

Review

Possibilities of Using Organic Waste after Biological and Physical Processing—An Overview

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Abstract: With a rapidly increasing amount of waste, waste management is an extremely important issue. Utilising processes such as combustion and biological processing significantly decreases the accumulation and volume of waste. Despite this, huge volumes of resulting waste that still need to be managed remain. This paper identifies various methods of processing organic waste, discussing both thermal and biological techniques for waste management. Additionally, this paper demonstrates that the end products remaining after processing waste are oftentimes functional for agricultural use. These materials are excellent byproducts used to produce various organic, mineral and organomineral fertilisers. For instance, it appears that the production of fertilisers is the most promising method of utilising fly ash that results from the combustion of waste. In order to minimise the environmental risk of polluting soil with heavy metals, waste, as well as ashes resulting from combustion, must meet the criteria for the limit of contaminants.

Keywords: organic waste; fertiliser; combustion; composting; pyrolysis; digestate



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1. Introduction

Global waste production has vastly increased over the last decades, and still continues to grow. According to the World Bank, [1], the world produces approximately 2.01 billion tonnes of solid municipal waste annually. At least 33% of the waste is not managed in a way that is safe for the environment. The amount of municipal solid waste generated per person globally per day averages 0.74 kg but varies from 0.11 to 4.54 kg. The dynamics of change in the amount of waste are staggering. The total mass of waste produced in 2019 was more than 2% higher than in 2018. A systematic global growth of the amount of generated waste is observed on all continents. Unfortunately, no signs of its slowing down are recorded. It is estimated that in 2050, the global production of solid municipal waste will increase by approximately 70%, reaching 3.4 billion metric tonnes. Such a situation is a result of an increase in the human population, urbanisation and economic growth, as well as the purchasing habits of consumers. The greatest amount of waste is generated by developed countries, accounting for 34% of the global volume. Daily production of waste per resident in high-income countries is expected to increase by 19% by 2050. In countries with low and average income, an increase in the amount of generated waste is expected to reach approximately 40%. There is also the issue of regions developing more rapidly, such as Sub-Saharan Africa, South Asia or the Middle East and North Africa. In these regions, total waste production will double and triple by 2050 (Figure 1).

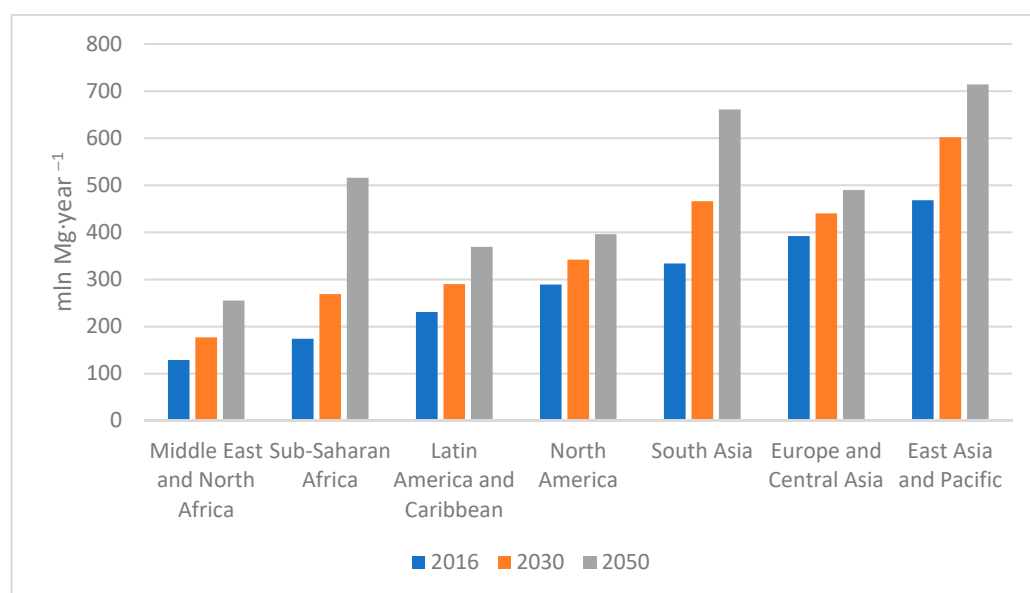


Figure 1. The amount of waste generated in the world in million tons [1].

The generated waste includes production of biodegradable waste. Developed countries produce 32% of biodegradable waste (food, green waste), and less developed countries more than 50%.

Such a fast increase in the amount of waste requires its disposal or utilisation. The most popular method of waste treatment is thermal processing of organic waste, its treatment and safe reintroduction to the environment. The second method is in line with the currently promoted European Green Deal policy implemented in the EU [2]. The primary direction of disposal of the generated mass of waste, however, is its thermal processing. Such a method of waste management has a number of advantages: (i) it is simple to implement, (ii) it minimises the amount of the resulting waste by several to a dozen times, (iii) many elements can be retrieved as a result of processing, (iv) the end product can be relatively easily managed and after treatment reintroduced into the environment, (v) thermal treatment makes energy recovery possible also.

Another method of organic waste disposal is its environmental management. In the European classification, many soils are classified as degraded or marginal soils [3,4]. One of the methods of increasing or maintaining the productivity of light soils is the application of appropriately processed waste organic matter. Such a measure is in accordance with the framework guidelines of the European Union that is changing the current “linear model” of waste production to the concept of the circular economy, i.e., so-called “closed-loop system”. One of the elements of the circular economy is reintroducing generated organic waste to the production cycle. Reducing the amount of waste by means of physical, chemical and biological processes always results in the production of other, different waste that requires disposal. Waste management needs to consider the question what waste will be obtained at the end of the “treatment line”, and how it can be managed. A number of types of waste generated by agricultural-food processing, animal farms or municipal economy show significant fertiliser potential, and can be directly applied in agriculture. The broader application for production of fertilisers would allow for substantial improvement of the nutrient balance, as well as soil organic substance in many countries. The resulting new fertilisers, however, need to meet the legal requirements for environmental use. Therefore, in June 2019, the European Parliament passed new regulations that opened the European market to all types of fertilisers, including organic and organic mineral ones, as well as new products produced from waste with a status of soil improvers or organic substrates [5]. As shown in many studies, the supply of such waste allows for obtaining considerably higher crop yields, which can contribute to securing food safety in the EU and worldwide.

Each of the methods of thermal recycling of waste is considerably different than the others (Figure 2).

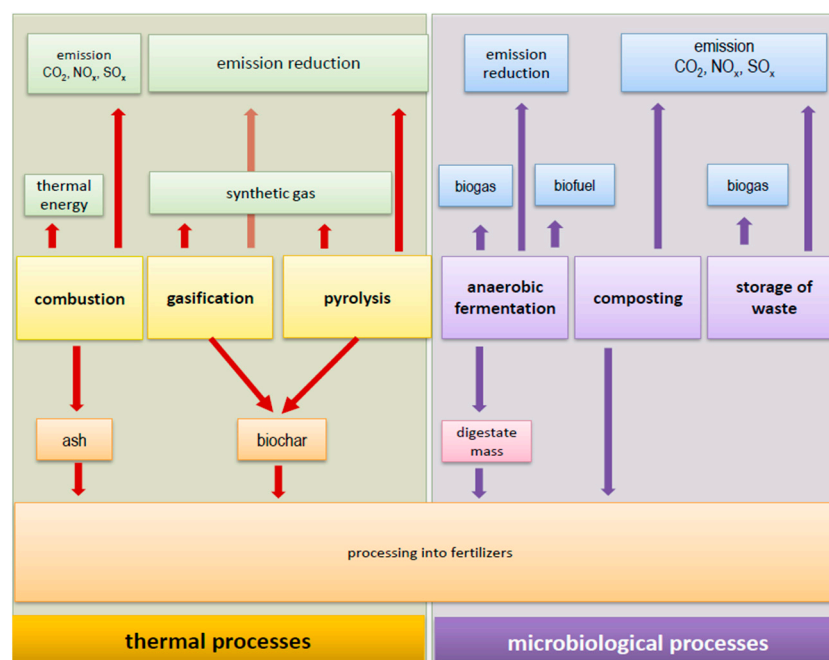
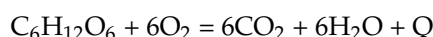


Figure 2. Directions and processes of organic waste utilisation.

2. Thermal Processes

Thermal treatments cover three thermal processes applied for obtaining different types of energy from biomass. They include (i) incineration, (ii) pyrolysis and (iii) gasification. Each combustion process is characterised by different dynamics of chemical transformations of solid fuel.

Incineration is the simplest and oldest way of obtaining energy from biomass. The incineration process can be presented by means of the following reaction



The incineration process includes three stages that are inseparably linked to one another:

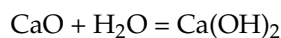
- (i) drying—aims at evaporating excess moisture and preparation of organic material for further incineration stages,
- (ii) degassing—usually occurs at low temperatures between 100 and 300 °C. At this stage, hydrocarbons are released. The rate of drying and degassing processes depends exclusively on the supplied heat.
- (iii) incineration—destruction of organic bonds with heat release

Particularly good incineration results are obtained by combining carbon with organic matter (biomass). Biomass shows a relatively low degree of coalification and high content of volatile organic compounds, as well as a small ash content. Such properties of biomass provide for its primary attractiveness as fuel for gasification. A drawback of biomass as fuel is that it is very diverse in terms of its qualitative characteristics. Carbon content depends on the development stage, at which plants for the combustion process were obtained.

The process results in a considerably smaller amount of waste remaining for management in the form of bottom ash.

Ash from biomass is the inorganic inflammable part of the fuel that remains after complete combustion of the biomass fuel [6,7]. Fly ash is the finest fraction of the bottom ash accumulated in dust filters [7,8]. Fly ash covers the fraction in a range of 0.27–1.80 g cm^{−3} [9].

Ashes are characterised by high pH [8,10], because in the combustion process, metals oxygenate to oxides, resulting in strong alkalis after reacting with water, in accordance with the following reaction:



Due to this, adding ashes to composts allows their drying from excess water, increases their pH and sanitises organic waste. The possibilities of the agricultural use of ash depend on the source of ashes. Fly ashes for municipal solid waste or other residues which pollutants are too much polluted to be reused, fly ashes from biomass combustion in power plants (combustion of clean biomass) or from “clean” agro-industrial residues can be used as usually they are not too much polluted. Fertilisation with ash should be therefore conducted on acidic soils, where the reaction de-acidifying the soil is observed immediately. According to Koivula et al. [11], an addition of 20% of ash to composts results in a reduction in the release of hydrogen sulphide (H_2S). This directly reduces the release of unpleasant odours from the compost prism. Rosenfeld et al. [12] also observed that an addition of 25% of wood ash with high carbon content results in effective reduction in odours in composts from green waste. Similarly, according to Kurola et al. [13], an addition of low doses (4–8%) of wood ash increased the pH of a compost prism, increasing heat production and microbiological activity. The authors also pointed out that an addition of wood ash reduces the content of heavy metals in composts from urban waste. Another method of disposal of ashes is their direct application to the soil. Serious problems with accumulated ashes occurred in the Czech Republic [14], where high costs were incurred for their storage. Zemanová et al. [15] proposed that one of possible applications of ashes from energy engineering use of biomass is their direct supply to the soil. A similar solution was proposed by Bradna et al. [16] to close the circulation of nutrients from biomass combustion. Additionally, Ribeiro et al. [17] recommend direct application of ash to the soil. The application of a $7.5 \text{ Mg} \cdot \text{ha}^{-1}$ dose of industrial and household ash allowed for obtaining an increase in bioavailable forms of macroelements Ca, Mg, K and P in the soil, as well as a decrease in the availability of Al. That is because the composition of ashes includes many elements necessary for the life of plants, such as Ca, Mg, K, P, S, Na, Fe, Mn, Zn, Al, Si, B, Mo, Ti, etc. Ashes can be successfully used directly in agriculture to obtain considerable increases in crop yields [8,9,17]. Direct application of ash, however, is only possible provided it poses no threat to the quality of the soil, crops or human health [18].

Another energy production combustion product is bottom ash. Its chemical properties are presented in Table 1.

Table 1. Chemical composition of slag [%] [19].

Raw MIX Components	CaO	Al_2O_3	Fe_2O_3	SiO_2	MgO
Blast furnace slag	39.70	8.80	2.09	39.08	4.08
Open-hearth slag	32.36	3.96	21.20	19.76	11.18
Limestone	52.12	0.24	0.18	1.53	0.48
Clay	7.57	12.8	6.32	50.45	3.97

Owing to their composition, gravels are useful for replacing clay in the production of clinker. Adding gravel results in the improvement of its durability with simultaneous reduction in energy expenditure by more than $0.85 \text{ mJ} \cdot \text{Mg}^{-1}$ [19].

Another method of bottom ash disposal is its use in the construction of roads, where the application of organic mineral mixtures appears very promising [20]. Similar study results have been obtained by many authors who pointed out that gravel-bituminous mixtures show better elasticity modules, rutting resistance, surface grip and resistance to humidity damage, as well as abrasion resistance than mixtures with natural aggregate, and can be high-quality replacements for natural aggregate [21–23].

Pyrolysis is a stage in both the combustion and gasification process. In the pyrolysis process, thermal decomposition of the structure of organic fuel results in the production of biochar as well as tar and gas products (Figure 3).

In the case of wood processing, charcoal, wood tar and solvent in the form of turpentine is obtained. It is characteristic that pyrolysis results in the transformation of solid fuel into two other forms: gas fuel and liquid fuel. Their contribution depends on the type and composition of biomass, as well as the way of conducting the pyrolysis process. It is particularly important that pyrolysis occurs with no access of oxygen or another oxygenating agent. In energy engineering, pyrolysis is currently treated as a promising future method for obtaining more useful forms of fuel [24]. The objective of the process of pyrolysis of organic materials is processing raw materials (coal, biomass) to useful forms of energy, recycling of raw materials (waste polymers) and production of semi-products constituting raw materials for further use.

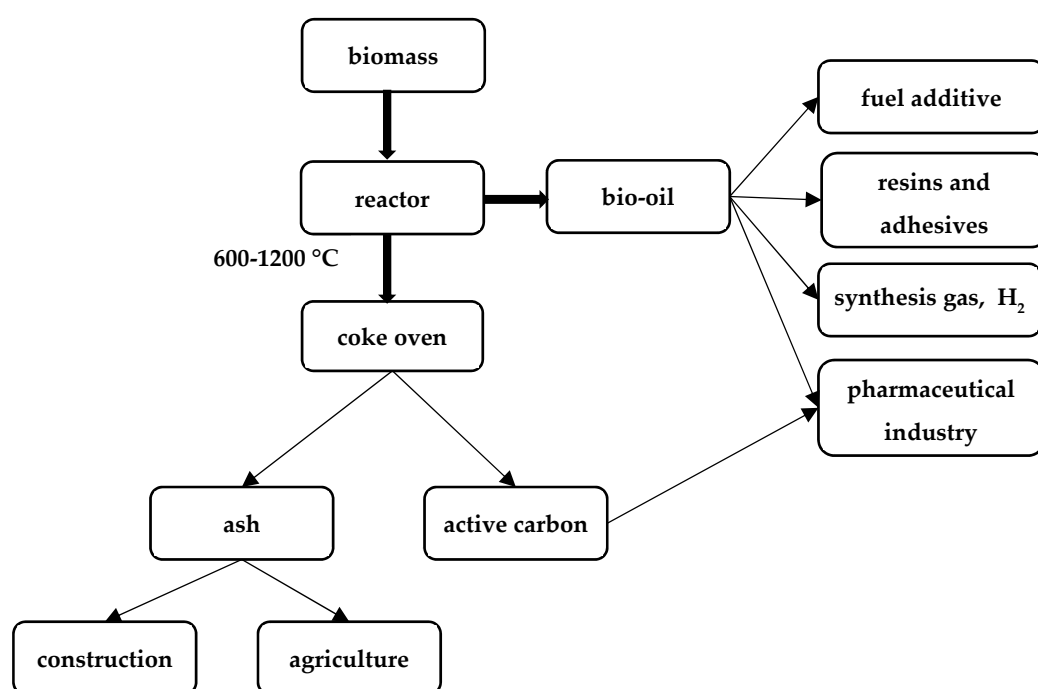


Figure 3. Scheme of pyrolysis.

Pyrolysis products find broad application in industry. Due to its structural properties and high reactivity, activated carbon is applied in the chemical, pharmaceutical, and food industry [25–27]. It is used for production of materials with high adsorption properties, applied, e.g., in clarifying, decolourisation of liquids, water filtration, or removal of traces of undesirable substances, including, e.g., phenols. Bio-oil is a compound derived from the depolymerisation and fragmentation of three key components of biomass: cellulose, hemicellulose and lignin [24]. A higher content of ash usually reduces the amount of obtained bio-oil. The chemical composition of bio-oil is more similar to biomass than to petroleum oils. A large group of compounds identified in pyrolytic oils includes: carboxylic acids, alcohols, phenols, esters, aldehydes, ketones and heterocyclic oxygen bonds. Amounts of bio-oil obtained from raw material are largely varied, and depend on the temperature, intensity of gas flow and type of feedstock. The highest yields of bio-oil are obtained from: expellers > maize cobs > rice husks > rice straw. The composition of bio-oil also includes water. Its content also varies in a range from 15 to 30%. The water phase can also be used to produce useful chemical compounds. Pyrolysis can be applied in the case of, e.g., used tyres. According to research, the efficiency of bio-oil increased with an increase in reaction temperature from 350 °C to 400 °C, but decreased to 57% when the temperature exceeded 400 °C. A higher fraction of TPO (Tire Pyrolytic Oil) in the oil

resulted in a reduction in the motor power with a simultaneous increase in the sulphur value. Pyrolysis can be also applied in the case of other substances, e.g., sewage sludge. As evidenced by Huang et al. [28], the chemical composition of bio-oil significantly depended on the pyrolysis temperature. Bio-oil obtained at low temperatures contained compounds such as alkenes, alkanes, long-chain fatty acids and esters, as well as aliphatic nitriles and amides. At high temperatures, aromatic compounds were accumulated, particularly N-heterocyclic compounds. Approximately 45% of bio-oil was obtained. The remaining 55% was biochar.

The third method of conversion of biomass energy to useful energy is its gasification, i.e., transformation of biomass into synthesis gas. Several hundred coal gasification reactors currently function around the world, whereas 90% of them are in China. The biomass gasification process itself is a high temperature process of its transformation to flammable gas substances under the influence of a gasification agent. Various substances can be subject to gasification, from medical waste to wood waste and plastics [29–32]. Gasification of coal is the most popular. Gasification is a process of transformation of fuel into gas whose main components are carbon oxide and hydrogen (Figure 4).

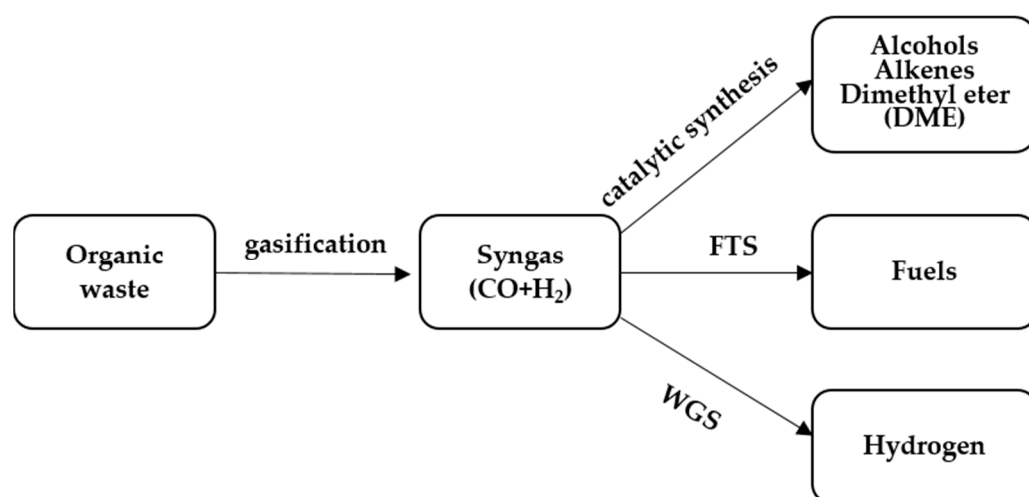


Figure 4. Schematic representation of the gasification processes involved in a thermochemical conversion of organic waste biomass. FTS—Fischer–Tropsch process; WGS—Water Gas Shift.

Hydrogen is applied in the production of ammonia and then fertilisers, and in refineries for refining petroleum products to motor fuels. The gasification process is conducted in chemical reactors working under high pressure, where fragmented organic material (usually coal) at a temperature of more than 1000 °C is exposed to oxygen and potentially an addition of water vapour. After treatment, gas obtained as a result of the reaction of partial combustion can be applied in chemical syntheses or energy engineering. The process of gasification of organic products shows strong development. As a result of accumulation of high amounts of waste biomass, an almost six-fold increase in the production of process gas is observed in 2018 in comparison with 2010. Gasification of biomass does not offer a considerable alternative to gasification of coals, because the theoretical efficiency of hydrogen from their processing in conversion to carbon oxide emission is similar. Four main processes can be designated during gasification, namely: drying, degassing, pyrolysis and proper gasification [33].

Chinweoke et al. [34] emphasise that gasification is a particularly good method for eliminating organic waste materials without damaging the environment. As a result of gasification of sawdust, they obtained 82.6% of carbon dioxide, 12.8% of hydrogen and 4.6% of methane. Su et al. [35] performed gasification of food waste. Such waste is characterised by the high content of organic matter. Food waste was subject to gasification in different reaction times (20–60 min) and at different temperatures (400–450 °C), and with different additions to food (NaOH, NaHCO₃ and NaCl) for the purpose of verification of

the effect of these factors on the efficiency and composition of the synthesis gas. It was determined that an increase in temperature and gasification time improves the efficiency of gasification. Antoniou et al. [36] conducted gasification of digestate. The digestate was composed of a mixture of pig manure (43%), cow manure (20%), maize and triticale silage (25%) and cereal bran (12%). The results showed that gasification of digestate at a higher temperature (850 °C) significantly increased gas yield. Simultaneously, ash rich in microelements was obtained (P, K, Ca, Mg) that can be used for fertiliser purposes. Lopes et al. [37] pointed out that gasification is a particularly good process for the disposal of high amounts of organic fractions of municipal solid waste collected through separate collection. The better the waste was segregated, the better was the obtained gas efficiency. Preliminary waste processing through segregation can be a practical way to develop a sustainable method of electricity production from MSW (municipal solid waste) through gasification and incineration. Similar to the previous cases, by-products of gasification are primarily ashes, and sometimes bottom ash. Gorazda et al. [38] evidenced that after the gasification process, the gasification remains are a valuable source of phosphorus and microelements, comparable with ash from sewage sludge. Combining the gasification process with retrieving nutrients, and the production of new fertilisers predominantly containing phosphorus, offers a chance for more environmentally efficient technologies in line with the principles of sustainable development. The problem of gasification of sewage sludge was also addressed by Thomsen et al. [39]. They evidenced that co-gasification of straw and sludge in gasifiers LT-CFB produced ash with high content of stable forms of C, phosphorus (P) and potassium (K), low content of heavy metals (particularly cadmium) and higher P availability for plants in comparison with monosludge ashes, therefore showing the best fertiliser properties among all the analysed materials. The authors also determined that gasification and co-gasification by means of the LT-CFB method is a highly efficient way of treatment and sanitation of sewage sludge for further use in agricultural systems. These dependencies were confirmed in other papers [40]. According to Zhu et al. [41], the obtained gravel after coal gasification is very good silica fertiliser, and can find broad application in agriculture for the improvement of mechanical properties and crop yielding. The conducted experiment evidenced that the application of fragmented bottom ash to the amount of 5% of weight significantly increased yields of rice. It was evidenced that appropriate application of CGFS as a resource of Si on an arable field can be considered a practical option of safe disposal of this industrial waste. Baniyadi et al. [42] suggest the application of by-products of gasification (biochar) as an addition to composts. It is a good environmental solution due to its efficiency in long-term protection of carbon resources in the soil. Such a procedure also creates a new market for unused biomass that is currently incinerated or stored. The obtained results showed that the available organic municipal waste in Ravenna can be used to produce high amounts of compost that can be used over an area of 700 ha/year of arable land. Patel et al. [43] evidenced that gasification products can be a good substrate for the production of not only phosphorus fertilisers, but also potassium fertilisers. The synthesis of potassium fertiliser was economically profitable for all analysed production capacities of gasification. The obtained potassium fertiliser retrieved from the remaining ash can cover 31% of annual demand for potassium fertiliser for cotton fields that originally supplied raw material.

3. Microbiological Processes

The key element of the EU strategy regarding bioeconomy [44] is biological processing of organic waste in aerobic or anaerobic conditions. Biological processes of waste processing are defined as the controlled transformation of waste by living organisms. Waste is subject to biochemical decomposition with the application of the ability to degrade, transform and stabilise organic matter. The organic fraction of municipal waste differs from “natural” organic waste in terms of physical and chemical properties, including the content of xenobiotics. It is therefore necessary to support and optimise biological waste degradation

of organic matter through appropriate steering of the decomposition process, and the application of various solutions and technical devices [45].

The composting process can be defined as autothermal and thermophilic biological decomposition of selectively collected biowaste by micro- and macroorganisms in the presence of oxygen, and under controlled conditions for the purpose of compost production. Compost can be defined as stable material, securely sanitary, similar to humus, rich in organic substances and not releasing unpleasant odours, obtained in the process of microbiological transformation of selectively collected biowaste [46–49].

Two technologies of aerobic processing of biodegradable waste are usually designated, namely open technology—composting in prisms in open space, and closed technology—composting in bioreactors (preliminary composting and maturing of compost in prisms) [50,51]. The former one involves conducting the process in natural conditions, on a prism not secured against atmospheric impact. The latter is conducted in artificial conditions—in closed facilities (boxes, tunnels, containers, or halls), where the composting process can be conducted in a controlled way.

The course of the composting process and quality of the obtained product—compost—depends on many factors such as: quality of raw material for composting, and particularly the value of the C/N ratio (Table 2), content of macrolelements and heavy metals, pH, fragmentation of raw material, moisture, oxygen access, etc.

Microorganisms decompose organic compounds to obtain energy for metabolism and nutrients (such as N, P, K) in order to maintain their population. C and N are the most important: carbon is used as a source of energy, and nitrogen is used for the construction of cell structure [52]. The value considered optimal for composting is C/N ratio of 25–30:1, although good composting efficiency can be obtained at an initial C/N ratio of 20–40:1 [53–55].

Moisture is a critical parameter in the composting process. It affects the rate of oxygen absorption, the activity of microorganisms and the temperature of the process [56]. Humidity optimal for efficient composting should be in a range of 50–60%. When moisture is lower than 30%, bacterial activity is limited, and above 65% the porosity of compost decreases, leading to anaerobic conditions and odour emission [57,58].

Table 2. Carbon/nitrogen ratios of various organic residues [50,55,59,60].

Material	C/N
Sewage sludge	10–30
Municipal solid waste	49–105
Food waste	14–17
Fruit wastes	20–49
Vegetable wastes	10–17
Green waste	10–30
Tree leaves	40–70
Cattle manure	13–18
Poultry manure	10–17
Maize residues	80–90
Wheat straw	100–150
Sawdust	150–500

pH is an important parameter in the composting process, because it affects the activity of microorganisms during composting [61]. A value optimal for biomass decomposition is pH in a range of 6.0–8.0. Low pH is usually a problem during composting of food waste. It contributes to limiting microbiological activity, slowing down biomass decomposition. Low pH also negatively affects temperature increase at the initial stage of the process of composting of household waste [62,63].

Composting is an aerobic process in which O₂ is used and gas H₂O and CO₂ are released. Therefore, aeration is an important factor affecting the quality of compost and activity of microorganisms in the composting process. Aeration also helps maintain the temperature of compost in the case of thermophilic decomposition of organic waste. Oxy-

gen content depends on the porosity of the compost prism, affected by the size and shape of particles, as well as moisture of the composted material [54,55]. CO₂ concentration in the prism should not exceed 15% to ensure maintaining oxygen concentration at a level necessary for the proper course of the process, i.e., 15–20% at the decomposition stage, and 5–10% at the maturation stage [62,64]. Two primary types of transformations of organic compounds occur during composting, namely mineralisation and humification. Mineralisation involves microbiological decomposition of organic compounds. Humification is a process of transformation of simple organic compounds into humic substances. In favourable conditions, the composting process runs through several phases with participation of different groups of microorganisms. At the stage of active decomposition, rapid decomposition of easily oxygenated organic compounds by intensively reproducing microorganisms is observed. This phase is characterised by a gradual increase in the temperature of the prism, from the temperature of the surroundings, through mesophilic temperatures of 25–45 °C, to thermophilic temperatures (more than 55 °C). Thermophilic temperatures are desirable, because they provide for hygienisation of the composted materials through neutralising pathogens, seeds of weeds or insect larvae. With a decrease in the share of high-energy compounds, the temperature of the compost decreases, and the prism again becomes dominated by mesophilic organisms. This phase is called the cooling phase. The maturing phase of compost involves the humification of material. It occurs at a temperature approximate to the temperature of the surroundings [46,48,53,55]. Proper course of these phases determines the quality of the end product, i.e., compost. Important parameters of the evaluation of compost quality include its maturity, defined as the degree of completion of the composting process specified based on the degree of humification of the composted material, and stability, i.e., the stability of the composted matter to further rapid degradation [65–67]. Compost maturity is determined based on the value of different physico-chemical and biological parameters (Table 3) such as: C/N ratio, humidity, pH, nitrification index—NH₄/NO₃ (NI), electrolytic conductivity, content of total organic carbon (TOC), humification index (HI), phytotoxicity tests (PT), germination index (GI), etc. [62,65–70].

Table 3. Parameters used to assess compost maturity.

Parameters	Values for Mature Compost	Reference
C/N ratio	<20:1	[70]
pH	8.0–9.0	[70]
EC	<9.0 ms cm ^{−1}	[70]
Organic matter	<50%	[71]
Humification index (HI)	≤2.4	[70]
Nitrification index (NI)	<3.0	[54]
Germination index (GI)	>80%	[69]

Due to the necessity of ensuring safety for the environment and human and animal health, an important aspect of recycling of organic waste by means of composting is the assessment of the quality of composts, considering among others content of heavy metals (As, Cd, Cr, Cu, Hg, Ni, Pb, Zn) and pathogenic organisms such as *Salmonella* sp., *E. coli*, *Ascaris*, *Trichuris*, *Toxocara* [71]. Excessive content of the aforementioned contaminants is characteristic of composts produced from municipal waste. It can exclude them as fertilisers for agricultural application [72,73]. In the composting process, waste is transformed into valuable and environmentally safe organic fertilisers the application of which contributes to the improvement of physical, chemical, and biological soil properties (Figure 5, Table 4). Composts are particularly recommended to be applied on marginal soils, with low fertility, where the introduction of organic matter and nutrients with compost to the soil increases its fertility and allows for restoring its use in agricultural production. Composts can also constitute a valuable substitute of mineral fertilisers in sustainable agriculture.

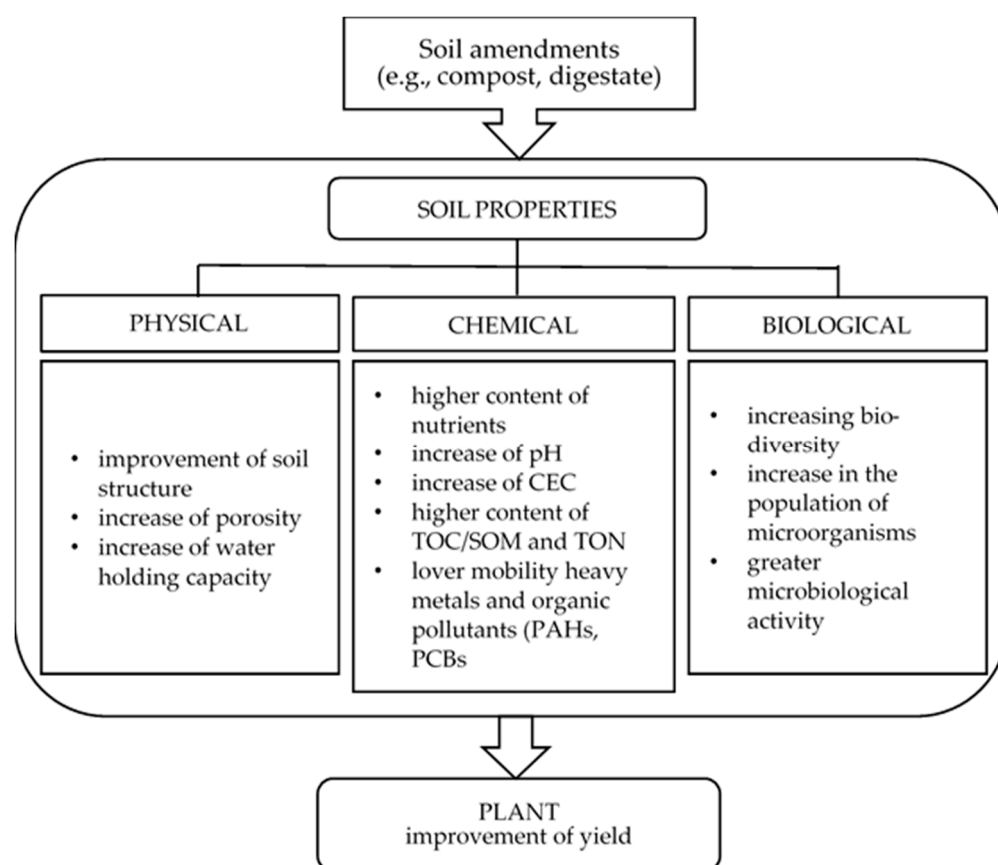


Figure 5. Effect of organic amendments application on soil properties and crops.

Table 4. Effects of compost application on different soil properties.

Compost Feedstock	Experimental Conditions	Effect on Soil Properties
Separately collected organic fraction of municipal solid waste [74]	Compost applied annually in doses: 0, 30, 60 Mg FW per ha. Soil silty-loam, pH 5.6, soil rich in organic matter and available forms of P, K	Increasing doses of compost improved (decreased) soil density from 1.31 to 1.16 g cm ⁻³ , increased total soil porosity from 49 to 54% and soil stability against water erosion (increase aggregate stability from 29 to 31%). Under applied doses and compared with the control treatment, soil pH increased to 6.5, TOC content reached more than 22 g·kg ⁻¹ . Soil total nitrogen, soil available phosphorus and soil available potassium increased by about 77%, 55–68% and 65–70%, respectively. CEC increased 63–74% compared with the control. The highest dose of compost significantly increased soil microbial biomass (by 300%) and dehydrogenase activity (by 77%) in relation to control object.
Sewage sludge (40%), straw (25%), bentonite (5%), rhyolite (30%) [75]	Compost applied from 2003 every 3 years in doses: 0, 9, 18, 27 Mg DM per ha. Soil—Arenosol, pH 5.3, SOM 0.9%, available phosphorus 240.1 mg P ₂ O ₅ kg ⁻¹ , available potassium 183.3 mg K ₂ O kg ⁻¹	Compost application positively affected the soil organic matter content in the 0–30 cm soil layer. The organic matter content of soil increased with increasing compost dose. The SOM content increased in each compost treatment by up to 1.0%. However, significantly higher values of SOM as compared with the control were observed only in the plots where the 18 Mg ha ⁻¹ compost dose was applied. The addition of compost significantly reduced the soil bulk density to 1.40–1.35 g cm ⁻³ in compost treatments from 1.5 g cm ⁻³ measured in control plots.

Table 4. Cont.

Compost Feedstock	Experimental Conditions	Effect on Soil Properties
MSW—municipal solid waste compost obtained from mechanically separated organic fractions from residual waste; BIO—biowaste compost obtained from co-composting of green wastes and source separated organic fractions of municipal solid wastes; GWS—compost obtained from green waste collected from private and public gardens (70%) and sewage sludge (30%) [76]	Composts applied every second year starting 1998 in an amount of 4 Mg of organic carbon per ha. Soil—Haplic Luvisol	All composts reduced bulk density and increased organic carbon concentrations, which improved apparent air permeability and gas diffusivity, but only a green waste-sewage sludge compost increased water-holding capacity
tannery sludge sugarcane bagasse, and manure mixed 1:3:1 v:v:v [77]	Long-term experiment (2009–2019), compost applied every year in doses: 0, 2.5, 5, 10 Mg per ha. Soil—“fluvent” soil (USDA Soil Taxonomy) presenting 100 g kg ^{−1} clay, 282 g kg ^{−1} silt, and 618 g kg ^{−1} sand	Soil pH, K, Ca, TOC, P, and EC increased about 0.5, 2.5, 3, 4, 5, and 9 times after the application of 20 Mg ha ^{−1} , respectively. Soil microbial biomass C (MBC) and N (MBN) decreased after the application of compost. In the 10th year, the highest values of MBC and MBN were found in unamended soils, while the lowest values were found in the treatments with application of 10 and 20 Mg ha ^{−1} compost

Anaerobic digestion (AD)—process of biochemical decomposition of solid and liquid organic matter occurring in an anaerobic environment. The primary objective of the process is transforming organic matter into biogas. The process also yields digestate which, similar to compost, can be used for fertiliser purposes. With an increase in the amount of generated waste, and particularly municipal and food waste, as well as an increase in demand for renewable energy, development of technologies of anaerobic waste processing has been observed in recent years [46,78–81]. Currently, biogas is primarily produced in agricultural biogas plants, where substrates usually include animal waste (e.g., manure), biomass from plants cultivated for this purpose (e.g., maize silage) or food waste [82].

The process of anaerobic decomposition of organic matter with the participation of specialised bacterial groups involves four stages: (a) hydrolysis, (b) acidogenesis, (c) acetogenesis and (d) methanogenesis [79].

At the first stage, large chain organic compounds (proteins, fats, carbohydrates) are transformed into compounds with a simpler structure and greater solubility, such as amino acids, sugars and large chain fatty acids (Figure 6). Then, the compounds are transformed into short chain fatty acids (acetic, propionic, butyric), including volatile fatty acids and other compounds such as NH₃, CO₂ and H₂. At the third stage, fatty acids are transformed into acetic acid and hydrogen. The last stage is methanogenesis in which methanogenic organisms transform acetic acid and hydrogen into methane [83]. In the process of anaerobic digestion, soluble organic compounds are decomposed, nitrogen compounds are transformed into ammonium nitrogen, bacteria, viruses and eggs of pathogens are destroyed, and the C/N ratio is reduced (Table 5).

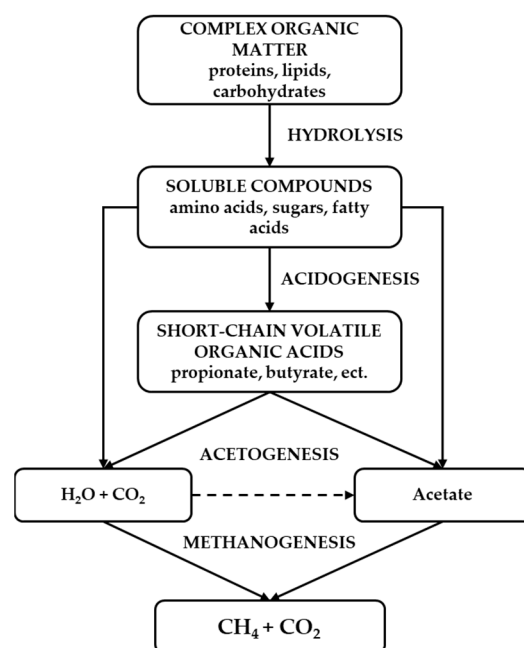


Figure 6. Anaerobic digestion process and reactions.

Table 5. Classification of biogas production technology.

Criterion	Type of Technology	Characteristics
Proces temperature	Mesophilic Thermophilic	30–40 °C (optimum 35–37 °C) 50–65 °C (optimum 55 °C)
Dry matter content	Wet	The feedstock is slurried with a large amount of water to provide a dilute feedstock of <15% dry solids (usually 10–15%)
	Dry	The feedstock used has a dry solids content of 20–40%
number of steps in the process	Single Step	All digestion occurs in one vessel
	Multi Step	Process consists of several digestion vessels. Usually, the rate limiting hydrolysis step of the anaerobic digestion process is separated from the methanogenesis (in a two-stage system). This results in increased efficiency as the two bacterial groups have different optimal conditions
Method of dosing substrates	Batch	The digester is loaded with raw feedstock and inoculated with digestate from another tank. It is then closed and left until thorough degradation has occurred. The digester is then emptied, and a new batch of organic mixture is added
	Continuous	The digester is fed continuously with waste material. Fully degraded material is continuously removed from the digester

No changes are usually observed in the content of the remaining macro- and microelements. Because only part of co-substrates is subject to the transformations and is transformed into biogas, anaerobic digestion also yields a by-product, namely digestate. According to the estimates of Tampio et al. [84], after the completion of the anaerobic digestion process, depending on the substrate characteristics, 90–95% of reactor feedstock remains as digestate. A relatively common method is the separation of digestate into the

solid and liquid phase. The solid phase contains up to 75% of stable organic matter. It is characterised by a small contribution of $\text{NH}_4\text{-N}$ in total N, a considerable content of phosphorus, calcium and magnesium, and alkaline reaction ($\text{pH} > 7.5$). It is therefore treated as an agent improving soil properties rather than fertilizer. The liquid fraction is characterised by a high ratio of $\text{NH}_4\text{-N}$ to total N, and a high concentration of potassium, and it is treated as fertiliser—a source of nitrogen and potassium easily available for plants [85–88]. Although the composition of digestate is relatively variable (Table 6), depending on among others the type of organic matter subject to the AD process, conditions of the fermentation process (pH , temperature, etc.), and management of digestate after the completion of the process, it is commonly used for fertiliser purposes on arable land and grasslands [86,88].

Table 6. Chemical composition of digestate from different substrates.

Digestate Substrates	DM	pH	Corg.	Ntot.	P	K	Ca	Mg	Zn	Cu	Cd	Pb
	%				g/kg DM				mg/kg DM			
corn silage, sugar bagasse beet, pomace of fruit, waste from dairy, manure [89]	6.56	8.50	357.0	3.10	1.04	1.22	1.90	0.27	93.9	12.5	0.18	<0.1
silage from corn and rye, apple pomace, and distillery decoction [90]	5.20	7.29	372.0	49.3	14.4	11.6	19.3	7.17	1450.0	134.0	2.47	39.7
sugar pulp from sugar beet processing plants [91]	2.5	7.50	229.0	23.0	1.59	11.9	112.0	8.40	295.0	88.0	2.20	42.4
cattle slurry, maize silage, haylage [92]	5.83	8.53	N/A	31.4	11.7	55.9	29.6	8.24	295.0	90.1	N/A	N/A
corn silage, manure, and vegetable waste [93]	25.3	7.1	398.0	12.3	7.9	14.1	20.0	4.7	170.7	30.4	0.05	1.9
animal manures (cow and poultry), solid wastes from citrus and olive processing plants, pruning materials, maize silage, crop residues, milk serum [94]	18.0	8.77	389.6	16.0	1.24	2.25	0.97	0.79	25.2	1.92	<0.01	0.07
agro-industrial residues, herbaceous biomass [95]	N/A	N/A	385.0	12.1	18.2	28.3	39.2	8.53	N/A	N/A	N/A	N/A
sewage sludge [96]	16.5	N/A	327.0	51.0	45.8	2.8	30.2	3.2	N/A	N/A	N/A	N/A
vegetable, garden, fruit [97]	N/A	N/A	295.0	20.0	26.0	7.0	43.0	8.0	N/A	N/A	N/A	N/A
municipal solid waste [97]	N/A	N/A	241.0	15.0	7.0	16.0	104.0	14.0	N/A	N/A	N/A	N/A

N/A—not analysed.

Research by many authors has shown that due to its properties, digestate has a positive effect on the physical, chemical and biological properties of soil. Garg et al. [98] evidenced that the application of digestate from waste organic matter of agricultural origin reduces the bulk density of soil and increases its capacity for retaining water. Pastorelli et al. [99] evidenced no effect of the application of digestate on changes in bulk density of soil, but they did evidence its positive effect on aggregate stability. Jaša et al. [100] observed a negative effect of the application of digestate on physical soil properties. After three years of application of digestate on light texture, sandy clay type soil, the authors observed an increase in bulk density and a decrease in porosity. The application of digestate results in an increase in the content of TOC (total organic carbon), TON (total organic nitrogen) and bioavailable forms of P and K in the soil [89,92,98,99,101]. Applying digestate on soil with a grain size composition of silty loam, strongly acidic ($\text{pH}_{\text{KCl}} 4.4$), poor in organic matter and bioavailable forms of nutrients, Głowacka et al. [89] evidenced an increase in the pH value of the soil and an increase in its cation exchange capacity (CEC), sum of exchangeable cations (EAC) and sorption complex saturation with exchangeable cations (BS). Pastorelli et al. [99] determined no effect of the application of digestate on the sorption properties of soil with a grain size composition of silty clay. Digestate can also have a positive effect on biological soil properties by increasing the soil microbial biomass and metabolic activity as a result of an increase in the content of Corg. and nutrients, and particularly N and P, in the soil [87,98,99,101]. The positive effect of digestate on soil properties usually results in an increase in the yield of crops and their quality. The positive effect of the application

of digestate was evidenced in the cultivation of horticultural plants—tomatoes [101,102], ornamental plants—rose-scented geranium [93], agricultural plants—wheat [103] and maize [104], and energy crops—*Pennisetum hybridum* [105] and *Sida hermaphrodita* [106], and grasslands [89,107,108].

In the world scale, food and green waste are the most popular and constitute as much as 44% (Figure 7).

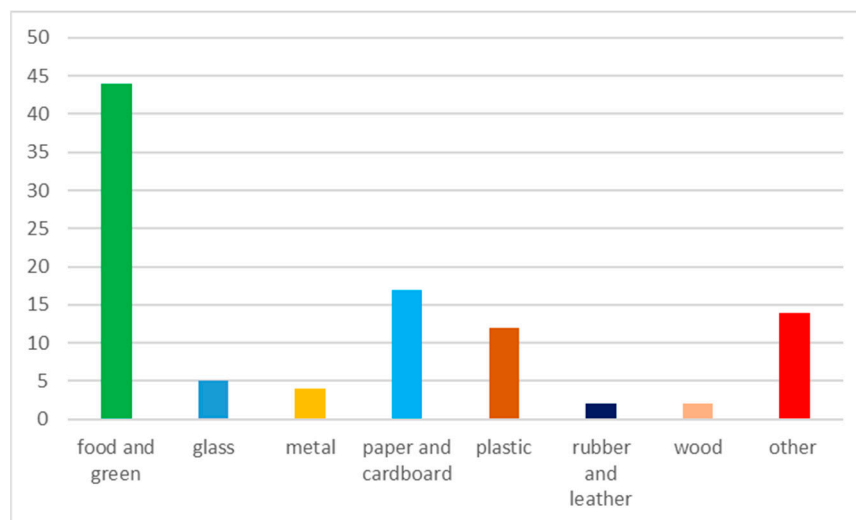


Figure 7. Global waste composition (%) [1].

The most popular methods of waste management are open dump and landfill (Figure 8). However, due to the large share of organic waste in the waste structure, composting and incineration should be the most desirable processes for their treatment.

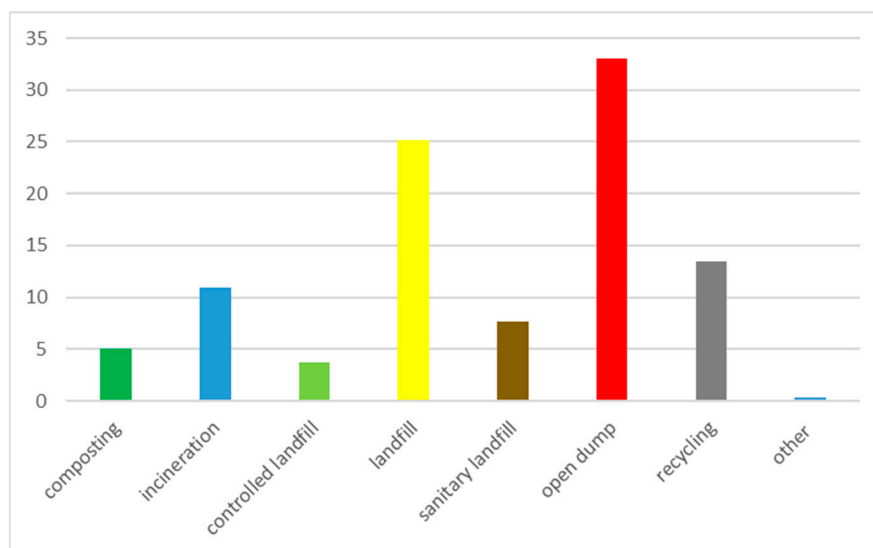


Figure 8. Global treatment and disposal of waste (%) [1].

4. Conclusions

In the next 30 years, the amount of produced waste will double, and on some continents even triple from the amount existing in 2020. This calls for the creation of principles of conduct with regard to waste processing. Due to the large share of organic waste in the waste structure, composting and incineration should be the most desirable processes for their treatment. Both methods are widely used; however, the one which will be chosen depends on the legislation of the given country. In less-developed countries, waste

management occurs through combustion. However, in Europe, the solutions in this area are determined by the European Parliament, which is implementing new legislation in the form of the European Green Deal. Organic waste should be recovered, treated and once again introduced into the environment. This course of action, amongst other things, stabilises the amount of organic material in the soil, as well as CO₂ emission into the atmosphere. Composting waste and using it in agriculture is the most cost-effective way of processing it. On the global scale, there is a systematic improvement of methods by which to treat waste and then recycle for use in technological processes. This course of action can be implemented in a circular economy in which the value of raw material and finished goods can be preserved for as long as possible while simultaneously minimising the amount of waste.

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