultivation, the estimates are derived from each country's mushroom production rate and a typical ratio for straw per tonne of mushrooms produced. Residue use in horticulture is assumed to be equivalent to that in mushroom cultivation. Together, these three categories (livestock, mushrooms and horticulture) amount to an estimated 21.6 Mt (ICCT, 2016).

The uses presented represent the main destinations of agricultural crop residues; however, other uses, for which no systematic data are available, may also account for a certain level of consumption, including industrial applications. One example that may gain increasing relevance is the production of biochemicals and biomaterials from cellulosic residues (ICCT, 2016).

The removal of agricultural crop residues from soils raises economic and environmental concerns, as these residues play a crucial role in maintaining and enhancing soil properties. They contribute to erosion prevention, the preservation and augmentation of soil organic matter, the retention of essential mineral nutrients, and the improvement of soil water-holding capacity (JRC, 2010). This quantity was estimated using a linear model, expressed in tonnes per hectare, for each EU Member State (ICCT, 2016). According to the ICCT, in 2020 in the EU-27, 181.6 Mt (dry basis) of crop residues corresponded to sustainable field retention requirements for soil quality (ICCT, 2021).

Identification and assessment of the viable technical solutions to promote circularity

Technical solutions for managing agricultural crop residues focus primarily on preventing and reducing their generation. Several approaches can be applied to minimise waste and reduce losses in agriculture, with their suitability depending on the type of crop, local conditions, and available infrastructure (Lackner and Besharati, 2025).

A solution for crop residues is their use as animal feed, providing several benefits such as an additional source of nutrients for livestock. Moreover, it also reduces livestock dependence on cereals intended for human consumption, alleviates financial pressures associated with waste management, and often provides a more cost-effective alternative to conventional feed. As a result, the use of unconventional feed sources has attracted growing interest in both developing and developed countries, where shortages in the quantity and quality of animal feed can be a challenge (Koul et al., 2022; Lackner and Besharati, 2025). Wheat straw is commonly utilised as animal feed, whereas rice straw is less frequently used due to its low digestibility; it is often better suited for applications such as the construction of animal shelters, like cattle shed roofs, owing to its lightweight nature, although the lifespan of such structures is typically limited to 2-3 years (Koul et al., 2022). In addition to being used as feed, straw and similar crop residues can also serve as bedding material for cattle and poultry (Joó et al., 2020).

Another solution involves using agricultural waste, including animal faeces, urine and manure, to feed microorganisms for the production of value-added products, such as bioplastics (Kircher et al., 2023). A variety of yeasts and bacteria can be employed for this purpose, while microalgae offer an alternative microbial pathway. Agricultural crop residues provide a suitable substrate for producing bioplastics, including polylactic acid (PLA) and polyhydroxyalkanoates (PHA), through controlled fermentation processes (Lackner and Besharati, 2025). PHAs hold significant potential as substitutes for conventional plastics due to their biodegradability, lower carbon intensity and status as a local resource. This biomaterial production pathway is currently regarded as both a forward-looking and commercially attractive technology (Joó et al., 2020).

Other solutions related to the production of new materials from agricultural crop residues include fibre production for industrial applications, bio-bricks, and the paper and pulp industry. Agricultural residues with high potential for fibre production include, for example, corn husks. For construction purposes, bio-bricks represent a sustainable and cost-effective alternative with a carbon-negative balance, based on agricultural residues. However, despite their advantages, bio-bricks are not yet suitable for structural load-bearing walls, and research is ongoing to enhance their mechanical performance. In the paper and pulp sector, non-wood agricultural residues such as cereal straw are gaining increasing attention. These resources can be used to produce pulp and paper, promoting the valorisation of agricultural waste while contributing to deforestation mitigation (Koul et al., 2022).

Composting remains one of the most widely used methods for managing agricultural waste and has been practised by farmers worldwide for centuries. Agricultural waste can be collected in heaps or tanks to undergo decomposition driven by natural microbial activity, producing compost suitable for agricultural applications. Composting - an aerobic process in which bacteria break down organic matter - and vermicomposting - a biological oxidation process involving both earthworms and microorganisms - are popular approaches. The resulting compost or vermicompost enriches soil with organic matter, supplies nutrients for fertilisation, and can even be used as a component in soilless agricultural substrates (Lackner and Besharati, 2025). At present, composting is particularly suitable for manure mixed with straw and other plant residues at the individual farm level, whereas large-scale composting requires significantly higher investment (Joó et al., 2020).

The use of animal manure and agricultural crop residues (organic fertilisers) enhances crop growth and yield, while also improving soil texture and stability. In addition, organic fertilisers have the advantage of releasing nutrients gradually. Compared to chemical fertilisers, they are a preferable option, as chemical inputs are associated with significant risks, including water pollution, soil infertility, and high costs related to processing, transport, storage, distribution, and application (Koul et al., 2022). Nutrient recovery technologies are effective in converting raw manure into valuable, nutrient-rich products. These processes involve the extraction and concentration of essential nutrients, such as nitrogen, phosphorus, and potassium, to produce high-value fertilisers. Unlike raw manure, the concentrated fertiliser is better suited for long-distance transport and application across different crops (Sadeghpour and Afshar, 2024). However, it is important to highlight the issue associated with the oversupply of manure in certain regions, where the concentration of intensive animal production leads to this excess. This can result in problems such as a gradual increase in soil phosphorus content, nitrate pollution, ammonia emissions, and heightened risks of water contamination. The surplus manure should be transported to other regions with low livestock activity (Garbs and Geldermann, 2018).

Soil mulching is another important technical solution. Mulch consists of a layer of organic or inorganic material applied to the soil surface to improve soil quality and protect it. Mulching mitigates the effects of solar radiation, reduces water evaporation, and enhances soil moisture retention. It also helps prevent erosion, maintains soil organic carbon, and provides a range of additional agronomic benefits (Lackner and Besharati, 2025; Koul et al., 2022). Common materials for mulching include grass clippings, leaves, straw, cereal husks, tree bark, wood chips, sawdust, decayed roots, palm leaves, animal manure, and other organic residues (Lackner and Besharati, 2025). It is important to note that plastic film and biodegradable film mulches also exist. Although these materials were not the focus of this analysis, their use have been addressed in published reports.

Another technical solution is the production of biofuels from agricultural crop residues, including bioethanol, biogas and syngas. Bioethanol can be derived from sugar or starch-containing crops, such as maize. Research has explored its production from a wide range of materials, including orange peels, and other fruit and vegetable residues. This biofuel can serve as a renewable energy source or as a supplement to conventional gasoline (Lackner and Besharati, 2025). It can also be a suitable source of ethanol for use in the pharmaceutical industry and other research laboratories (Ali et al., 2022).

Biogas production from agricultural waste, including animal faeces, urine and manure, offers another effective approach (Kircher et al., 2023). Collecting agricultural waste enables controlled methane generation through anaerobic digestion, where microorganisms decompose organic matter to produce biogas. Typically, biogas consists of 60-70% methane, with the remainder primarily carbon dioxide, along with minor amounts of hydrogen sulphide and hydrogen. The methane can be used for electricity generation through combined heat and power (CHP) units, as a fuel source, or for local applications such as cooking, heating, and lighting (Lackner and Besharati, 2025). Manure produced in intensive livestock systems is often directed to biogas plants, especially from large-scale farms. In addition to biogas, anaerobic digestion also produces digestate, which, due to its nutrient and organic matter content, can be used as fertiliser and soil improver (Joó et al., 2020; Ufitikirezi et al., 2024).

Another alternative pathway is the production of syngas from agricultural crop residues via gasification technology. This process provides a renewable option for electricity and heat production, allowing syngas derived from agricultural waste to replace fossil fuels. Gasification is most efficient for crop residues with low moisture content, such as straw, husks, and fibres, whereas anaerobic digestion is more suitable for wetter waste, such as animal manure (Lackner and Besharati, 2025; Ufitikirezi et al., 2024).

In addition to bioethanol, biogas and syngas, there are other biofuels with potential to be produced from agricultural waste, such as biohydrogen, biobutanol and biodiesel (Koul et al., 2022).

Agricultural waste can be converted into biochar, a carbon-rich material produced through pyrolysis. Pyrolysis involves heating organic matter in an oxygen-limited or oxygen-free environment. Approximately 50% of the carbon in the waste is retained in the biochar, in contrast to open-air decomposition, where a significant portion of carbon is lost to the atmosphere. Beyond its potential to reduce atmospheric carbon dioxide, biochar has demonstrated considerable value in environmental applications, including carbon sequestration, soil enhancement, water purification, and environmental remediation (Lackner and Besharati, 2025; Koul et al., 2022). Residues such as corn stalks, barley straw and bran, and sawdust have proven effective as biochar for adsorbing pollutants, including heavy metals (Lackner and Besharati, 2025). In the pyrolysis process, bio-oil is also produced, which has the potential to be used, among other applications, as a substitute for diesel, as well as in the production of resins and fertilisers. In addition, the gas generated during the process can likewise be utilised to produce electricity, heat, or both (Ufitikirezi et al., 2024).

Agricultural crop residues are also widely used in mushroom production, where wheat straw serves as a growing medium (Joó et al., 2020). Various edible mushroom species are cultivated worldwide using agricultural crop residues as substrates. Examples of these substrates include rice straw, wheat straw, corn husks, and sugarcane straw, among others (Koul et al., 2022).

magellan circle

3drivers