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Treatment and valorization of bio-waste in the EU

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ABSTRACT

Moving away from fossil feedstock requires industrial sectors to switch to renewable raw materials. One option is the processing of biomass. However, agricultural, forestry and marine production of biomass cannot be expanded indefinitely. The linear value chains established in the fossil-based economy, leading from primary raw material to products and then to waste, are therefore no sustainable option. Instead circular value chains that recycle waste and make it available again as a raw material are needed. This also applies to bio-waste, as it arises in the primary production of biomass, as well as residual and waste materials from their processing, use and disposal. This paper reports on the volumes and current processing of bio- and biogenic wastes in the EU, presents recycling options that can lead to higher value added and employment as well as a lower environmental footprint, and also discusses the research, infrastructure and framework conditions needed.

1. Introduction

Closing material cycles in a comprehensive circular economy model is necessary to achieve the UN Sustainable Development Goals (SDGs) (Schroeder et al., 2019). In 2015, the EU Commission therefore adopted a package of measures to close material cycles through a circular economy (EC, 2015a), which addresses in particular the treatment and reuse of waste. Waste is to be avoided wherever possible and unavoidable waste is to be reused rather than landfilled or incinerated. The package of measures includes the following targets:

- By 2030, 65% of municipal waste is to be recycled.
- By 2030, the proportion of municipal waste sent to landfills is to be reduced to 10%.
- Landfilling of separately collected waste will be prohibited.
- Recovery and recycling systems will be promoted.

A significant part of the waste materials addressed here is bio-waste. Its management is regulated in Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (EUR-Lex, 2018) which has been consolidated in 2018. Concerning bio-waste the directive asks in article 22

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member states to ensure, by 31 December 2023, that „bio-waste is either separated and recycled at source, or is collected separately and is not mixed with other types of waste". Member states may allow waste „with similar biodegradability and compostability properties…recoverable through composting and biodegradation, to be collected together with bio-waste“. The directive continues, that „by 31 December 2024, the Commission shall consider the setting of preparing for re-use and recycling targets for construction and demolition waste and its material-specific fractions, textile waste, commercial waste, non-hazardous industrial waste and other waste streams, as well as preparing for re-use targets for municipal waste and recycling targets for municipal bio-waste. To that end, the Commission shall submit a report to the European Parliament and to the Council, accompanied, if appropriate, by a legislative proposal.“

This manuscript aims to contribute to the necessary discussion on the status and on the potential of recycling of bio-waste (e.g., food and garden waste) and bio-based wastes (e.g., wastes deriving from bio-based materials including plastics). The recycling of these wastes is of particular importance in the future circular economy because it i) represents a sustainable alternative to the use of the fossil carbon and energy sources oil, natural gas and coal and ii) relieves the limited production capacity of biomass for industrial purposes. In the following, the average treatment of these wastes in the EU and in exemplary member states is analyzed. Subsequently, new recycling options and the research requirements for their realization are discussed.

2. Methods

The following Eurostat databases were used to analyze the volume and treatment of biogenic wastes in the EU:

- Generation of waste by waste category, hazardousness and NACE Rev. 2 activity [ENV_WASTRT] last update: 04/01/2022 11:00 (Eurostat, 2022a)
- Treatment of waste by waste category, hazardousness and waste management operations [ENV_WASTRT] last update: 04/01/2022 11:00) (Eurostat, 2022b).
- Regulation on waste statistics (EC) No. 2150/2002 (EUR-Lex, 2002), amended by Commission Regulation (EU) No. 849/2010 (EC, 2010a). Data on the generation and treatment of waste is collected from the member states. The information on waste generation has a breakdown in sources according to NACE classification and household activities and in waste categories according to the European Waste Classification for statistical purposes. The information on waste treatment is broken down to five treatment types (recovery, incineration with energy recovery, other incineration, disposal on land and land treatment) and in waste categories. The Member States are free to decide on the data collection methods. The general options are: surveys, administrative sources, statistical estimations or some combination of methods.

The data sets contain a breakdown into 51 waste categories according to the European Waste Classification for statistical purposes (EC, 2010a). It is a mainly substance-oriented classification, and it distinguishes hazardous and non-hazardous waste. The classification is linked to the administrative classification List of Wastes: (EC, 2010a). The generation of waste is attributed to either production or consumption activities. The actor handing over the waste to the waste management system is regarded as the source.

In this study, only waste classified as non-hazardous was considered. The most recent data available is for the year 2018, i.e. Great Britain, which in the year 2020 left the EU is included in the data set. The following non-hazardous biogenic wastes, based on their Code, were investigated using the Eurostat database (Fig. 1).

For the analysis of the sectors from which the waste under consideration originates, the NACE categories were considered (EC, 2010b) (Fig. 2).

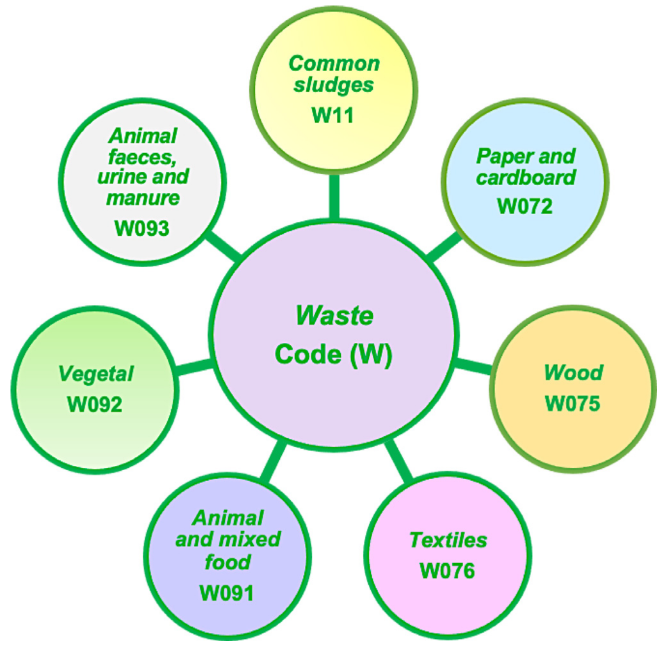

Fig. 1. Codes of the analyzed waste categories according to the Nomenclature of Economic Activities (NACE).

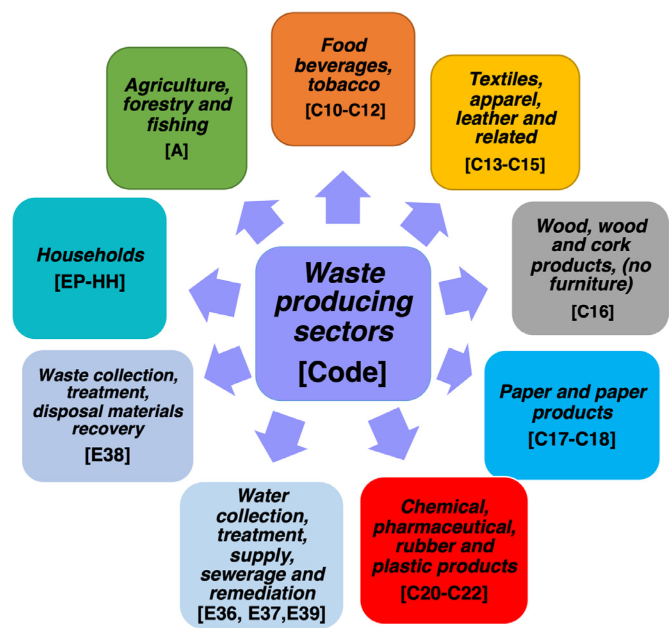

Fig. 2. Sectors generating waste according to NACE.

The waste was analyzed in terms of recovery methods, using the respective Eurostat database (Eurostat, 2022b). This database includes the recovery routes according to the Waste Directive 2008/98/EC D1-D12 and R1-R11 (EURO-Lex, 2008) (see Table 1).

3. Results

In the following sections, the volume of various non-hazardous biogenic waste materials generated in European countries is first presented (Section 3.1). This is followed in Section 3.2 by an analysis of the industrial and private sectors according to NACE-classification from which these waste materials originate, and finally, in Section 3.3, the treatment of these wastes is analyzed followed by concrete examples from selected countries.

Table 1
Codes of waste treatment operations.

Operation	Code
Deposit into or onto land (e.g., landfill etc.)	D1
Land treatment (e.g., biodegradation of liquid or sludgy discards in soils etc.)	D2
Deep injection (e.g., injection of pumpable discards into wells, salt domes or naturally occurring depositories, etc.)	D3
Surface impoundment (e.g., placement of liquid or sludgy discards into pits, ponds or lagoons, etc.)	D4
Specially engineered landfill (e.g., placement into lined discrete cells which are capped and isolated from one another and the environment, etc.)	D5
Release into a water body except seas and oceans	D6
Release into seas/oceans including sea-bed insertion	D7
Incineration on land	D10
Permanent storage (e.g., placement of containers in a mine, etc.)	D12
Use principally as a fuel or other means to generate energy	R1
Solvent reclamation/regeneration	R2
Recycling/reclamation of organic substances which are not used as solvents (including composting and other biological transformation processes)	R3
Recycling/reclamation of metals and metal compounds	R4
Recycling/reclamation of other inorganic materials	R5
Regeneration of acids and bases	R6
Recovery of components used for pollution abatement	R7
Recovery of components of catalysts	R8
Oil-refining or other reuses of oil	R9
Land treatment resulting in benefit to agriculture or ecological improvement	R10
Use of wastes obtained from any of the operation numbers R1 to R10	R11
Waste exchange to submit them to one of the operations indicated in R1 to R11	R12
Storage of waste pending any of the operations numbered R1 to R12 (excluding temporary storage, pending collection, on the site where the waste is produced)	R13

3.1. Non-hazardous biogenic waste volume per country

Tables 2a and 2b show the volumes of waste generated in the year 2018 in the EU28 plus selected non-member states such as Turkey and Norway, as they are listed by Eurostat (Eurostat, 2022a; Eurostat, 2022b). In total, 237 million metric tons of non-hazardous biogenic waste materials are collected annually in seven categories in these countries. The most important categories in terms of volume are W092 (vegetal wastes) with a share of 25%, and, with 24% each W072 (paper and cardboard wastes) and W075 (wood wastes). Together, these categories account for about 75% of the non-hazardous biogenic waste.

With regard to the volume of the individual categories in the different countries, the following peculiarities should be mentioned. Italy reports a particularly high incidence of sludges (W11), accounting for 29% of the total European volume. Italy is also the leader in the production of textile wastes (W076; share 20%) and animal and mixed food wastes (W091; share 20%). With a share of 36%, Spain produces the highest volume of animal faeces, urine and manure in Europe (W093); for all other categories, the Spanish share is below 10%. Also, the Netherlands supply a high share of animal faeces, urine and manure (27%). When considering the total waste volume, more than 10% of the total volume of bio-waste is individually generated in Germany, France, Italy and the United Kingdom.

3.2. Origin of non-hazardous waste volumes per sector

This section analyzes selected sectors according to NACE from which the waste under consideration originates (Table 3a,b). The total amount of waste considered in Table 3a, 229 million tons, almost coincides with the total amount mentioned in Table 2a of 237 million tons. The selected NACE sectors thus produce 97% of the total biogenic waste. This confirms that the NACE relevant sectors for the present analysis have been selected. When looking at the total waste volume of the individual sectors, it can be seen that households and services generate 40% of the total waste volume, with households accounting for more than half of that. In particular, households are leading in supplying paper and cardboard wastes (W072), and vegetal wastes (W092), while for services (W072) paper wastes have the highest share with 30%. Sewage sludge originates 60% from water treatment (E36, E37, E39). With a share of 25-30% each comes wood waste with the construction [F] and furniture sectors [C24-C25], textile waste (W076) with households (EP-HH) and the textile sectors (C13-C15), and categories W091-W092 (animal and mixed food, vegetal waste from households) come with the food sector (C10-C12).

3.3. Examples of treatment and utilization of non-hazardous biogenic waste

The following table (Table 4) shows how waste was treated, or recovered, on average in the EU28 in 2018, namely through landfilling, incineration, energy recovery and recycling. These methods are defined as follows:

Landfilling is defined in the Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste (EUR-Lex, 1999a). Incineration means incineration without energy recovery (EUR-Lex, 2019). Recovery of energy and materials (recycling), means any operation the principal result of which is waste serving a useful purpose by replacing other materials which would otherwise have been used to fulfill a particular function, or waste being prepared to fulfill that function, in the plant or in the wider economy (CIWM, 2022). The recovery codes are listed in Section 2.

The first thing to notice is that for the waste categories considered, the total volume of treated waste is reported to be 174,650 million tons per year. This volume represents only 76% of the total volume of biowastes given in the Table 3a (229 million tons). It is also clear when looking at the treated volume of the individual waste categories that no category is completely treated. The range of the percentage of treated waste is from 60% (W11, sludges) up to a maximum of 82% (W092 animal faces, urine and manure). Where the 18-24% untreated portion of the generated waste which remains, is not reported.

If looking on the volumes reported as treated only for all waste categories, the percentage that is recycled to compost, fertilizer, or biogas (R2-R11) reaches in average 79%. Recycling ranges from 48% (W075, wood waste) to 99% (W072, paper and card board waste). Energy recovery reaches a share of in average 16%, but a share of more than 10% is reported only for textile wastes (W076, 12%), sludges (W11, 15%), and for wood wastes (W075, 47%). Incineration without energy recovery plays only a minor role of in average 3% with a highest share of 8% (W093, animal faeces, urine and manure) and 11% (W11, sludges). The same applies to landfilling (1.5% in average), which reaches shares of up to 8% each for sludges (W11) and textile wastes (W076).

For individual member states, the shares of recycling methods can deviate considerably from the EU28 averages. Some examples of disposal practices in individual countries are therefore presented below.

3.3.1. W11 Sludges: the case of Bulgaria

The National Strategic Plan for Sludge Management 2014-2020 sets goals in line with Bulgarian and European legislation. These targets are for the recovery of sludge generated by waste water treatment plants (WWTP) with a deadline at the end of 2018 and include achieving 60% recycling and material recovery and 20% for energy recovery. Urban waste-waters are defined as a mixture of domestic and industrial wastewater, and often include rainwater runoff through a central sewage system. Total amount of non-hazardous sludge has been 90,049 tons in 2018. 53,083 tons came from urban waste water treatment plants (WWTP), while the rest of 36,966 tons were attributed to the industry. Major quantities of sludge are generated in the WWTP of Sofia (23,101 t dw), Ruse (6,614.46 t dw) and Plovdiv (4,810 t dw) (EEA, 2019). The sludge is rich in plant nutrients important for crop production. In recent years, interest in sludge composting in Bulgaria has gradually increased. The process and final product quality is regulated by the Regulation on separate collection of bio-waste and treatment of biodegradable waste from 2017 (Council of Ministers, 2017). One way of the utilization of sludge common in Plovdiv district is composting. Apart from sludge, the agricultural byproduct straw produced in the region is also used in the composting process. Due to the high temperatures of 60-65°C, which are reached during the process, unwanted biological materials (microflora, seeds, etc.) are inactivated, and by composting organic matter is converted into compost. At the end of the process, to improve the quality as fertilizer, earthworms are applied to the fresh compost obtained. In this way, vermicomposting takes place, enriching and improving the obtained vermicompost. This method of sludge utilization is a practice in various WWTPs in Plovdiv district and is documented in the annual report of the Bulgarian Executive Environmental Agency. Table 5 lists the volumes and way of treatment of sludge (W11) in Bulgaria in the year 2018 (EEA, 2019). According to Eurostat (Eurostat, 2022b) a share of 15% has been treated. The whereabouts of the remainder of 76,393 t (85%) is not reported.

As can be seen from Table 5, landfilling was the most applied kind of treatment with 13,320 t (14.8%). 12 tons (0.1%) were disposed by incineration (D10). Recovery operations for energy (R1) and recycling (R2) were applied in 2018 for 300 tons (0.3%) and 24 tons (0.03%), respectively. This is a very small amount for recycling compared to the data of 2016 when Eurostat reported 70,2036 tons to be recycled (R3) representing a share of 68.1% of the total sludges (W11) generated. According to our survey, the lack of use of stabilized sludge in agriculture in 2018, is plausibly explained by storing before treatment (R13 - storage of waste pending any of the operations from R1 to R12). In addition, in 2018 no sewage sludge was co-incinerated and used as secondary fuel (R1), although there are kilns suitable for the incineration of sewage sludge in the three large cement plants in Bulgaria. For this reason, the goals set in the National Strategic Plan for 2018 (Council of Ministers, 2017) for utilization of sludge by energy recovery (R1) have not been met.

3.3.2. *W072 Paper and cardboard wastes: the case of Poland*

The data discussed below come from the national Database on Products and Packaging as well as Waste Management BDO (BDO, 2022). Since the information in BDO is collected on the basis of the European waste classification (EWC), the waste codes listed in tables 6 were selected for analysis.

In Poland, in 2019, the most frequently used methods of recycling and recovery were processes described by codes: R3 and R12 - including, inter alia, preliminary processes such as disassembly, sorting, crushing, thickening, granulating, drying, shredding, conditioning, repackaging, separating, blending or mixing before being subjected to any of the recycling and recovery processes.

R3, received in total 1,298,225.112 tons of waste and constitutes the main mass of paper and cardboard waste. On the other hand, the processes covered by code R12, were subject to a total of 51,819.797

Table 2a
Non-hazardous biogenic waste per European country[a]

Country	Waste (t/year) W11	W072	W075	W076	W091	W092	W093	Total/country
AUSTRIA	413,358	1,595,892	1,348,171	68,348	837,580	1,387,235	50,914	**5,701,498**
BELGIUM	843,021	3,380,865	3,882,374	199,456	1,245,076	7,504,038	69,174	**17,124,004**
BULGARIA	90,049	498,445	333,367	24,315	62,346	301,839	107,670	**1,418,031**
CROATIA	21,918	254,733	95,275	10,357	53,295	78,782	537,000	**1,051,360**
CZECHIA	216,877	1,370,067	287,604	131,614	97,556	959,982	64,659	**3,128,359**
CYPRUS	10,721	50,305	6,525	2,629	50,715	28,724	3,027	**152,646**
DENMARK	163,059	658,138	571,406	26,854	382,768	946,471	243,306	**2,992,002**
ESTONIA	37,880	95,683	182,245	4,155	45,222	72,048	69,282	**506,515**
FINLAND	641,887	525,456	4,320,632	14,456	617,557	421,142	42,481	**6,583,611**
FRANCE	1,374,486	7,290,000	7,147,773	238,998	3,761,395	7,796,189	300,000	**27,908,841**
GERMANY	1,597,623	7,631,010	11,674,219	338,342	1,928,713	12,220,636	670,687	**36,061,230**
GREECE	120,663	839,574	78,060	9,100	329,521	482,640	300,042	**2,159,600**
HUNGARY	167,733	670,546	131,839	21,537	102,870	328,071	338,632	**1,761,228**
IRELAND	774,183	795,667	210,853	7,865	975,447	168,589	25,113	**2,957,717**
ITALY	6,057,237	5,613,205	5,239,390	519,214	5,410,415	2,979,959	64,110	**25,883,530**
LATVIA	18,098	91,069	56,670	226	114,056	143,825	0	**423,944**
LITHUANIA	46,492	177,826	156,808	11,710	36,137	364,981	21,030	**814,984**
LUXEMBOURG	14,229	94,462	27,399	7,494	47,305	81,199	456	**272,544**
MALTA	9,096	14,469	9,738	1,195	13,160	5,089	9,954	**62,701**
NETHERLANDS	631,802	2,051,242	2,616,516	126,208	2,434,803	9,392,578	3,518,566	**20,771,715**
NORWAY	232,164	792,972	769,470	6,180	581,508	181,885	0	**2,564,179**
POLAND	574,802	2,527,943	2,095,240	131,985	590,826	1,738,453	297,269	**7,956,518**
PORTUGAL	964,073	1,064,915	399,965	103,954	176,581	168,367	13,205	**2,891,060**
ROMANIA	224,079	653,446	2,731,800	41,150	200,724	873,499	19,719	**4,744,417**
SLOVAKIA	459,064	319,930	449,431	16,311	58,910	377,202	376,378	**2,057,226**
SLOVENIA	50,140	219,744	94,146	9,905	80,100	104,429	66,477	**624,941**
SPAIN	1,603,261	3,379,352	1,114,863	94,334	2,138,666	2,383,628	4,769,448	**15,483,552**
SWEDEN	416,745	940,297	1,775,392	10,696	730,183	836,897	911,776	**5,621,986**
UNITED KINGDOM	2,902,716	10,453,351	7,466,319	199,813	4,396,874	6,307,488	189,952	**31,916,513**
BOSNIA and HERZEGOVINA	4,019	31,925	220,573	3,238	21,738	22,695	9,315	**313,503**
ICELAND	4,034	35,104	27,171	1	30,114	9,647	696	**106,767**
LIECHTENSTEIN	2,544	6,153	0	0	3,693	6,478	0	**18,868**
MONTENEGRO	10,234	9,350	27,648	109	9,727	31,909	4,270	**93,247**
NORTH MACEDONIA	3,569	111,391	4,092	4,578	11,863	7,256	0	**142,749**
SERBIA	136,570	190,512	67,756	11,320	27,580	47,285	70,334	**551,357**
TURKEY	341,138	1,679,571	687,987	231,836	137,376	712,321	512	**3,790,741**
Total per category	21,179,564	56,114,610	56,308,717	2,629,483	27,742,400	59,473,456	13,165,454	**236,613,684**
Share (%)	9	24	24	1	12	25	6	
Total EU28	20,450,000	53,280,000	54,500,000	2,370,000	26,920,000	58,450,000	13,160,000	**229,130,000**
Share (%)	9.2	23.2	23.7	1	11.7	25.5	5.7	

[a] Eurostat, 2022a

Table 2b
Non-hazardous biogenic waste per country (%) from the global waste production[a]

Country	Waste (%/ volume)							
	W11	W072	W075	W076	W091	W092	W093	Total/country
AUSTRIA	2.0%	2.8%	2.4%	2.6%	3.0%	2.3%	0.4%	**2.4%**
BELGIUM	4.0%	6.0%	6.9%	7.6%	4.5%	12.6%	0.5%	**7.2%**
BULGARIA	0.4%	0.9%	0.6%	0.9%	0.2%	0.5%	0.8%	**0.6%**
CROATIA	0.1%	0.5%	0.2%	0.4%	0.2%	0.1%	4.1%	**0.4%**
CZECHIA	1.0%	2.4%	0.5%	5.0%	0.4%	1.6%	0.5%	**1.3%**
CYPRUS	0.1%	0.1%	0.0%	0.1%	0.2%	0.0%	0.0%	**0.1%**
DENMARK	0.8%	1.2%	1.0%	1.0%	1.4%	1.6%	1.8%	**1.3%**
ESTONIA	0.2%	0.2%	0.3%	0.2%	0.2%	0.1%	0.5%	**0.2%**
FINLAND	3.0%	0.9%	7.7%	0.5%	2.2%	0.7%	0.3%	**2.8%**
FRANCE	6.5%	13.0%	12.7%	9.1%	13.6%	13.1%	2.3%	**11.8%**
GERMANY	7.5%	13.6%	20.7%	12.9%	7.0%	20.5%	5.1%	**15.2%**
GREECE	0.6%	1.5%	0.1%	0.3%	1.2%	0.8%	2.3%	**0.9%**
HUNGARY	0.8%	1.2%	0.2%	0.8%	0.4%	0.6%	2.6%	**0.7%**
IRELAND	3.7%	1.4%	0.4%	0.3%	3.5%	0.3%	0.2%	**1.3%**
ITALY	28.6%	10.0%	9.3%	19.7%	19.5%	5.0%	0.5%	**10.9%**
LATVIA	0.1%	0.2%	0.1%	0.0%	0.4%	0.2%	0.0%	**0.2%**
LITHUANIA	0.2%	0.3%	0.3%	0.4%	0.1%	0.6%	0.2%	**0.3%**
LUXEMBOURG	0.1%	0.2%	0.0%	0.3%	0.2%	0.1%	0.0%	**0.1%**
MALTA	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	**0.0%**
NETHERLANDS	3.0%	3.7%	4.6%	4.8%	8.8%	15.8%	26.7%	**8.8%**
NORWAY	1.1%	1.4%	1.4%	0.2%	2.1%	0.3%	0.0%	**1.1%**
POLAND	2.7%	4.5%	3.7%	5.0%	2.1%	2.9%	2.3%	**3.4%**
PORTUGAL	4.6%	1.9%	0.7%	4.0%	0.6%	0.3%	0.1%	**1.2%**
ROMANIA	1.1%	1.2%	4.9%	1.6%	0.7%	1.5%	0.1%	**2.0%**
SLOVAKIA	2.2%	0.6%	0.8%	0.6%	0.2%	0.6%	2.9%	**0.9%**
SLOVENIA	0.2%	0.4%	0.2%	0.4%	0.3%	0.2%	0.5%	**0.3%**
SPAIN	7.6%	6.0%	2.0%	3.6%	7.7%	4.0%	36.2%	**6.5%**
SWEDEN	2.0%	1.7%	3.2%	0.4%	2.6%	1.4%	6.9%	**2.4%**
UNITED KINGDOM	13.7%	18.6%	13.3%	7.6%	15.8%	10.6%	1.4%	**13.5%**
BOSNIA and HERZEGOVINA	0.0%	0.1%	0.4%	0.1%	0.1%	0.0%	0.1%	**0.1%**
ICELAND	0.0%	0.1%	0.0%	0.0%	0.1%	0.0%	0.0%	**0.0%**
LIECHTENSTEIN	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	**0.0%**
MONTENEGRO	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	0.0%	**0.0%**
NORTH MACEDONIA	0.0%	0.2%	0.0%	0.2%	0.0%	0.0%	0.0%	**0.1%**
SERBIA	0.6%	0.3%	0.1%	0.4%	0.1%	0.1%	0.5%	**0.2%**
TURKEY	1.6%	3.0%	1.2%	8.8%	0.5%	1.2%	0.0%	**1.6%**

[a] Eurostat, 2022a

tons of waste. A detailed breakdown of both values depending on the waste code is presented in Table 6.

Other ways to recycle paper and cardboard waste include processes such as use as a fuel or as a means to generate energy (R1), recycling or recovery of inorganic materials other than metals and their compounds (R5), reuse of waste that was generated as a result of any of the recycling processes (R11), storage prior to recycling and recovery (R13) (see Table 6).

Data collected in the BDO database on the recycling of paper and cardboard waste (W072) in 2019 in Poland is in line with the data from the Eurostat database for 2018. The BDO database reports a total of 1,356,353.855 t of recycled and energy-recovered paper and cardboard waste (R1, R5, R11, R12, R13). In 2018, in total, 1,324,479 t of paper and cardboard waste was recorded in the Eurostat database.

3.3.3. W075 Wood waste

3.3.3.1. The case of Germany. Wood waste is classified and recorded according to the Waste Wood Regulation (2002a) (see Table 7). According to the German Federal Environment Agency (UBA), in Germany 8.6 million tons of wood waste were reported in 2016, close to 50% of its

Table 3a
Non-hazardous biogenic waste generated by EU28 from different industrial sectors (NACE)

Industrial sector	Waste (1,000 t/year)							
	W11	W072	W075	W076	W091	W092	W093	Total
Agriculture, forestry and fishing [A]	170	80	140	0	1,160	4,050	11,610	17,210
Food products, beverages and tobacco products [C10-C12]	2,690	1,460	340	40	8,520	16,090	670	29,810
Textiles, wearing apparel, leather and related products [C13-C15]	10	250	70	660	30	20	0	1,040
Wood and products of wood and cork, except furniture [C16]	10	80	13,610	0	0	120	0	13,820
Paper and paper products [C17-C18]	1,480	5,510	3,270	10	10	30	0	10,310
Chemical, pharmaceutical, rubber and plastic products [C20-C22]	220	690	550	80	290	840	10	2,680
Water collection, treatment and supply, sewerage, remediation activities [E36, E37, E39]	12,050	40	160	0	80	100	10	12,440
Waste collection, treatment and disposal activities, materials recovery [E38]	2,050	7,140	11,070	260	1,200	3,950	90	25,760
Services [G-U_X_G4677]	1,300	15,830	5,460	190	6,370	5,550	620	35,320
Other NACE*	340	3,190	14,310	240	2,155	1,990	150	22,375
TOTAL (EU28)	20,450	53,200	54,500	2,370	26,920	58,450	13,160	229,050
Weight (%)	9%	23%	24%	1%	12%	26%	6%	

Source: EUROSTAT 2022 (https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN_custom_1882210/default/table?lang=en)

Table 3b
Shares of non-hazardous biogenic waste generated by EU28 in different industrial sectors (NACE)

Industrial sector	Waste (%) according the code in each NACE industrial sector							Share (%)
	W11	W072	W075	W076	W091	W092	W093	
Agriculture, forestry and fishing [A]	0.8	0.2	0.3	0.0	4.3	6.9	88.2	**7.5**
Food products, beverages and tobacco products [C10-C12]	13.2	2.7	0.6	1.7	31.6	27.5	5.1	**13.0**
Textiles, wearing apparel, leather and related products [C13-C15]	0.0	0.5	0.1	27.8	0.1	0.0	0.0	**0.5**
Wood and products of wood and cork, except furniture [C16]	0.0	0.2	25.0	0.0	0.0	0.2	0.0	**6.0**
Paper and paper products [C17-C18]	7.2	10.4	6.0	0.4	0.0	0.1	0.0	**4.5**
Chemical, pharmaceutical, rubber and plastic products [C20-C22]	1.1	1.3	1.0	3.4	1.1	1.4	0.1	**1.2**
Water collection, treatment and supply, sewerage, remediation activities [E36, E37, E39]	58.9	0.1	0.3	0.0	0.3	0.2	0.1	**5.4**
Waste collection, treatment and disposal activities, materials recovery [E38]	10.0	13.4	20.3	11.0	4.5	6.8	0.7	**11.2**
Households [EP-HH]	0.6	35.6	10.1	37.6	26.4	44.0	0.0	**25.4**
Services [G-U_X_G4677]	6.4	29.8	10.0	8.0	23.7	9.5	4.7	**15.4**
Other NACE*	1.7	6.0	26.3	10.1	8.0	3.4	1.1	**9.8**
TOTAL % (EU28)	100	100	100	100	100	100	100	**100**

Source: EUROSTAT 2022 (https://ec.europa.eu/eurostat/databrowser/view/ENV_WASGEN_custom_1882210/default/table?lang=en)

Table 4
Different non-hazardous biogenic waste categories from EU28 classified by treatment.

Waste Code	Landfil D1-7, D12		Incineration D10		Energy recov. R1		Recycle (compost, fertilizer, biogas) R2-R11		Other treatments		Total waste treated	Total waste NACE	Waste treated from total NACE
	1,000 t	%	1,000 t	%	1,000 t	%	1,000 t	%	1,000 t	%	1,000 t	1,000 t	%
W11	997	8.2	1,290	10.6	1,830	15.0	7,400	60.7	673	5.5	12,190	20,450	59.6
W072	10	0.0	0	0.0	410	1.2	34,800	98.8	0	0.0	35,220	53,280	66.1
W075	210	0.4	2,160	4.6	21,910	46.7	22,490	48.0	110	0.2	46,880	54,500	86.0
W076	150	8.8	10	0.6	210	12.4	1,320	77.6	10	0.6	1,700	2,370	71.7
W091	300	1.5	450	2.2	1,250	6.1	18,280	89.5	70	0.3	20,420	26,920	75.9
W092	770	1.6	110	0.2	1,950	4.1	45,060	94.1	20	0.0	47,910	58,450	82.0
W093	140	1.4	850	8.2	630	6.1	8,640	83.6	70	0.7	10,330	13,160	78.5
Total	2,577	1.5	4,870	2.8	28,190	16.1	137,990	79.0	953	0.5	174,650	229,130	76.2

Table 5
Sludge (W11) treated in Bulgaria (2018).[a]

W11	Treatment	Quantity (tdw)	Share (%)
Generated sludge		90,049	100.00
Treated sludge		13,656	15.20
Disposal	Landfill (D1, D5, D12)	13,320	14.80
	Incineration (D10)	12	0.10
Recovery	Energy recovery (R1)	300	0.30
	Recycling (R3)	24	0.03

[a] EEA, 2019

construction and demolition wood waste, 30% wood working and processing waste, and 20% woody packing, urban and bulky waste. 79% of it is recycled for energy (R1), 15% for materials (R2-R11), and 6% is disposed of in a thermal facility (D10) if recovery of wood waste is not possible for economic, organizational or other reasons. In the wood industry, material recycling mainly leads to composite materials such as chipboard. Energy recovery mainly generates electricity and heat in waste wood power plants (UBA, 2020). However, Eurostat reports only 6.7 million tons of wood waste recovered for energy; this corresponds to 79% of the 8.6 million tons reported by the German Federal Environment Agency. Eurostat does not provide any information on recycling and incineration, referring to confidentiality. It can therefore be plausibly assumed that the distribution of use reported by the Federal Environment Agency corresponds to reality. Furthermore, Table 7 also contains data on waste containing hazardous substances, which have not been included by Eurostat.

In addition to the domestic waste wood volume, waste wood is imported, so that a total of about 10,000 t of waste wood has to be treated in Germany (UBA, 2020).

3.3.3.2. The case of Denmark. The majority of waste wood in Denmark comes from Construction and Demolition (C&D) and Households, which account for 42.4% and 40.7% of the non-hazardous wood waste, respectively (Danish EPA, 2020). The most dominant ways of treatment are

Table 6
Recycled, recovered or pre-processed paper and cardboard with a breakdown into waste according to EWC[a] in Poland.

Code of waste	Type of waste	Process of waste treatment (t)					
		R1	R3	R5	R11	R12	R13
03 03 08	Wastes from sorting of paper and cardboard destined for recycling	-	266,547.878	109.804	-	3,687.919	826.142
15 01 01	Paper and cardboard packaging,	9.980	802,306.553	125.314	115.470	22,530.760	518.120
19 12 01	Paper and cardboard from mechanical processing of wastes	-	211,651.144	1,538.974	699.089	6,213.065	-
20 01 01	Paper and cardboard	-	17,719.537	0.026	48.432	19,388.053	2,317.595
Total		9.980	1,298,225.112	1,774.118	862.991	51,819.797	3,661.857

[a] BDO, 2022

Table 7
Volume of different wood wastes in Germany (2016).[a]

Short designation according to waste catalog	Volume [1,000 t]
Bark and cork waste	210
Sawdust, shavings, cuttings, wood, chipboard and veneer containing dangerous substances	1
Sawdust, shavings, cuttings, wood, particle board and veneer other than those mentioned in 03.01.04	1,981
Bark and wood waste	360
Total wood working and processing	2,552
Wood packaging	556
Wood from "packaging containing residues of or contaminated by dangerous substances" (share 15%)	5
Total packaging waste	561
Wood	2,834
Wood from "glass, plastic and wood containing hazardous substances or contaminated by hazardous substances" (share 90%)	567
Wood from "other insulation material consisting of or containing hazardous substances" (share 75%)	8
Wood from "mixed construction and demolition wastes other than those mentioned in 17. 09.01, 17. 09.02 and 17. 09.03 (share 20%)	636
Total construction and demolition waste	4,044
Wood containing hazardous substances	26
Wood other than that mentioned in 20.01.37	497
Total municipal waste	523
Wood from bulky waste (45%)	917
Total waste wood	**8,597**

[a] UBA, 2020

R12 (22%) and R13 (29%; both storage and preparation for treatment), R3 (23%; material recycling), and R1 (15%; energy recovery). All together, these four treatments cover 89% of the treated wood waste. For the wood waste from C&D and Households, the vast majority is treated via either R13, R3 or R1. Only a small fraction (<10%) is incinerated with energy recovery. For both C&D and households, wood waste is often characterized as bulky waste and part of the bulky waste collection for households (such as discarded furniture). The sheer size of the wood waste makes it easy to sort and thus the collection rate for waste wood is relatively high.

After collection, the wood waste is visually inspected at the recycling facility. Impurities are removed and discarded and the quality of the wood waste is determined and sorted into fractions based on the quality. Untreated wood is shredded into wood chips and used as input for particle board production where it substitutes use of primary wood (Teknologisk Institut, 2019). Wood waste with contaminating impurities, such as paint, plastics, etc. and impregnated wood, is sorted and incinerated with energy recovery. Larger pieces of waste wood from e.g. C&D are often collected with intention for recycling, and this secondary wood can be bought by companies or citizens. Thus, the wood can substitute primary wood in new buildings or for other purposes such as furniture making. A good example of recycling of waste wood is the use of waste wood from demolished buildings for construction of utility sheds for tools, bicycles and/or dumpsters. The waste wood materials are not allowed to be used in primary buildings, but are accepted for use in secondary buildings. Hereby, the wooden sheds avoid use of steel, which is often used for constructing sheds in Denmark.

3.3.4. W076 Textile waste: the case of Romania

In Romania, a total of 41.150 tons of textile waste (W076) were reported for the year 2018; 16.244 tons (39%) of which were subjected to waste treatment and 12,445 tons (30%) of which were recycled (Eurostat, 2022b). The Romanian National Waste Plan aims for reducing textile waste to a share of 1% of the total municipal waste by 2025, but no concrete actions were indicated so far (Staicu, 2019). According to Staicu (2019) in Bucharest, the clothing reuse seems to be the main practice of textile recycling developed by private and public stakeholders. Examples for recycling practices by private actors are repair and second hand shops, flea and online markets, charities and online groups for clothing exchange; public stakeholders are less active. Especially for wool waste, landfilling (D1-7; D12) or incineration (D10) are applied on large scale in Romania (Rajabinejad et al., 2019).

3.3.5. W091 Animal and mixed food waste

3.3.5.1. The case of Romania. Food waste of Romania is produced mainly by households (49%) and industrial food processing (37%), followed by retailers (7%), the public sector (5%) and agriculture (2%) (Gheorghescu and Bălăn, 2019). Food waste is due to shopping in excess and seldom reuse of leftover (Stancu et al., 2016). Thus, an appeal to reduce consumes leading to less waste is launched by Petrescu-Mag et al. (2019). The studies show that Romanian consumers are neutral concerning the environmental issue, the recycling of food packaging being their main activity (Muresan et al., 2021).

The retailers have also a large responsibility concerning food waste policy. A positive example was given by Lidl Romania which reduced the amount of food waste by donating the food about to expire to charities that serve the needs of disadvantaged groups (Cantaragiu, 2019).

Reduction of waste from dairy Romanian industry was performed by introducing a monitoring platform for the traceability of dairy products inside the Romanian farm (Marin et al., 2019).

Producing energy is a promising direction for food waste valorization in Romania. The waste from the meat processing industry may be successfully used as new primary energy source (Marculescu et al., 2016). Other waste comprising food (food court waste-FCW) has high calorific value and may be used in power plants as well as for combustible gas production (Stănciulescu et al., 2018). Romania has a high natural potential for biogas production based on the raw material available in agriculture and animal husbandry, industrial waste from the food industry, municipal waste, etc. (Clodnițchi and Nedelcu, 2018; Coșbuc et al., 2021).

3.3.5.2. The case of Finland. In Finland it is general policy to reduce food waste (Silvennoinen, 2016; Hartikainen et al., 2020) by adopting a variety of optimization strategies. Despite optimization, generation of waste in NACE categories W091 and W092 is inevitable, and therefore sorting, recycling and other treatment of this waste needs to be focused on. Finland produced 617,557 tons of waste fractions W091 (animal and mixed food waste; Table 2a) in the year 2018. Of this waste 95% is recycled in various forms, mainly through anaerobic fermentation that generates biogas, followed by composting that generates soil improver material and fertilizer for landscaping use, and in some cases for field use in crop production. Whenever the scale is too small for economically feasible biogas fermentation, composting is used alone for generation of soil improvers.

An aspect that complicates the end use alternatives of composting is that in some cases also waste water treatment plant sludges are composted, and these sludges may contain residues of medicines and other chemicals that limit the usability for fertilizing crop cultivation. For this reason, some waste treatment stations in Finland have composted wastewater sludge separately from fractions that are considered cleaner, such as animal and mixed food waste (W091) and vegetal wastes (W092). These cleaner fractions are after composting suitable for agricultural use.

A small part – 5% - of the W091 waste is used for energy recovery, which is justified when the local scale is too small and the logistics becomes too expensive. Landfill disposal stood in the last completed statistics for a 0.1% share, but current EU and Finnish legislation will rule out this fraction completely. A very small share is incinerated without energy recovery, but this is also likely to be phased out.

For detailed statistics Finland (and other EU countries) use List of Waste (LoW) coding (preceded by the EWC coding). Since W091 also includes “mixed food waste” the classification includes 25 specific subcategories from the three categories "Animal waste generated from food production and processing”; “Plant based waste generated from food production and processing" and "Mixed waste generated from food production and processing". These fractions are compiled from six LoW waste categories starting with 02 01 Agricultural types of animal wastes and 02 02 Food industry type animal wastes, and ending with 02 06 Waste generated by bakery and sweets industry. The categories in LoW include many subjects and is based on site of generation rather than type of waste.

3.3.6. W092 Vegetal waste: the case of Finland

In the case of Vegetal waste (W092) the Finnish treatment is shared mainly by recycling (53.8%) and energy recovery (43.3%). If recycling is considered as the optimal treatment, the European average is here better with a 94.2% recycling share. One reason for this difference may be the high share of forestry waste in the Finnish Vegetal waste. StatFin statistics for 2018 (StatFin, 2018) show that 107,222 tons of waste was used for energy recovery. The treatments of vegetal waste subcategories are not specified in the statistics, but may include wood chips used for animal cages and stables, and to some degree as structural material in composting.

In Finland a substantial portion of vegetal waste is used for energy recovery. The paper and pulp industry as well as sawmills use forestry residues etc. scrap wood for heating. Waste wood is also used for production of wood pellets for burning in furnaces etc. Other wood based waste from the furniture, the particleboard, as well as the paper and pulp industry are categorized outside of W092.

A small share of the W092 in Finland was in the last statistics covered by disposal at landfills (2.7%) but this practice will apparently be phased out due to legislation and efforts towards a higher sustainability.

In the LoW system W092 vegetal wastes is simple to categorize since it contains only the LoW fractions "02 01 07 forestry waste" from the category "02 01 agricultural, gardening, fish farming, forestry, hunting, and fishing waste" and "20 02 01 biodegradable waste" from the category "garden and park waste, including cemetery treatment waste".

3.3.7. W093 Animal faeces. The case of Poland

According to the data reported in the database of Waste Management BDO (BDO, 2022) in Poland, in 2019, animal faeces, covered by the European classification code 02 01 06, were recycled in the amount of 190,394.682 tons. Recycling included composting and other biological transformation processes denoted by the code R3. Recovery, not classified as recycling, was carried out in installations and devices in a total of 88,677.306 tons of animal faeces. Of these, 18,682.176 tons was used as a fuel or a means to produce energy, marked with the recovery code R1, and 69,995.13 tons was used for the recovery of organic substances as a result of composting or other biological processes marked with the code R3. A more detailed analysis of the data collected in the BDO database leads to the conclusion that subjecting animal faeces to recorded recycling or recovery is not a common phenomenon, present in all the administrative units of the country (voivodeships) in the country. The data for 2019 include the recycling of animal faeces in only 7 out of 16 districts (voivodships). On the other hand, the recovery of energy or organic substances from animal faeces was registered in 9 provinces. Installations intended for both recycling and recovery are present only in 5 voivodships.

This situation results from the current regulations in Poland. Pursuant to the Ordinance of the Minister of Climate of 23 December 2019 (Journal of Laws, 2019) on the types of waste and the amount of waste for which there is no obligation to keep a record of waste, animal faeces marked with the European waste code 02 01 06 are not subject to the obligation to register, regardless of the amount generated during the year. The data provided above, registered in the Database on Products and Packaging and Waste Management BDO, come from companies that are obliged to submit reports. These are mainly companies that have obtained an integrated permit, or a permit to generate waste, or to collect or process waste.

Due to the effect of the current legal status and the resulting data collection method, there are significant discrepancies between the data from the national BDO database from 2019 and from the Eurostat database from 2018, in which the volumes of animal faeces subject to total recycling and energy recovery are much higher and accounted for 444,834 tons. To fully illustrate the method of handling animal excrements in Poland, it should be stated that, according to the information provided in the 2020 Report on Biogas, the annual production of cattle and pig faeces reaches 99,000,000 tons, of which 78,000,000 tons is manure. Manure from other animals, including poultry, is over 20,000,000 tons. Typical management of the largest part of animal excrement, i.e. manure, consists of its systematic removal from premises where animals are kept and keeping it in heaps, from which it is collected and spread on fields for fertilization purposes 2-3 times a year (Dach et al., 2020).

4. Discussion

This section first discusses the transparency of waste statistics in Europe followed by the potential for improvement of utilizing biogenic wastes based on the status of the current waste management. This is followed by an analysis of the need for research and the necessary adjustments to the infrastructure and framework conditions in order to be able to realize the potential for improvement.

4.1. Transparency of waste statistics

For the data collection, the Eurostat sources indicated under Methods and the national databases indicated in the National Examples in Section 3.3 were used. This has resulted in inconsistencies that were not resolvable for the authors as external users of the databases. For example, it is an obvious gap in Eurostat that, as noted in 3.3, the whereabouts of a significant proportion of wastes are not reported. This reporting gap needs to be addressed in a way that is easily accessible to external users. In addition, it is important to note that data collection is done in EU countries by national statistical authorities in compliance with common EU statistical regulations and standards, monitored by Eurostat.

The reconciliation of the National databases with Eurostat is also laborious and not always free of inconsistencies. One of the reasons seems to be lying in the W-codes used by Eurostat to aggregate National Waste Statistics data categorized according to the LoW (formerly EWC) codes. Therefore, a harmonization of the W-codes for waste fractions and also of codes of waste treatment is suggested.

4.2. Status of waste treatment

For all types of waste studied, Eurostat indicates that recycling and energy recovery dominate, while landfilling and incineration without energy recovery account for only a small share. However, a look at the National statistics makes it clear that recycling leads to very different products. A high share of material recycling can only be reported for paper waste (W072), which is upgraded to paper again. For all other types of waste, recycling means preferential use as an energy source, as fertilizer, as a raw material for biogas fermentation, or especially in case of sludges (W11) hydrothermal liquefaction (HTL) (Zhao et al., 2014). Therefore, preferably the content of plant nutrients (fertilizer) or energy (energy recovery) is used. What is more, the carbon bound in the waste materials is released as CO_2 almost completely after a relatively short time. In the case of energy sources, this applies immediately upon combustion, and in the case of fertilizers (e.g. compost) within weeks or months. Only little carbon is transformed to humic materials and thus long-term stored in farm land when utilizing biogenic waste either directly or after treatment as fertilizer (Bernal et al., 1998). The ecological advantage of these waste recycling methods must therefore be questioned. Economically, the value added of the products such as energy and fertilizers is low. And finally, the value chains of these prod-

Table 8
Potential outputs from valorization of CO_2 generated from waste materials.

Method	Product output	Reference
Photosynthesis	Biomass, vegetable oil, Fine chemistry	Iglina et al., 2022
Methanization	Methane	Tripodi et al., 2020
Electrochemistry	Formic acid	Fan et al., 2020
Microbial electrosynthesis	Methane, Organic acids, Alcohols	Patil et al., 2015
Chemocatalysis	Methanol	Ren et al., 2022
Power2x	Hydrocarbons	Dittmeyer et al., 2019

ucts are short and thus, from a societal point of view, the job creation potential is also small.

4.3. Optimization potential of waste treatment

These considerations lead to the question of which options for waste recycling could avoid CO_2 emissions, achieve higher added value as well as longer value chains and thus, provide higher employment potential.

CO_2 emissions can be reduced by giving priority to material recycling. In this way, the carbon bound in the waste remains bound in products. If these products can serve as feedstock for further transformation stages, the starting point for longer value chains and thus also higher value creation and job potential is achieved. One example is the purification of bio-methane from biogas, which can be used as a carbon source for the production of basic chemicals in the chemical industry. The cascade recycling of biogenic waste is also conceivable. For example, sewage sludge (W11) could serve as a carbon source in a first stage, and in a second stage only the residues from the first stage, rich for example in minerals, would be used as fertilizer. Since these have at least a reduced carbon fraction, the CO_2 emission potential of this residual material would also be reduced. Where the residual materials cannot be applied to fields because of being too high in pollutants, at least individual plant nutrients, e.g. phosphate, could be extracted.

The fact that CO_2 emissions from waste recycling can also be included in cascade utilization has so far been almost completely overlooked. CO_2 can be reduced and up-cycled by a variety of technologies, such as photosynthetically active microalgae (Tossavainen et al., 2019), power2x technologies, electrochemistry, bioelectrochemistry (such as microbial electrosynthesis), and chemocatalysis. Potential outputs are shown in Table 8.

From an economical point of view only highly concentrated CO_2-streams from point sources is cost-efficiently accessible. This applies to CO_2 from bio-waste cogeneration plants, energy production from biogas, and from biogas fermentation. All of these options can help mitigate ecological damage and increase the value-added and job potential of waste recycling by increasing raw material efficiency.

4.4. Technology gap and research demand

In the following part, the research and technology requirements necessary for raising the optimization potential of waste utilization are discussed on the basis of selected examples. Despite the fact that many individual scientific investigations on the improvement of waste treatment are currently being carried out, so far there is little information in the literature on specific data indicating advantages in long-term effect, as well as detailed cost in all residues analyzed in this paper.

4.4.1. W11 Sludge

The recycling of sludge is necessary because sludge treatment accounts for 50% of the costs of wastewater treatment (Domini et al., 2022). If only because of the large volume of sewage sludge, at least some of it will probably continue to be used directly as fertilizer. However, in order to protect soil and aquifer the continuation of this way of usage requires control and continuous evaluation as well as the evolution of the process of environmental conditions (Zhou et al., 2020).

Continued research on biogas fermentation substrates (Breda et al., 2020; Das et al., 2020; Donatello and Cheeseman, 2013; Zhao et al., 2014; Zhou et al., 2020) and process technology is needed to overcome economic and technical obstacles for quality biogas production (Breda et al., 2020; Donatello and Cheeseman, 2013). Another option for adding value to sludge is transforming it to pet-coke (Das et al., 2020) or biochar (Zhao et al., 2023). In addition, bacteria producing biodegradable biopolymers (i.e., polyhydroxyalkanoate, PHA) are able to also use sludge as feedstock (Interreg, 2021; Lorini et al., 2022). Sludge valorization (and more in general the valorization of several types of urban biowastes) towards PHA production has been thoroughly examined in the frame of a recent Horizon 2020 project entitled "RESources from URban BIo WaSte (RES URBIS)“ (Moretto et al., 2020).

Sludge can be gasified to synthesis gas (CO, H_2), which is an established carbon source in the chemical industry. Chemical Fischer-Tropsch catalysis transforms synthesis gas into hydrocarbons with limited selectivity; in contrast, biotechnological methods like gas fermentation result in high selectivity. Especially gas fermentation whole cell catalysts and the related process technology asks for intensive research. This is all the more so because such processes bind carbon in products.

Primary sewage sludge or the residues of its incineration or gasification contain valuable inorganic plant nutrients. In 2017, the Sewage Sludge Ordinance was amended. According to this, sewage sludge containing at least 20 grams of phosphorus per kilogram of dry matter, as well as corresponding ash from sewage sludge incineration, must be subjected to phosphorus recovery after the transitional period from 2029, depending on the size of the sewage treatment plant. How the future phosphate recovery from sewage sludge may look like is shown in Fig. 3. In general, the recovery of plant nutrients from sludge is a future topic that should be worked on more intensively scientifically.

4.4.2. W072 Waste paper and cardboard

The recycling of waste paper is an example of ecologically exemplary recycling that closes the material cycle. Concerning economics it is worth noting that the production of pulp from recyclable paper requires 10 GJ to 13 GJ less energy per ton than the production of virgin pulp (CTCN, 2016). Coated papers, such as Tetrapak packaging, can represent a challenge for paper recycling. Here, research is needed that takes the recyclability of the coatings into account as early as product design in the development stage.

4.4.3. W075 Waste Wood

One of the main problems of utilization of wood waste from used lumber is the contamination by paints, heavy metals etc.. Technologies to remove such pollutants are under development (Welsch, 2021) but more research is necessary in order to increase the rate of material recycling.

Wood waste can also be a valuable resource as a carbon source and for functional molecules. Thus, like all organic materials, wood can be gasified to produce the synthesis gas already mentioned. Incomplete decomposition to bio-oil and biochar is achieved by heating in the absence of air (pyrolysis). Pyrolysis is particularly suitable for small capacity plants, which can be mobile and therefore may be suitable for building a decentralized infrastructure of waste utilization in rural areas. Fractionation can be used to isolate functional fractions from bio-oil. Furthermore, the lignocellulose of the wood waste can be broken down to sugars from cellulose and hemicellulose as well as aromatics to be achieved from lignin.

4.4.4. W076 Textile waste

Recently forty-one studies were reviewed, and it was concluded that textile reuse is more valuable than recycling (Sandin and Peters, 2018). From these studies, 85% worked with recycling and 41% with reuse while 27% worked with both reuse and recycling. The most studied recycling type is fibre (57%), followed by polymer/oligomer (37%), monomer (29%), and fabric (14%). Further-

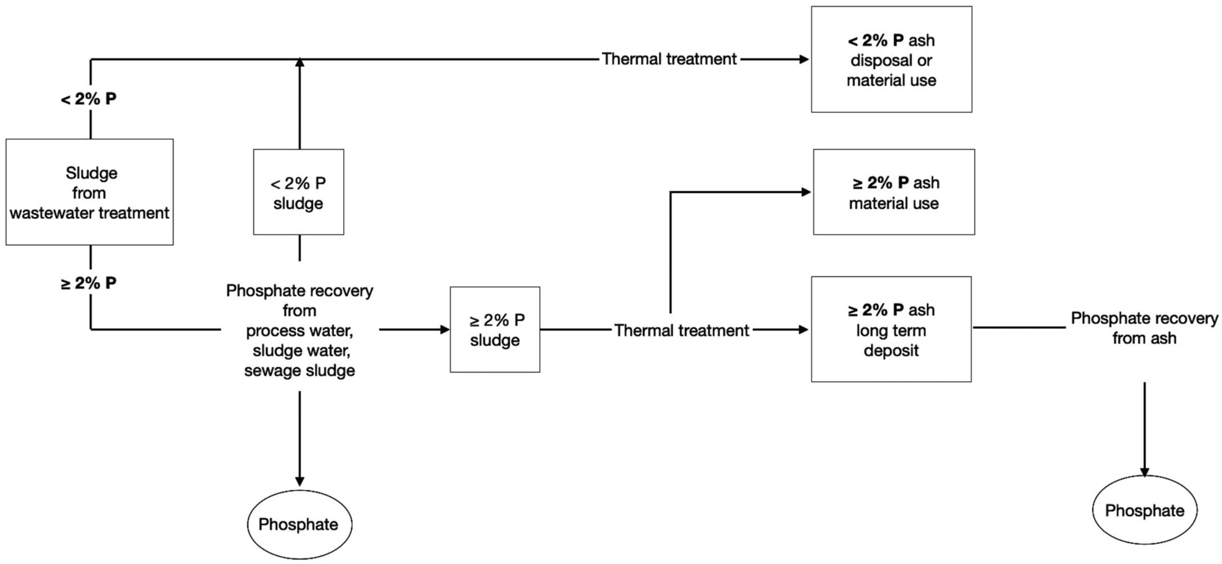

Fig. 3. Future possible disposal and recovery routes for sewage sludge from wastewater treatment plants.

more, cotton (76%) and polyester (63%) were studied the most (Sandin and Peters, 2018). The state of art concerning textile waste was presented recently (Stanescu, 2021).

Concerning textile waste, innovative recycling techniques are under way. Sectors such as construction and geotechnical engineering create new products or substitute raw materials they used until now. Research demand lies not only in product development but also in cost-efficient sorting the fibers and separating them from toxic substances. Early recycled fibre known as BLEND products are already on the market (Rahman et al., 2022; Juanga-Labayen et al., 2022).

In 2018, the Waste Framework Directive was amended by the EU Directive 251/2018 (EUR-Lex, 2018b; EFTA, 2021), requiring the separate collection of textile waste to become compulsory by 2025.

Producers have also obligations to introduce circular business models for production, and reuse, respectively, recycling textiles. Creating markets for products such as second hand, reparable, containing recycled fibres etc. is necessary (Köhler et al., 2021). Especially global commercial cross border chains need monitoring tools.

Last but not least, education of the consumers to change their behaviour patterns is compulsory. All these elements should be subject of continuing research.

4.4.5. W091 Animal and mixed food waste

Avoiding waste is a general demand but in the food sector it is a special priority. Therefore the “EU Platform on Food Losses and Food Waste” was established in 2016, bringing together players from both public and private sectors (EC, 2015b). This platform facilitates cooperation and communicates best practices to prevent and reduce food waste.

In 2017, a digital network was set up in order to improve collaboration under the Horizon 2020 project “Resource Efficient Food and dRink for the Entire Supply cHain” (REFRESH) (Bos-Brouwers et al., 2020).

Education of producers and consumers is of great importance. For instance new methods to the handling, processing, and delivery of products need to be developed. Thus, lot sizes, seasonal food, local production and cooperation, logistics, and innovative recipes may ensure circular food procurement (Alhola et al., 2019). Another consumer related topic is source-separated collection schemes (Mihai and Minea, 2021).

Food waste that is not avoidable is difficult to recover due to its composition (high water content, high biodegradability). In addition to producing biogas, it offers the option to deliver industrial substances such as dyes, enzymes, organic acids and essential oils using ultrasound, extraction under pressure and microwave extraction (Shen et al., 2015; Stillwell et al., 2010; Mohanty et al., 2022; Paritosh et al., 2017; Holm-Nielsen et al., 2009; Meyer et al., 2018). Currently, special attention is given to cultivating insects on food waste to transform it into protein, fat, and functional molecules like antimicrobial peptides (AMP).

Furthermore, food waste may be used as raw material for producing peptides (Sommella et al., 2016), starch, pectin and ethanol (Ng et al., 2020), fatty acids and lactic acid (Pleissner et al., 2015), and succinic acid (Brunklaus et al., 2018), as well as biopolymers (PHA) through biotechnological routes (Moretto et al., 2020), etc.

4.4.6. W092 Vegetal waste

Vegetal waste has high potential for utilization in the food and organic production sector. Functional food development can be based on agricultural by-products and plant residues (skins, kernels, husks, seed hairs, etc.) due to the high nutritional value of these materials. In addition, these residues can be valorised in bakery and in the production of dairy products, as well as in the food supplement industry. Furthermore plant residues can deliver actives for antiseptic and antibacterial cleaning products. Another area that is facing the exploitation of plant residues is the pharmaceutical industry as many fruits and peels have anti-cancer or therapeutic effect on diseases such as diabetes etc. (Lau et al., 2021, Omre et al., 2018). In order to find widespread industrial application, these recycling routes require considerable research along with the entire process chain. This concerns the collection of waste, its preservation, standardization and processing.

4.4.7. W093 Animal faeces, urine and manure

Beside utilization as fertilizer, animal faeces and urine are used to produce biogas, some of it is upgraded to public transport fuel (Díaz-Vázquez et al., 2020; Afazeli et al., 2014; Holm-Nielsen et al., 2009; Meyer at al., 2018). Like from sludge, biopolymers (PHA) can be produced from manure by biotechnological methods (Guillen et al., 2018).

The technologies of utilization of this waste have advanced to the point where important inorganic elements can be recovered with the most important of them being phosphorus and nitrogen. However, as mentioned before, biogas production and usage come with significant CO_2-emissions. Therefore, the treatment of this waste should combine carbon recovery (biogas), nutrient recovery (fertilizer) and CO_2 utilization (CCU) in order to exploit the full potential of this waste.

These examples of research needs do not purport to be complete. For all categories of waste, current methods of collection, storage and treatment require at least the further development of methods if not the establishment of entirely new methods and the corresponding adaptation of infrastructure. These fields alone have considerable research needs. Further research is necessary to achieve acceptance for waste recycling itself and for the resulting products among companies, consumers and the waste management sector, to accelerate the development of biowaste biorefineries in Europe (Fava et al., 2015; Fava et al., 2021). Because this acceptance is to be achieved less by mandatory regulations than by persuasion, it must be possible to justify the necessity of waste recycling ethically. This area of research, which may seem rather remote to natural scientists, is also an important building block in the development of the circular economy. The result of ethical considerations like e.g. the UN Sustainability Goals (UN-SDG) is to be discussed further below.

4.5. Necessary infrastructure including energies

Increased recycling of biogenic waste into chemical products will require remodeling of the industrial infrastructure. This concerns the logistics of waste collection, sorting, preservation and standardization of waste in order to be able to offer specified industrial raw materials. Standardization might include degradation of woody materials to sugar, cellulose, and hemicellulose, anaerobic fermentation of suitable organic waste materials to bio-methane, pyrolysis and gasification of any organic material to bio-oil, respectively synthesis gas, or transforming especially food waste materials into insect biomass. Because biogenic waste as any biomass carries a rather limited carbon content of lower than 50% and also contains water, the catchment area of processing facilities is limited, for which a decentralized industrial structure must therefore be established in preference. The inclusion of biogenic CO_2 in the spectrum of carbon sources also requires the provision of reduction equivalents such as hydrogen, the production of which is very energy-intensive. Accordingly, the development of capacities for generating and distributing sustainable energies is necessary.

4.6. Supportive framework conditions

The recycling and disposal of bio-waste and residues is basically regulated by the Directive on Waste (2008/98/EC) (EUR-Lex, 2008), the Directive on Packaging and Packaging Waste (1994/62/EC) (EUR-Lex, 1994), and the Directive on the Landfill of Waste (1999/31/EC) (EUR-Lex, 1999b). In 2014, the EU Circular Roadmap was adopted and the three Directives mentioned above were also revised on this basis. Finally, the EU Commission adopted the New Circular Economy Action Plan in 2020. According to this plan, biogenic waste and residual materials must be collected separately in order to keep them available for recycling. For this purpose, the EU prescribes the introduction of Separate Collection Schemes (SCS) in all member states and, for defined wastes, the achievement of certain quotas of separate collection (see Table 9) (ZeroWasteCities, 2020).

Table 9
Separate Collection Schemes (SCS) and share of separate collection of waste materials.[a]

	Time	2015	2024	2025	2030	2035
Waste Type		***Biobased Waste and Residuals*** (%)				
Paper		SCS		75	85	
Biowaste			SCS			
Wood			SCS	25	30	
Waste oil				SCS		
Textile				SCS		
			Municipal waste (%)			
Minimun for recycle, reuse				55	60	65
Maximum Landfilling						10

[a] ZeroWasteCities, 2020

In March 2020 the 2[nd] Circular Economy Action Plan (EC, 2019a) has been adopted as part of the European Green Deal (EC, 2019b). Concerning biobased wastes, the Circular Economy Action Plan aims among other things on reducing food waste by the EU farm-to-fork strategy (EC, 2019c).

On 14.07.21 the commission presented, in the frame of the Green Deal, the package of measurements „Fit for 55“ (EC, 2019d) in order to reduce CO_2-emissions by 55% in 2030 compared to 1990. For this purpose, a variety of instruments were listed, which together should achieve the goal. These are "the legal instruments for achieving the goals agreed in the European Climate Act" and also "the fundamental reorientation of our economy and society for a just, green and prosperous future." It is precisely this reorientation that is the subject of the Green Deal, which equally contains a roadmap of various measures for more efficient resource use through the transition to a clean and circular economy. It follows that there are important unified targets, so it makes sense to examine the instruments and measures according to their impact for the bioeconomy. The instruments mentioned in the climate package "Fit for 55" are not finalized, but it is a package of proposals that partly tightens previous measures and adds new ones, like:

- *Emissions trading is to be tightened considerably and extended to new sectors.*
- *The use of renewable energies is to be strengthened.*
- *The Energy Efficiency Directive is also to be revised.*
- *The infrastructure and associated fuels for low-emission modes of transport are to be expanded.*
- *Revision of the burden-sharing regulation for the member states*
- *Tax policy is to be aligned with the goals of the European Green Deal.*

The almost complete ban on landfilling by 2035 and the intensification of separate collection and recycling are effective in strengthening the circular economy. However, waste policy remains contradictory with regard to the energy recovery of residual waste. The EU taxonomy classifies the energies generated in this way (electricity, heat) as sustainable (EC, 2020). Therefore, the biogenic CO_2 emissions generated here are neither recorded nor subject to the EU Emissions Trading Scheme. As a consequence, incentives to reduce emissions from processes such as composting, anaerobic digestion, incineration by combining anaerobic digestion or incineration with CO_2 capture or utilization (CCS, CCU) are not even considered and therefore no significant research is conducted on them.

The EU Parliament does want to include waste incineration plants in the European emissions trading system. However, according to the proposal of rapporteur Peter Liese, this will not take place until 2028, as the parliamentarians fear that with inclusion in the ETS, more waste will be dumped. To this end, a follow-up assessment report, which is to be drawn up by 2025, has been adopted. Currently, only in Norway are the emissions from waste-to-energy plants priced. Consequently, to avoid high cost for emissions allowances, the waste-to-energy plant in Oslo decided to capture and geologically store CO_2 (CCS) in the future (Oslo, 2022).

In addition to emission, pricing the sustainability criteria for bioenergy should be sharpened. In order to be able to evaluate waste incineration according to the German Fuel Emission Trading Act (BMUV, 2020), a balance method is needed to determine the share of biogenic and fossil materials in the waste input. This method was developed at the Vienna University of Technology and applied in more than 40 European waste incineration plants without any additional measurement effort. It is able to determine fossil CO_2 emissions, the share of energy carriers or the share of plastics in real time as well as retrospectively (Schwarzböck et al., 2016). The use of fixed values for CO_2 emissions is problematic because there are large differences between the waste treat-

Table 10
Possible ties between the utilization of biogenic waste and the United Nations Sustainable Development Goals (UN-SDGs).

Indicative gaps to be optimized	Key SDGs
Social perception of wastes as resources	1, 2, 4
Reduction of the waste volume at the origin site	1, 9, 11, 12
Building new skills for employees	4, 9, 12
Creation of future jobs	1, 4, 9, 12

ment plants and because the implementation of the European Circular Economy leads to changes in the waste composition.

Finally, two fundamental aspects remain to be noted:

1 The Commission's regulations on climate protection interfere with EU fundamental rights, which do not specify the primacy of climate protection in fundamental rights considerations. On the contrary, the European Court of Justice emphasizes, e.g. in emissions trading, that this should take place with the least possible impact on economic development and employment. So remains for the member states to advocate for solidarity-based burden-sharing that takes into account CO_2 emissions from waste incinerators and landfills, thus giving policy a stronger focus on biogenic residues.
2 The EU directives specify the year from which defined quantitative target dates must be achieved. Nevertheless, it happens too often that these targets are not achieved by the required date. It would therefore be advantageous if the regulations also specified the date from which a national implementation plan must be adopted.

4.7. Contribution of optimized waste treatment to UN-SDG

The treatment and recycling of biogenic waste, with its economic, ecological and social results, contributes directly to support the achievement of the United Nations Sustainable Development Goals (UN-SDGs). These are 17 goals agreed by Heads of Governments in 2015 aiming to shift the world towards more sustainable and resilient pathways by 2030, also taking into account the needs of developing countries (Gusmão Caiado et al., 2018). The SDG achievement is foreseen to stimulate actions in areas of critical importance for humanity and the planet to accomplish economic growth, social inclusion, and environmental protection (United Nations, 2015). In this context, the exponential growth of global population along with the increasing demand for food and resources make the associated management, reuse, and valorization of biogenic wastes of pivotal importance to the attainment of numerous SDGs. However, the limited social perception of biogenic waste utilization as secondary resources remains one of the most challenging aspects which still hinder a wider exploitation thereof. The contribution of biogenic wastes to the elaboration of UN-SDGs targets is manyfold and involves aspects dealing with circularity, responsible production and consumption, and nutrition (Granato et al., 2022; Backes and Traverso, 2022), as highlighted in Table 10.

As an example, since biogenic waste is available everywhere (regardless of the state's level of development maturity), its reuse and recycling contribute creating new jobs and enhancing agriculture productivity, thus representing a step towards both poverty (SDG 1: No poverty) and hunger (SDG 2: Zero hunger) reduction. A main driver in this process is also the attainment of quality education to improve awareness of sustainable development (SDG 4: Quality education). This education leads to new skills among employees regardless of their gender (SDG 5: Gender equality) and these empowered employees enable innovation in industry (SDG 9: Industry, innovation and infrastructure) and decent work and economic growth (SDG 8). Clearly, innovation is not only essential for deploying industrial solutions which contribute reducing waste generation at production sites but also for developing new routes of waste valorization towards renewable energy production (SDG 7: Affordable and clean energy). At urban level, this latter aspect is closely linked to waste collection and separation issues which, if properly addressed, can contribute reducing the adverse environmental impact of cities (SDG 11: Sustainable cities and communities). Along this line, the opportunity to reduce waste volumes not only by prevention, but also through reduction, recycling, and reuse (i.e., the 3R concept), allows decoupling economic growth from environmental degradation thereby increasing resource efficiency (SDG 12: Responsible consumption and production). This also contributes to the reduction of CO_2 emissions and thus to climate protection (SDG 13: Climate action), because the emissions that would otherwise occur through biodegradation in landfills, incineration or energy recovery are avoided. Overall, all these practices perfectly fit with the development of the circular bioeconomy model.

5. Conclusion

A significant volume of biogenic waste is annually produced in Europe, with an estimation of 237 million tons in 2018 referred to seven specific codes of non-hazardous biogenic waste.

The EU has extensive regulations on the classification and collection of waste as well as on its storage, recovery or disposal. However, implementation in the member states varies greatly. In some states, waste that can be recycled per se is still landfilled. However, the deadline for this type of disposal expires in 2030, so the EU-wide volume of waste to be recycled will increase. The waste that is currently recycled for energy and materials leads to low value-added products (heat, electricity, biogas, compost) in accordance with the regulations. Considerable and so far largely untapped potential lies in the use of biogenic waste as a carbon source for chemical and added-value products generation. This potential meets at the same time a growing large market, because the European chemical industry itself has declared to change its raw material base from fossil to renewable carbon sources. In order to recycle biogenic waste on a large scale industrially, there is a significant need for research in appropriate practices for its collection, standardization, and transformation, as well as for the development of innovative and efficient technologies for waste valorization. Further research is needed in the area of product design to integrate recyclability into new production chains. There is also a need for research into the monitoring of waste recycling in order to be able to measure the closing of material cycles. The aim of recycling biogenic waste as completely as possible has an impact on industrial supply chains and business models and, last but not least, requires consumer acceptance. Here, too, there is a need for research. Finally, it should not go unmentioned that the EU regulations must be adapted to the advancing state of the art of waste recycling and the changing markets for recycled products in such a way that they give priority to material recycling and transformation into high-value products.

Overall, the exploitation of the potential biogenic waste as a resource instead of a waste to be simply disposed of is the core of the circular bioeconomy model.

CRediT author statement

The authors declare that as a team they equally contributed to conceptualization, writing, reviewing and editing of the paper. Manfred Kircher and Marianna Villano coordinated the conceptualization. Manfred Kircher has analysed the data of waste volume and waste processing in the EU, and Elisabet Aranda coordinated the finalization of the Results-section. National data were provided by Stefan Shilev (Bulgaria), Joanna Surmacz-Górska (Poland), Manfred Kircher (Germany) Morten Ryberg (Denmark) Michaela Dina Stanescu (Romania), and Martin Romatschuk (Finland). More National data provided by Elisabet Aranda (Spain) and Argyro Tsipa (Cyprus) could not be included in the text due to space limitations but contributed to the discussion of bio-waste treatment. In particular, Constantinos Vorgias and Panayiotopoulos Athanasios (optimization potential and research needs), Manfred

Kircher (infrastructure), Gabi Schock (framework conditions), and Marianna Villano (UN-SDG) contributed to the Discussion section. The final editing was done by Manfred Kircher, Elisabet Aranda, and Michaela Dina Stanescu.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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