

Article

Organic Municipal Waste—Testing and Analysis of End Products for Use in the Circular Economy and Their Potential Implications for Climate Change Mitigation

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Abstract

Municipal organic waste is one of the types of waste generated mainly in households but also by other producers. The key to managing this waste is to use appropriate treatment processes to reduce its negative impacts on the environment. The composting process involves the decomposition of persistent organic pollutants and their binding with the organic fraction. This study involved quantitative and qualitative research and analyses of organic waste contained in mixed municipal waste and selectively collected waste in Poland between 2020 and 2024. The aim of the study was to compare the final parameters of two types of organic waste after biological treatment, assess their potential management pathways within the circular economy, and discuss their potential relevance to greenhouse gas mitigation. The research results showed that, after applying the same biological processes to the two analyzed organic waste streams, the final products exhibited significant differences in physicochemical parameters, which necessitates the use of different management methods. The first end product can be classified as compost—a potential fertilizer—and must meet quality requirements for an organic soil improver. The second end product can be used for land reclamation if it meets all three criteria: an AT₄ (four-day aerobic respiration activity of the material) value of <10 mgO₂/g dry weight, loss on ignition of less than 35%, and organic carbon content of less than 20% dry weight. The products of the biological treatment of organic waste include fertilizers and stabilized waste intended for further processing.

Keywords: organic waste; sustainable development; recycling; climate change; environmental protection

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1. Introduction

1.1. The Importance of Organic Waste in Environmental and Water Resource Protection

Organic waste is one of the most important fractions in the municipal waste stream and plays a key role in the context of environmental protection, particularly in reducing greenhouse gas emissions, protecting soil quality, and securing surface and groundwater [1,2]. The key to municipal organic waste management is the selective collection of this waste directly from the producer in order to shorten the supply chain to the treatment plant [3,4]. The processing of organic waste—and, in particular, its biostabilization in processes and facilities that provide the best available technologies—is part of the circular economy concept. Its aim is to reduce greenhouse gas emissions and energy consumption by creating closed-loop processes in which the waste generated is treated as raw material or fuel in subsequent stages of production [5,6]. In many European Union countries, the biodegradable fraction accounts for 30 to 45% of the mass of mixed municipal waste, with its share depending on the local conditions, seasonality, and the collection system. Such a high share of the organic fraction makes its proper management crucial for the environment [7,8]. Municipal waste containing a biodegradable fraction should not be landfilled, as this causes a number of hazards, including biogas production, volatile organic compound emissions, leachate generation, and the risk of the diffuse pollution of surface and groundwater [9,10]. Insufficient biological stabilization of organic waste can lead to the release of dissolved organic carbon, biogenic compounds, and substances with high oxygen demands, posing a threat to aquatic ecosystems and groundwater quality [11–13].

Biodegradable organic substances have an adverse effect on the oxygen balance of water. Improper management of organic waste means that hazardous organic substances contained in sewage and leachate can be introduced into water, posing a significant threat [14]. From the point of view of hazards, refractory organic pollutants that are not biodegradable by microorganisms, or are only biodegradable to a small extent, are particularly significant. Therefore, a key challenge in municipal organic waste treatment plants is the generation of leachate during aerobic and anaerobic processes. This applies to the intensive composting phase, as well as aerobic stabilization. The leachate produced must be collected, treated, and, if it meets the parameters, discharged into sanitary sewage systems or watercourses. This treatment of organic leachate prevents the migration of pollutants into surface and groundwater [15,16]. The biological treatment of organic waste mainly involves composting and anaerobic fermentation. These processes stabilize organic matter, reduce its negative impacts on the environment, and recover energy and nutrients in a manner consistent with the concept of a circular economy [17,18]. For this reason, the quality and environmental safety of the end products of these processes are of particular importance from the point of view of soil and water resource protection [19,20].

1.2. Organic Waste Streams: Selective Biowaste and the Organic Fraction of Mixed Waste

Municipal waste management systems around the world vary greatly depending on the country, geographical location, and strategy. The situation is similar with regard to the treatment of organic waste, which, regardless of the country, presents variable value in the municipal waste stream. In view of the growing level of consumption and the amounts of waste generated, different countries are implementing individual systems aimed at minimizing the negative impacts on ecosystems [21]. In Poland, municipal waste management systems distinguish between two basic streams of organic waste sent for biological treatment. The first is municipal organic (biodegradable) waste collected selectively at the source, consisting mainly of kitchen and green waste from households, green space maintenance, and marketplaces. The second stream is the organic fraction contained in mixed municipal waste, which is the result of errors in the segregation process, a lack

of monitoring of selective collection, or errors during the transport and storage of municipal waste [22,23]. The organic fraction contained in mixed municipal waste is most often separated in mechanical–biological treatment (MBT) plants, which operate on the basis of applicable legal acts [24]. MBT plants carry out two technological processes, i.e., mechanical and biological waste treatment, integrated into a single waste treatment process in order to prepare the waste for recovery processes, including recycling, energy recovery, thermal conversion, or disposal processes, such as landfilling and thermal conversion [25,26]. Numerous studies indicate that the method of collection (avoiding contamination, e.g., with ash) and the separation of the organic fraction in the mechanical process have a significant impact on its physicochemical properties and the homogeneity and quality of the organic fraction [27,28]. The composition of municipal waste depends on many variables, including the geographical region, population density, economic activity, eating habits, season, and the collection system in place. Research on the morphologies of municipal waste and organic waste focuses on basic parameters and properties, including the content of individual fractions, biodegradable fractions, mineral fractions, calorific value, granulation, and moisture content [29,30]. Organic waste collected separately is usually characterized by higher content of easily biodegradable organic matter; a lower proportion of inert fractions, i.e., biologically inactive mineral components and other non-biodegradable materials; and lower concentrations of heavy metals and physical contaminants such as plastics and glass [31,32]. On the other hand, the organic fraction separated from the mixed waste stream is characterized by greater heterogeneity, increased moisture content, and increased mineral and metallic contamination, which can negatively affect both biological processes and the quality of the final products [33,34]. These differences are directly relevant not only to the technological efficiency of processing but also to the potential impacts of the products on the soil–water system in the event of their further use [35,36]. Organic waste separated from the municipal waste stream during mechanical treatment (screening) is characterized by increased contamination, a lower proportion of biodegradable fractions, and high mineral fraction content. These properties require that the treatment process be subject to the specific monitoring of process parameters, with a particular emphasis on the duration of the process [37,38].

1.3. Biological Treatment Processes and the Quality of End Products

Currently, municipal waste management, including that of organic waste, is one of the most serious problems of modern civilization. The problem of waste management forces the development of new methods for the processing, recovery, and reuse of waste. Any product that is not managed and has no specific purpose acquires the properties of waste. Every piece of waste becomes a potential raw material or resource once it is managed. Therefore, every material obtained, processed, and transported by humans can be either a resource and a useful product or waste with varying degrees of nuisance to the environment [39]. Both selectively collected organic waste and the organic fraction separated from the mixed municipal waste stream are usually subjected to similar biological processes under aerobic and anaerobic conditions. The technology of biological processing with oxygen (composting) in closed bioreactors involves the active phase with the collection, accumulation, and treatment of wastewater and the purification of process air [40]. The same process can be carried out in piles in open areas with mechanical aeration, which is the compost maturation process. The end result of this process is a product in the form of compost or stabilized waste [41]. Anaerobic fermentation carried out in fermentation chambers is a closed process, the products of which can be digestate, stabilized waste (subjected to aerobic stabilization), and municipal biogas [42]. The biogas produced in this process is of added value; once purified, it can be used for energy processes as a renewable

energy source and as a gaseous fuel to power vehicles after converting biogas to biomethane. The diversification of energy sources with energy from renewable sources is an important aspect of a country's energy mix, acting as a potential regulator between technological innovation, energy prices, climate regulations, and inflation [43,44]. The use of different combinations in organic waste treatment planning allows for process control, the qualitative analysis of end products, and the monitoring of the environmental impacts of end products and installations [45,46]. However, the results of laboratory, semi-technical, and full-scale studies clearly indicate that the use of the same technologies does not lead to products of comparable quality if the nature of the input, i.e., the quality of organic waste, differs [47,48]. The products of the biological treatment of selectively collected biowaste generally exhibit more favorable physicochemical properties, including a higher degree of biological stabilization, greater compositional homogeneity, and lower heavy metal concentrations, which increases their potential for fertilizer applications [49]. On the other hand, products derived from the organic fraction separated from the mixed waste stream, despite meeting the formal stabilization criteria, often have limited usability and are mainly used for the reclamation of degraded areas or landfilling. This highlights the key role of the feedstock origin in shaping the quality and environmental safety of end products [50,51].

1.4. Indicators of Biological Stabilization of Organic Matter

In the literature, there is growing interest in the potential use of composting methods as a means of optimizing the chemical and biological properties of organic waste. During the composting process, specific conditions are created, involving increased microbial activity and high temperatures, which contribute to the elimination of sanitary hazards in composted materials. The composting process breaks down persistent organic pollutants (POPs), but the high organic matter content limits their degradation due to the formation of so-called bound residues that are inaccessible or very difficult to access for microorganisms. It can also be a method of pollutant disposal, involving their permanent stabilization in the material [52,53]. Integrated municipal waste treatment and the biological stabilization of organic matter may support circular economy objectives and contribute to climate change mitigation by reducing the potential for methane generation compared with the landfilling of untreated biodegradable waste [9,17,48]. The degree of biological stabilization is one of the basic criteria for assessing the quality and environmental safety of products of the biological treatment of municipal organic waste. For this purpose, respirometric indicators have been widely used, including the four-day aerobic respiration activity of the material (AT_4) [5,13,54]. AT_4 values enable a quantitative assessment of residual biological activity and reflect the degree of organic matter decomposition during biological processes. Literature studies confirm the good correlations between this indicator and other measures of material stabilization and maturity. At the same time, it has been shown that AT_4 values differ significantly between products derived from selective biowaste and the organic fraction of mixed waste, even when using similar technological processes [55,56]. From the point of view of water resource protection, an insufficient degree of biological stabilization may increase the risk of organic compound migration and oxygen deficiency in the receiving environment [57,58]. Biological activity indicators are supplemented by parameters describing the quantitative content of organic matter, such as total organic carbon (TOC) and loss on ignition, as well as equivalent indicators, e.g., volatile matter content [59]. These parameters are commonly used in the assessment of the quality of composts, digestates, and stabilizers, allowing the determination of the proportion of residual organic matter in the material [60]. However, the interpretation of TOC and loss on ignition values should take into account the degree of biological stabilization and the

nature of the input, as high organic matter content is not always a clear indicator of product immaturity [61]. At the same time, elevated levels of residual organic carbon may increase the potential for the release of dissolved organic matter and biogenic components, which is important for groundwater quality [62]. For this reason, the literature emphasizes the need for the combined interpretation of organic matter content indicators and biological stabilization parameters [63].

1.5. National Context—Poland

Published statistics show that, in 2024, Poland generated 14,158,000 Mg of municipal waste—an increase of 5.3% compared to the previous year. The amount of selectively collected municipal waste is steadily growing. In 2010, selective collection accounted for only 8.6% of the municipal waste collected (860,000 Mg), while, in 2024, it reached 42% (5,469,000 tons), with an increase in the amount of selectively collected waste (by 9%) compared to the previous year. Over the last five years, data have shown that, in Poland, selectively collected organic waste accounts for an increasing share of municipal waste, with a 38.9% increase in the amount of selectively collected organic waste in 2024 compared to 2020. This progress demonstrates the increasing effectiveness of the selective collection of organic waste in Poland and the need to adapt existing facilities to process it. In Poland, the last decade has seen the dynamic development of municipal waste management systems, including both the expansion of existing mechanical–biological treatment facilities and the construction of new ones [64]. Legal issues related to the processing of organic waste in Poland are regulated, among others, by the regulation on the mechanical–biological treatment of unsorted (mixed) municipal waste, which came into force on 24 January 2023 and imposes new obligations on operators [65]. This applies in particular to the obligation to unload and mechanically treat mixed municipal waste in a closed facility, i.e., a building. The technological process and technical conditions must include a sealed base and a ventilation system that limits the release of dust into the air, i.e., reduces emissions into the environment and odor nuisance. The floor of the facility must prevent leachate from entering the environment. The collected leachate should be treated and managed in an environmentally safe manner, preventing it from entering surface and groundwater [66,67]. The operator of the installation is free to choose specific technical solutions and may use techniques not mentioned in the Best Available Techniques (BAT). Moreover, an equivalent level of environmental protection must be ensured [68]. There are approximately 200 mechanical–biological waste treatment plants operating in Poland, which differ in terms of complexity, equipment, and the technologies used. Regardless of the type of technology used, the mechanical–biological waste treatment process in each plant consists of several basic stages. The first is sorting the waste by type, size, shape, and color, followed by the separation of recyclable materials and the biological fraction subject to stabilization—mechanical treatment. The next stage is the transfer of non-recyclable waste for thermal treatment or biological stabilization under aerobic or anaerobic conditions. The need to optimize food production and consumer awareness have a significant impact on the amount of waste generated by residents, which indirectly correlates with the economic and energy efficiency of organic waste treatment processes among operators and producers and the final price of the product [69,70].

Research available in the national literature indicates that the organic fraction separated from the mixed municipal waste stream is characterized by significant variability in composition and an increased proportion of inert fractions and mineral impurities, which is reflected in reduced organic matter content and slower biological stabilization processes [71]. Studies conducted in MBT plants in Poland have shown that, even when using similar biological processes, the quality parameters of stabilizers vary significantly depending on the characteristics of the input and the degree of its contamination [72–74]. On the other

hand, selectively collected biowaste is characterized by greater homogeneity in composition and a higher proportion of easily biodegradable organic matter, which promotes more efficient composting and anaerobic fermentation processes [75,76]. National studies confirm that the products of the biological processing of selectively collected biowaste have more favorable physicochemical parameters, including higher organic carbon content and lower levels of contamination, which increases their potential for utilization compared to products obtained from mechanically separated organic fractions [77,78]. Effective waste management, including that of organic waste, should be supported by smart technologies, including geographic information systems (GIS), big data analytics, and artificial intelligence (AI). The use of these tools can effectively support the sustainable use of resources and promote the development of low-carbon and circular waste management systems. Modern IT tools can be used to control organic waste treatment processes in order to monitor the progress of technological processes in terms of quality and to meet the requirements for compost and waste such as “stabilizers” [79]. Organic waste management in Poland is subject to and will continue to be subject to constant changes resulting from global and local trends. The amount of waste generated in a given period will be influenced by many variables that often stimulate an increase or decrease in the amount of waste produced. These may include, for example, socioeconomic factors, legal regulations, the occurrence of pandemics such as COVID-19, promotional campaigns, and economic crises [80]. Research in this area shows a correlation between the average monthly income and residents’ lifestyles, expressed, among other aspects, in household water and electricity consumption. Another important aspect is the impact on waste generation resulting from the evolution of cities, expressed in increasing levels of prosperity, but also in the depopulation of cities and the overall demographic situation [81,82].

1.6. Research Gap and Justification for Further Research

The Polish literature on the subject points to a lack of comparative studies that evaluate the products of the biological treatment of both organic waste streams in parallel in terms of quantity and quality, using uniform indicators of biological stabilization and organic matter content. This applies in particular to parameters such as AT_4 respiratory activity, total organic carbon (TOC), and loss on ignition, which are key from the point of view of the classification of end products and their further safe management [83,84]. This gap justifies the need for analyses covering the period after the introduction of the mandatory selective collection of biowaste, taking into account current quantitative data and qualitative research results relating to national conditions. Despite the wide range of research on biological treatment technologies for organic waste, there is still a lack of comprehensive comparative analyses integrating quantitative data on waste streams with a qualitative assessment of end products based on uniform indicators of biological stabilization and organic matter content. This gap is particularly evident in national conditions, in the context of systemic changes related to the implementation of the mandatory selective collection of biowaste and the new version of the regulation on the conditions for the mechanical–biological treatment of organic waste and the required parameters to be achieved, especially for “stabilizers”. Filling this gap is crucial for the rational and environmentally safe management of biological treatment products and for the protection of soil and water resources.

2. Materials and Methods

2.1. Study Scope and Data Sources

The study concerned the quantitative and qualitative analysis of two municipal biodegradable waste streams in Poland: the organic fraction mechanically separated from

mixed municipal waste and source-separated municipal organic waste. The analysis covered the period from 2020 to 2024. In addition, the current legislation concerning permitted municipal waste treatment technologies, treatment processes, waste codes, and the parameters required for the classification and further management of the resulting products and waste was examined. The applicable legal acts were identified through the Internet System of Legal Acts available on the official website of the Sejm of the Republic of Poland [85].

The quantitative analysis was based on official data published by Statistics Poland. The study used data from annual publications, including Municipal Infrastructure the Local Data Bank in the category “State and Environmental Protection”, and the Geostatistics Portal of Statistics Poland [86–88]. The collected data covered municipal waste generation, selective collection, organic waste collection, recovery, recycling, energy recovery, and disposal processes in Poland between 2020 and 2024.

The qualitative component of the study was based on technical reports and scientific publications presenting the results of physicochemical analyses of products obtained from the biological treatment of municipal organic waste in Poland. The literature-derived data concerned two groups of materials: stabilized waste produced from the organic fraction mechanically separated from mixed municipal waste and compost products obtained from source-separated municipal organic waste. The analysis focused primarily on parameters describing biological stability, organic matter content, nutrient content, moisture, and selected contaminants. The quantitative and qualitative results are presented in tabular and graphical form.

2.2. Selection of Cases and Analytical Methods

The data concerning the treatment of the organic fraction mechanically separated from mixed municipal waste were obtained from a technical report covering 25 mechanical–biological treatment installations in Poland [89]. Five installations, designated A–E, were selected purposively for the comparative assessment because they represented different technological configurations used in Poland, including anaerobic digestion followed by aerobic stabilization and different variants of aerobic treatment in enclosed reactors, modules, halls, and open maturation areas.

The selected installations were included because the source report provided a comparable set of data for the main stages of the biological treatment process, including the input material, the material after the intensive treatment phase, and the final stabilized waste. The available parameters included moisture content, AT_4 respiration activity, loss on ignition, and organic carbon content. The selected cases were used to compare different technological configurations and were not intended to constitute a statistically representative sample of all mechanical–biological treatment installations operating in Poland.

The six compost cases, presented as C1–C6, were selected purposively from four Polish studies [90–94]. This selection was designed to enable a comparative assessment of the final compost products derived from two different feedstock pathways relevant to the aims of the study. Cases C1–C4 represented composts produced exclusively from source-separated municipal organic or green waste, whereas C5–C6 represented composts produced from mixtures containing both source-separated organic waste and the organic fraction mechanically separated from mixed municipal waste. The inclusion criteria were (1) the municipal origin of the biodegradable feedstock; (2) aerobic biological treatment resulting in a final compost-like product; (3) a clearly identifiable feedstock composition; and (4) the availability of a common set of physicochemical parameters, including organic matter, total nitrogen, organic carbon, phosphorus, and potassium, expressed on a dry matter basis or convertible to comparable units. Studies with insufficient information regarding feedstock origin, incomplete parameter sets, or non-comparable units were not

included. The selected cases were used for an illustrative comparative assessment and were not intended to constitute a statistically representative sample of all composting facilities in Poland.

The study analyzed research results based on scientific publications available in the literature on the subject, and the results were presented in graphical form using the Statistica software, version 14.1.0.4, a research tool for the statistical analysis of research results. For this purpose, an agglomeration algorithm in the form of cluster analysis was used to group objects into increasingly larger sets (clusters), using a certain measure of similarity or distance. A typical result of this type of grouping is a hierarchical tree diagram. The Ward method was used as the agglomeration method, which presents the distances between clusters and uses a variance analysis approach, resulting in the minimization of the sum of squares of deviations in any two clusters. In order to determine the measure of distance between objects in the agglomeration method, the Euclidean distance, i.e., the geometric distance in multidimensional space, was used when forming clusters. In this method, Euclidean distances (and squares of Euclidean distances) are calculated based on raw data rather than standardized data. In order to analyze the mutual correlations between the individual parameters of stabilized organic waste (stabilizer) and the product, which was compost, 3W scatter analysis was used, in which graphs are used to visualize the interdependencies between three variables representing the X, Y, and Z coordinates in three-dimensional space. In addition, 3W surface graphs are used for three variable values in the X, Y, Z system of a categorized 3W graph for data (variable values corresponding to coordinate sets), enabling comparisons between subsets (categories) of data [95]. Hierarchical cluster analysis was used as an exploratory tool to visualize similarities among the analyzed cases.

2.3. Organic Waste Treatment Technologies

Municipal waste treatment technologies, types of processes, waste codes, and the parameters required to be achieved for a given type of waste are contained in the following legal acts: the Waste Act [96,97], the Act on Maintaining Cleanliness and Order in Municipalities [98,99], the regulation on the waste catalog [100], and the regulation on the mechanical–biological treatment of unsorted (mixed) municipal waste [65]. The latter legal act specifies the requirements for the mechanical–biological treatment of unsorted (mixed) municipal waste, the types of installations in which this process may be carried out, and the types of waste generated as a result of these processes. The legislator defines organic waste (biowaste) as biodegradable waste from gardens and parks; food and kitchen waste from households, catering establishments including restaurants and canteens, mass catering establishments, offices, wholesalers, and retail outlets; and similar waste from establishments producing or marketing food. Biodegradable waste, on the other hand, is waste that undergoes aerobic or anaerobic decomposition with the participation of microorganisms. With this in mind, the best available techniques are used to treat organic waste separated from the mixed municipal waste stream and selectively collected municipal organic waste. In connection with this, two main technologies for the treatment of organic waste are currently used in Poland. These include composting, involving recovery (R) or disposal (D) processes carried out under aerobic conditions, with the participation of microorganisms, resulting in a change in the physical, chemical, or biological properties of the waste. The second technology is fermentation, involving recovery (R) or disposal (D) processes carried out under anaerobic conditions, with the participation of microorganisms, resulting in a change in the physical, chemical, or biological properties of the waste. These processes result in products in the form of compost and biogas, as well as waste. Figure 1 shows a diagram of the processing of organic waste separated mechanically from the mixed municipal waste stream and selectively collected municipal organic waste

[101,102]. Based on the treatment pathways shown in Figure 1, the final physicochemical parameters of the resulting waste and products were selected for comparative analysis. The technologies presented are in accordance with the law in force in Poland and show division into technologies, processes, and the types of waste generated and the processes in which they can be further processed. Waste codes marked with an asterisk (*) in the index are classified as hazardous waste.

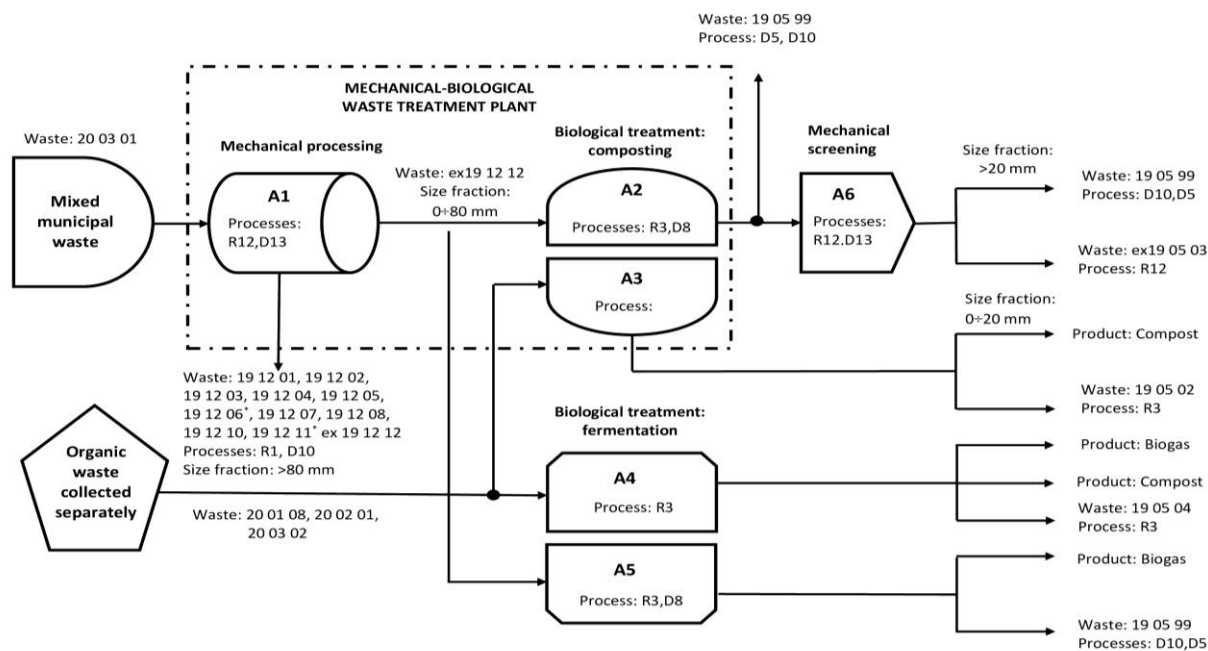


Figure 1. Diagram of the processing of mixed municipal waste and selectively collected organic waste.

The mechanical–biological treatment of unsorted (mixed) municipal waste consists of two processes: mechanical waste treatment and biological waste treatment. These two processes are combined into a single integrated technological process for treating this waste in order to prepare it for recovery processes, including recycling, energy recovery, thermal conversion, or disposal processes, such as landfilling and thermal conversion. This process is carried out in a facility consisting of a set of stationary technical devices, shown in Figure 1, and incorporating technologies A1, A2, A5, and A6. The waste codes shown in Figure 1 constitute a list derived from the Regulation of the Minister of Climate of 2 January 2020 on the waste catalog [100] and the Commission Decision of 3 May 2000, replacing Decision 94/3/EC establishing a list of wastes pursuant to Article 1(a) of Council Directive 75/442/EEC on waste and Council Decision 94/904/EC establishing a list of hazardous waste pursuant to Article 1(4) of Council Directive 91/689/EEC on hazardous waste (notified under document number C(2000) 1147), (2000/532/EC), L226/3 [103].

Waste sent for the mechanical–biological treatment of unsorted (mixed) municipal waste is unloaded in a closed facility, which is a building within the meaning of the Construction Law (Journal of Laws of 2021, item 2351, as amended) [104]. This location of the installation prevents atmospheric factors from affecting the waste, and it is equipped with a sealed base to prevent leachate from entering the environment, as well as ventilation devices and devices to limit pollutant emissions, particularly the release of dust into the air.

The purpose of the mechanical processing of mixed municipal waste is to separate two fractions. The “oversize fraction”, with a particle size greater than 80 mm, consists of

waste from mechanical processing that can potentially be used in recycling processes or as waste-derived fuel. This waste can undergo recovery or disposal processes. In contrast, the separated “undersize fraction”, with a particle size of 0–80 mm, consisting mainly of organic waste, is intended for biological treatment in aerobic and anaerobic processes (A2 and A5 technologies in Figure 1). Waste separated into the “oversize fraction” and the “undersize fraction”, in accordance with the regulation on biological–mechanical waste treatment, constitutes waste with code 19 12 12, i.e., other waste (including mixed substances and objects), being distinct from mechanical waste treatments listed in 19 12 11.

Technology A2 can be implemented in open composting piles located on a sealed site or in closed bioreactors with intensive aeration and post-process air purification. The product of this process is a “stabilizer”, which is waste with code 19 05 99, known as other unlisted waste, and waste with code 19 05 03, which is compost that does not meet the requirements (unsuitable for use). The A5 technology is implemented in the form of anaerobic thermophilic fermentation in closed and sealed bioreactors. The end product of this process is biogas, which, after appropriate purification, can be used to generate electricity and heat. This process also produces “stabilizer” waste, classified as waste code 19 05 99, known as other unlisted waste, as in the case of aerobic processes.

As part of the technologies presented in Figure 1, biological treatment processes are also carried out on selectively collected organic waste. Selectively collected organic waste is intended for biological treatment in aerobic and anaerobic processes, as part of technologies A3 and A4, presented in Figure 1. In Poland, anaerobic (fermentation) and aerobic (composting) technologies are used for the biological treatment of selectively collected municipal organic waste. The most popular technology in Poland for the biological treatment of selectively collected municipal organic waste with codes 20 01 08 (biodegradable kitchen waste), 20 02 01 (biodegradable waste), and 20 03 02 (market waste) is the process of aerobic composting in windrows. The result of this process is a product that is compost, intended for use in agriculture and horticulture, enriching and improving its physical, chemical, and biological properties (technology A3 in Figure 1). Selectively collected municipal organic waste can also be processed in anaerobic processes in closed bioreactors for thermophilic fermentation. This mainly applies to the same types of waste as in composting in piles. The fermentation process takes place in closed and sealed chambers, where biogas is produced as a source of renewable energy, which, after purification, is used to produce electricity and heat. After the composting process is complete, the second product, alongside biogas, is digestate, which is left to mature in piles and then screened and stored (A4 technology in Figure 1).

3. Results and Discussion

3.1. Organic Waste in the Municipal Waste Stream

Municipal waste generated in households and other businesses and institutions is collected in specially marked containers and bags. The municipal waste collected from producers in Poland in 2020–2024, broken down by stream, including selectively collected waste, is presented in Table 1 [105–109].

Table 1. Quantities of municipal and biodegradable waste collected in Poland in 2020–2024.

Type of Waste	2020	2021	2022	2023	2024
	In Thousand Mg				
Municipal waste collected from producers, total	13,116	13,673	13,420	13,447	14,158
Mixed municipal waste collected from producers	8142	8234	8059	7979	8206

Municipal waste collected separately and collected from producers (excluding organic waste)	3364	3596	3447	3425	3715
Separately collected organic waste collected from producers	1610	1842	1913	2043	2236

The results of the study showed that selectively collected organic waste accounted for 12% to 16% of the municipal waste in 2020–2024. On the other hand, for organic waste, the amount collected selectively increased by 38.9% when comparing 2020 to 2024. This progress demonstrates the effectiveness of the selective collection of organic waste in Poland. Table 2 shows the fractions of municipal waste collected separately per capita in Poland in 2020–2024 [105–109].

Table 2. Selectively collected waste per capita in Poland in 2020–2024.

Fraction of Municipal Waste Collected Separately per Inhabitant	2020	2021	2022	2023	2024
	kg per Inhabitant				
Total waste, including:	129	143	141	145	158
Paper and cardboard	13	14	14	15	16
Glass	19	20	21	19	20
Plastics	12	13	14	15	16
Mixed packaging waste	14	15	15	15	16
Bulky waste	18	19	16	16	20
Organic waste	41	48	50	54	59

The research and analysis of six fractions of municipal waste collected selectively in Poland over a five-year period showed that, in quantitative terms, there was an increase in all years. The exceptions were glass and bulky waste. However, the largest increase in the amount of waste collected per capita between 2020 and 2024 was recorded for organic waste, amounting to 43.9%. The municipal waste treatment processes in Poland in 2020–2024, broken down into recovery and disposal, are presented in Table 3 [105–109].

Table 3. Municipal waste treatment processes broken down into recovery and disposal in Poland in 2020–2024.

Municipal Waste Treatment	2020	2021	2022	2023	2024
	In Thousand Tonnes				
Municipal waste directed to recovery operations, including:	7733	8207	8198	6502	7511
Material recycling	3499	3681	3585	2120	2596
Organic recycling (composting or fermentation)	1578	1824	1899	1686	1814
Incineration with energy recovery	2656	2702	2714	2696	3101
Municipal waste intended for disposal operations, including:	5384	5467	5221	4159	4260
Landfilling	5218	5296	5108	4067	4257
Incineration without energy recovery	166	171	113	93	3

The data in the table show that the smallest amounts of waste were sent for recovery in 2023 and 2024, while the amounts were higher in 2020–2022. This may be due to the low quality of selectively collected waste and restrictions on recycling and waste storage by plant operators. On the other hand, in the area of waste sent for disposal, there was an 18.4% decrease in the amount of waste landfilled between 2020 and 2024. Figure 2 presents an analysis of organic waste recycled in composting and fermentation processes and other waste.

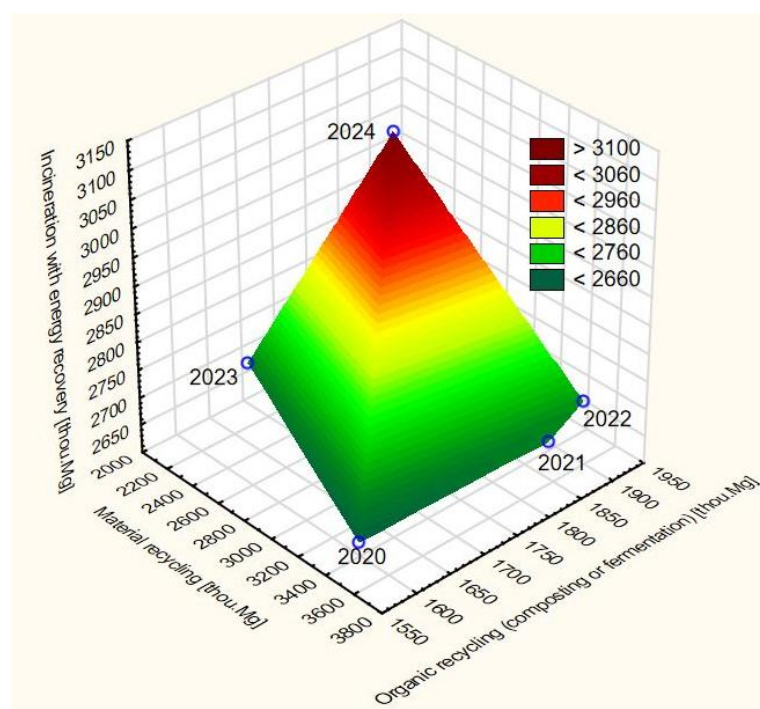


Figure 2. Waste subjected to recycling processes in Poland in 2020–2024.

In 2024, the largest amount of organic waste subjected to organic recycling processes, i.e., composting and fermentation, was recorded, amounting to over 1.8 million Mg, as well as waste subjected to thermal treatment and material recycling; see Figure 2. The parameters for 2024 are as follows: $x = 2596$; $y = 1814$; $z = 3101$. This result may indicate similar potential for organically recycled waste and material recycling, as well as the high growth rate of organic waste in 2020–2024. The breakdown of waste by type and the share of this waste in recovery processes in Poland in 2020–2024 is presented in Table 4 [105–109].

Table 4. Share of organic waste in recovery processes in Poland in 2020–2024.

Type of Waste	2020	2021	2022	2023	2024
Separately collected organic waste, total [in thousand Mg]	1610	1842	1913	2043	2236
Share of organic waste in total waste (OW_T) [%]	12	13	14	15	15
Waste sent for recovery, total [in thousand Mg]	1578	1824	1899	1686	1814
Share of organic waste in total waste sent for recovery (OW_R) [%]	20	22	23	26	24
Separately collected organic waste, total [kg per inhabitant]	41	48	50	54	59
Share of separately collected organic waste per capita in total waste (OW_PC) [%]	32	33	35	37	37

The systematic increase in the amount of selectively collected organic waste in Poland in 2020–2024, as shown in the examined studies, amounted to 38.9% in 2024, which translates directly into an increase in the amount of this waste in the total amount of municipal waste collected. This is confirmed by further research results in the area of the share of organic waste in recovery processes, which increased by 3.74% between 2020 and 2024, amounting to 1814 thousand Mg. Figure 3 shows a percentage comparison of the share of organic waste in three areas, described as follows: OW_T—the share of organic

waste in the total waste; OW_R—the share of organic waste in recovery processes in total; and OW_PC—the share of selectively collected organic waste per capita in total.

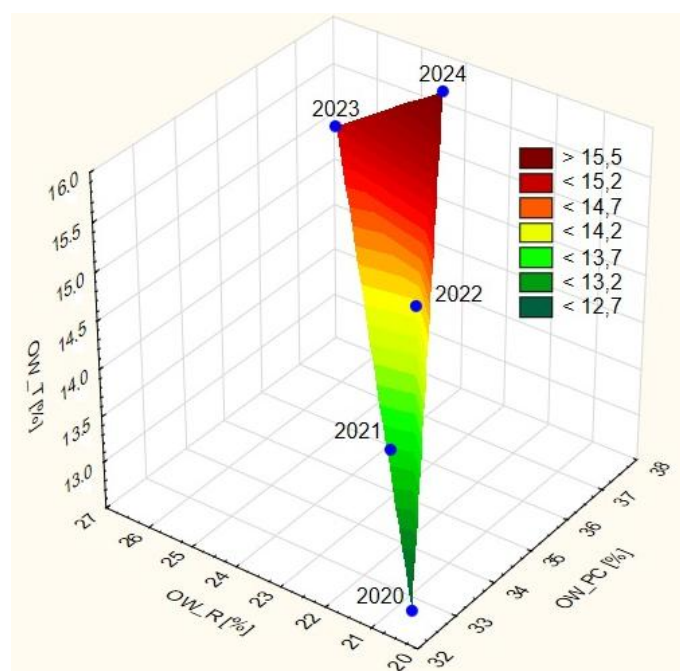


Figure 3. Share of separately collected organic waste in recovery processes.

The year 2024 saw the largest increase in the share of separately collected organic waste among municipal waste and the share of such waste collected per capita in the total. However, in the case of the share of organic waste in recovery processes in relation to the total, there was a decrease of 2.32% year on year. The parameters for 2024 are $x = 37.56$; $y = 24.14$; $z = 15.8$, which may indicate a significant increase in organic waste compared to 2020.

3.2. Organic Waste Separated from Mixed Municipal Waste

The study analyzed the results of tests on organic waste separated from mixed municipal waste as a 0–80 mm fraction, intended for biological treatment in five different facilities. Plant A involves anaerobic fermentation in closed fermentation chambers (intensive phase), followed by waste stabilization in containers with aeration and leachate collection and then maturation in piles on open ground. The municipal biogas produced in this process is recovered and used for energy purposes. Installation B is an anaerobic fermentation process in closed bioreactors (intensive phase), followed by the aerobic stabilization of the fermented waste in piles on a sealed concrete surface. The municipal biogas produced is purified and then used for energy purposes. Installation C is a biological treatment process under aerobic conditions, in which, in the first stage, the waste undergoes intensive treatment in closed bioreactors with effluent discharge and post-process air purification, located in a closed hall, and then the waste undergoes a maturation process in piles in an open area, with the mechanical turning of the waste. Installation D involves the processing of organic waste under aerobic conditions in closed composting modules with post-process air purification (intensive phase), followed by the maturation of the waste in piles located in an open area with mechanical turning in the maturation yard and leachate drainage. Installation E, on the other hand, enables the biological processing of organic waste under aerobic conditions inside a closed hall in concrete boxes, mechanically aerated, with post-process air purification (intensive phase), and then the waste is transported to an open composting yard, where mechanically aerated piles are formed

[89]. Selected parameters of the undersize fraction containing organic waste, which is the input for biological treatment in a given type of plant, are presented in Table 5, which is our own compilation based on [89].

Table 5. Parameters of organic waste before biological treatment: undersize fraction 0–80 mm.

Installation Type	Organic Waste Ratio [%]	Parameter		
		Moisture [%]	Organic Carbon [% Dry Matter]	Roasting Loss [% d.m.]
Installation A	63.3	60.6	21.2	35.2
Installation B	55.6	34.7	20.5	35.7
Installation C	47.9	51.3	22.6	41.2
Installation D	41.9	27.9	22.8	39.1
Installation E	28.2	25.4	14.3	31.3

Organic waste separated from the mixed municipal waste stream in a mechanical process constitutes the 0–80 mm fraction. An analysis of the test results showed differences in the biodegradable fraction content, with an average value of 47.38%, and varying moisture content, with an average value of 39.8%. These differences may result from the different types of areas where the waste is generated and from the municipal waste segregation and transport system in place. The condition for the proper biological treatment of organic waste separated from the mixed municipal waste stream is to achieve $AT_4 < 10 \text{ mg} \cdot \text{O}_2 \cdot \text{g}^{-1} \text{ s.m.}$ by the final waste product, which is “stabilized waste” with code 19 05 99, known as other wastes not mentioned. AT_4 is a parameter expressing the oxygen demand of a waste sample over 4 days, expressed in $\text{mg O}_2/\text{g d.m.}$ It is determined in a short-term microbiological test used to assess respiratory activity. In addition, after the final process, the waste should have a loss on ignition of less than 35%, and the organic carbon content should be less than 20% of the dry weight. Table 6 presents the final parameters for intermediate processes and the final product, which is “stabilizer”, derived from our own study based on [89].

Table 6. Final parameters of organic waste after biological treatment.

Installation Type	Final Parameters							
	After the Intensive Phase				Final Waste: “Stabilizer”			
	Moisture [%]	AT_4 [mg $\text{O}_2/\text{g d.m.}$]	Roasting Loss [% Dry Matter]	Organic Carbon [% d.m.]	Moisture [%]	AT_4 [mg $\text{O}_2/\text{g d.m.}$]	Roasting Loss [% Dry Matter]	Organic Carbon [% Dry Matter]
Installation A	43.2	13.3	32.0	20.8	37.7	5.7	25.2	14.8
Installation B	42.2	12.4	30.1	17.1	36.1	5.2	26.5	15.3
Installation C	43.0	13.6	34.7	20.5	23.3	6.2	28.2	14.7
Installation D	36.9	15.0	36.3	19.2	20.9	2.2	29.2	16.6
Installation E	38.7	16.3	30.8	16.5	8.3	7.7	29.1	14.8

Organic waste subjected to biological treatment in processes representing all types of installations ultimately achieved the required parameters in terms of AT_4 values, with an average value of 5.4 [mg $\text{O}_2/\text{g d.m.}$]. The other criteria concerned the loss on ignition and organic carbon content. In this case, too, the required values were achieved, and the “stabilizer”, as the final waste product of the treatment of organic waste separated from the municipal waste stream, can be sent to landfill or thermal treatment. Additionally, after mechanical treatment, it can be used as waste for the reclamation of degraded areas. The

results of these studies are also confirmed by other scientific publications, indicating the variability in parameters at subsequent stages of the organic waste treatment process from mixed municipal waste streams. Examples of MBT installations in Poland, cited in relevant publications, show that the waste constituting the “stabilizer” ultimately becomes stabilized organic matter intended for further use [110,111].

Figure 4 presents the results of the tests together with an analysis of the moisture content of organic waste at each stage of its processing according to the following notation: H_B —moisture content of organic waste before biological processing; H_D —moisture content of waste after intensive processing; and H_A —moisture content of final waste.

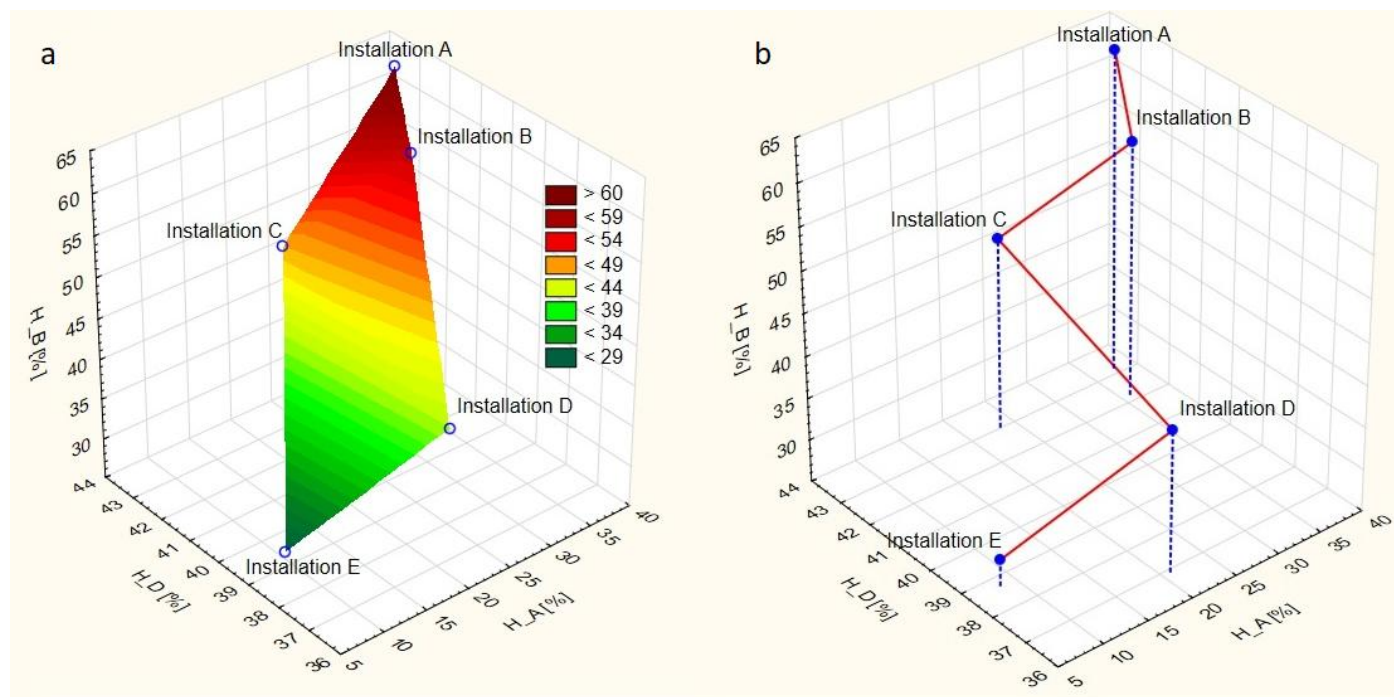


Figure 4. Moisture content of organic waste at each stage of its processing: (a) 3W surface graph, (b) scatter plot with trend line.

Tests of the moisture content of organic waste at each stage of its processing showed that the highest moisture content was found in waste from installation A, amounting to $x = 37.7$; $y = 43.2$; $z = 63.3$. However, the results of the scatter analysis in this trajectory chart showed that the ratios of the moisture content of organic waste before biological processing to the moisture content during processing (variable Y) and to the moisture content of the final waste (variable X), namely variables x and y , took the following values: $x = 0.16$; $y = 1.18$. The average moisture content of organic waste in installation A was 63.31%. This may be due to the fact that the waste was prepared and processed in an anaerobic fermentation process in closed fermentation chambers (intensive phase), which requires additional moistening of the waste in the intensive phase, followed by the collection and drainage of leachate. On the other hand, the lowest moisture content was found in waste in installation E, processed under aerobic conditions inside a closed hall in concrete boxes, amounting to $x = 8.3$; $y = 38.7$; $z = 28.2$, with an average of 25.07%. These organic waste moisture values confirm the relationship with the type of process and its location, i.e., in a closed hall.

In the next stage of the research, the parameters of drying loss (Figure 5) and organic carbon (Figure 6) were analyzed. This focused on organic waste before the treatment process and that achieved in the intensive and stabilizing phase of the final waste.

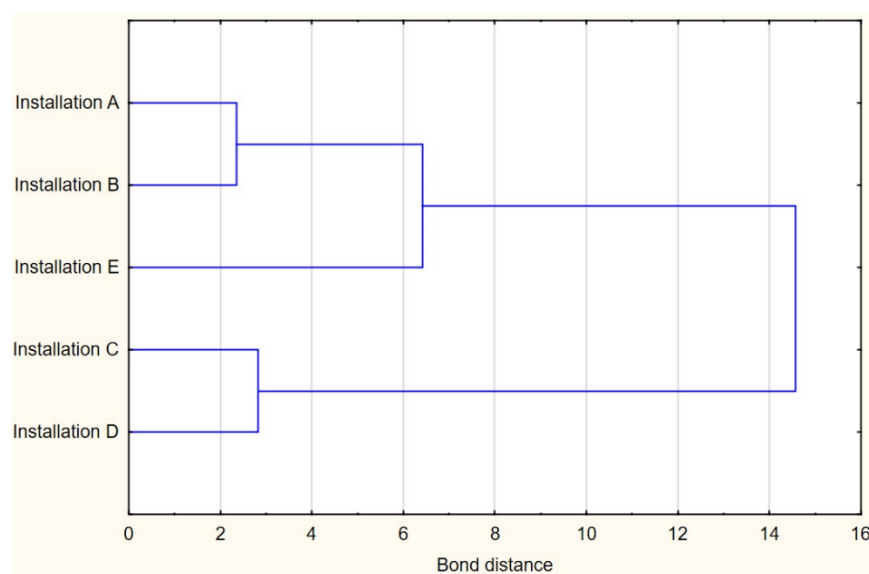


Figure 5. Dendrogram of bond distances for organic waste incineration losses depending on the type of installation.

An analysis of the effectiveness of reducing the loss on ignition values for organic waste processed in a given installation in order to achieve the permissible level showed that the facilities (installations) form three clusters. The smallest bond distance occurs at the level of the first cluster, containing installation A and installation B. The agglomeration distance for the first bond is $x = 2.36$; $y = 4.48$. The second cluster contains installation C and installation D. The agglomeration distance for the second bond is $x = 2.83$; $y = 1.51$. The third cluster is installation E, with a bond distance of $x = 14.62$; $y = 2.46$. All clusters are connected by a bond with parameters $x = 14.60$; $y = 2.46$. This state of the bonds within the dendrogram indicates a slight discrepancy between the individual values of the incineration losses in installations, for which the distance difference is $x = 4.08$. The results of research on organic waste incineration losses depending on the type of installation confirm the correctness of the biological treatment process for organic waste. The studies conducted in [112,113] have shown that MBT installations enable the recovery of organic waste in the form of a stabilized organic fraction, intended for safe storage or use for the reclamation of degraded areas as compost that does not meet the requirements.

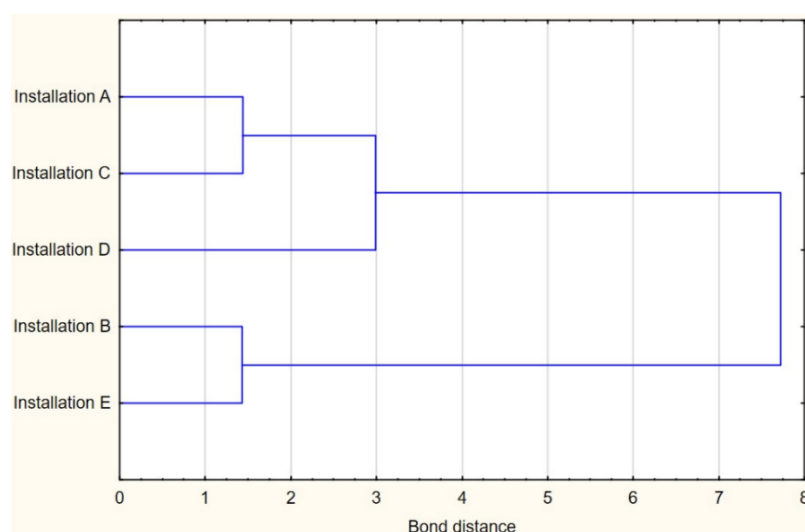


Figure 6. Dendrogram of bond distances for organic carbon values in organic waste depending on the type of plant.

An analysis of the effectiveness of organic carbon reduction for organic waste processed in a given facility in order to achieve the permissible level showed that the facilities (installations) form three clusters. The shortest distance between connections occurs at the level of the first cluster, containing installation B and installation E. The agglomeration distance for the first connection is $x = 1.42$; $y = 1.48$. The second cluster contains installation A and installation C. The agglomeration distance for the second bond is $x = 1.51$; $y = 4.48$. The third cluster is installation D, with a bond distance of $x = 2.98$; $y = 3.73$. All clusters are connected by a bond with parameters $x = 7.71$; $y = 2.53$. This state of the bonds within the dendrogram indicates a small discrepancy between the individual organic carbon values in the installations, for which the distance difference is $x = 1.56$. The results obtained indicate that the biological treatment of organic waste separated from the mixed municipal waste stream is carried out correctly. One of the three parameters indicating the possibility of the further and safe use of the final waste (stabilizer) is the AT_4 parameter. Figure 7 shows the share of organic waste (biodegradable fraction) before the biological treatment process in individual installations and the AT_4 values after intensive treatment and after stabilization.

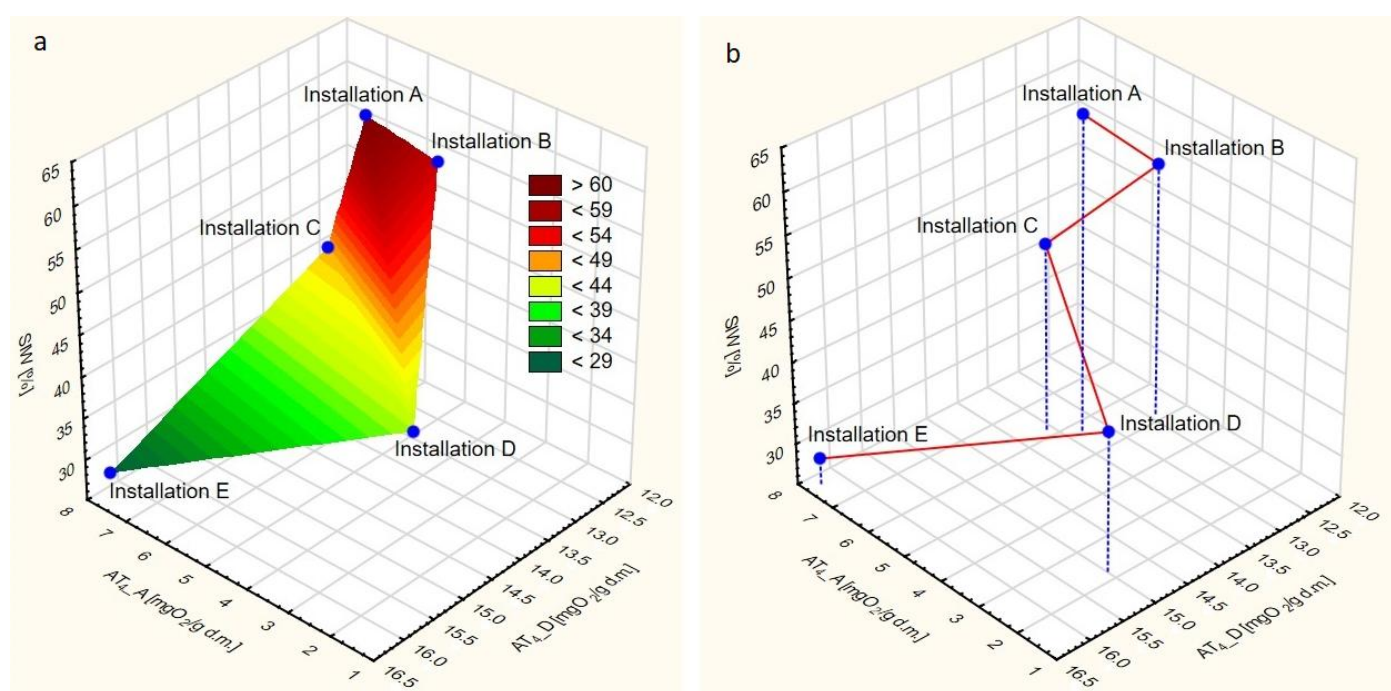


Figure 7. AT_4 values in waste after intensive treatment and after stabilization to the share of the biodegradable fraction: (a) 3W surface graph, (b) scatter plot with trend line.

Studies of the biodegradable fraction in organic waste prior to its treatment in facilities of a given type showed the highest organic content in facility A, at 66.3%, and the lowest in facility E, at 28.2%. The calculated processing index (efficiency of biodegradable fraction reduction) showed that plant A has an index of 4.75, while plant E has an index of 1.73. The analysis of the dispersion of the AT_4 of the two variables, together with the track line, showed the following values for installation A: $x = 0.091$; $y = 1.06$. Meanwhile, for installation E, the values were $x = -1.24$; $y = -0.65$. The average AT_4 parameter for waste resulting from the final processing of the organic fraction separated from mixed municipal waste is $5.4 \text{ [mgO}_2\text{/g d.m.]}$. This is less than 46% of the required limit value for this waste. The research conducted in [114,115] shows that the efficiency of the biostabilization process of organic waste separated in MBT installations still requires control and continuous monitoring, starting with a thorough morphological analysis of the input material. This

has a particular impact on municipalities' ability to achieve the legally required recycling rate. Without the participation of MBT plants in the municipal waste management system, the required recycling level might not be achieved, which could have serious financial consequences for local governments. In order to achieve the required final parameters for the "stabilized product", plant operators must continuously optimize the process parameters. This mainly concerns the duration of the process, the process parameters (temperature, humidity), and the timing of sample collection for laboratory testing. In addition, plant operators should have a management policy in place as part of their process documentation. This includes, for example, quality management based on the ISO 9001 standard [116] and environmental management in accordance with the ISO 14001 standard [117]. The procedures outlined in these standards will enable the real-time monitoring of the process and the quality of the final product, as well as its continuous improvement.

The results of the research and their analysis carried out in this study showed that organic waste separated from the mixed municipal waste stream, processed in installations of this type, meets the requirements for waste classified as "stabilized", code 19 05 99: other wastes not otherwise specified. This type of waste can be safely stored in landfills for non-hazardous and inert waste or subjected to thermal conversion in energy recovery facilities. In addition, this waste can be subjected to mechanical processing (separation of the 0–20 mm fraction), and, as waste with code 19 05 03, designated as compost not meeting the requirements, it can be used for the reclamation of degraded areas and landfills.

The interrelationship between the AT_4 value, combustion loss, and organic carbon content is crucial in assessing the stabilization of municipal solid waste following mechanical-biological treatment. AT_4 is a key parameter that determines the oxygen demand of the waste over four days; a value below 10 mg O_2 /g dry weight indicates that the waste meets the requirements for a stabilized product and can be landfilled. The ignition loss and total organic carbon are also important indicators that help to assess the quality and stability of the waste. These values should remain in a constant ratio, meaning that changes in one of these parameters can lead to changes in the others. These values are crucial for the proper landfilling and disposal of municipal waste.

Meeting the applicable stabilization criteria indicates a reduction in the residual biological activity of the treated material. Compared with the direct landfilling of untreated biodegradable waste, biological stabilization may reduce the potential for subsequent methane generation [118,119]. Landfill gas emissions may generate environmental and health concerns at both local and global scales [120]. At the local level, methane accumulation may create fire and explosion hazards, and, at sufficiently high concentrations in confined spaces, it may displace oxygen. However, the potential health effects in communities located near landfills should not be attributed to methane alone, because landfill gas also contains carbon dioxide, hydrogen sulfide, non-methane volatile organic compounds, and other trace pollutants [121,122]. Exposure to these mixtures and associated odors has been linked in the literature to respiratory irritation, headaches, nausea, and reduced quality of life, although the strength of the evidence varies among studies [121,122]. At the global level, methane contributes to climate warming and to the formation of tropospheric ozone [115,120,123]; therefore, reducing methane emissions from the landfilling of biodegradable waste may provide indirect climate and public health co-benefits [124,125]. These effects were not quantified in the present study and are considered potential implications supported by the literature, rather than directly demonstrated outcomes.

3.3. Separately Collected Municipal Organic Waste

Organic waste collected separately undergoes biological treatment under aerobic (composting) or anaerobic (fermentation) conditions. The result of the biological treatment of organic waste is a product in the form of compost, which is an organic fertilizer

or soil conditioner, intended for use in agriculture and horticulture, enriching and improving the physical, chemical, and biological properties of the soil. Biogas is also a source of added value from the fermentation process. In order to meet the criteria for compost, the requirements specified in the legal acts in force in Poland [126,127] are applied. These conditions must be met by the compost producer in order to obtain an administrative decision from the Minister of Agriculture and Rural Development regarding the applicant's permission to market an organic fertilizer or a soil improver. Organic fertilizers and soil improvers must meet the following requirements: organic matter content $\geq 20\%$ dry matter; potassium, K_2O , $\geq 0.2\%$ dry matter; phosphorus, P_2O_5 , $\geq 0.2\%$ dry matter; and total nitrogen, N, $\geq 0.3\%$ dry matter. In addition, organic fertilizers and soil improvers in solid form must meet the permissible requirements for the following parameters: chromium Cr ≤ 100 mg/kg dry matter; cadmium, Cd, ≤ 5 mg/kg dry matter; nickel, Ni, ≤ 60 mg/kg dry matter; lead, Pb, ≤ 140 mg/kg dry matter; and mercury, Hg, $\leq$ mg/kg dry matter [128–130]. In order to analyze the methods of waste treatment technology and the final effects of these processes, the study used data published in reports on the biological treatment of municipal organic waste in Poland [131–133].

The qualitative studies carried out in this work for selectively collected municipal organic waste focus on the analysis of the quality of the compost resulting from the treatment of selectively collected organic waste (green waste) and treated under aerobic conditions (compost piles). The organic waste processed in aerobic facilities came from various regions of Poland and was the result of studies available in the literature [134–137]. Selected parameters of composts from the aerobic processing of selectively collected organic waste are presented in Table 7.

Table 7. Selected parameters of composts after biological processing of waste.

Parameter	Unit	C1	C2	C3	C4	C5	C6
Organic matter content	% dry matter	58.18	45.54	48.27	52.17	24.2	27.4
Total nitrogen	% dry matter	7.35	14.35	1.15	0.98	10.8	11.9
Organic carbon	% dry matter	25.46	6.24	12.4	12.8	12.4	12.8
Phosphorus	% dry matter	10.41	11.62	11.49	10.91	0.58	0.55
Potassium	% dry matter	0.34	0.53	0.22	0.17	0.42	0.39

The composts presented in Table 7 differ in their parameters, despite the fact that they originated from the aerobic processing of organic waste. The parameters that distinguish these composts are their total nitrogen and organic carbon content. With the exception of C5 and C6, these composts meet the minimum requirements for fertilizers that improve soil parameters. The composts listed in Table 7 as C1, C2, C3, and C4 resulted from the processing of exclusively selectively collected organic waste. In contrast, the composts designated as C5 and C6 resulted from the processing of a mixture of selectively collected organic waste and organic waste separated on a rotary screen from a mixed waste stream. The consequence of this process is low organic matter content in the compost, reaching 24.2% and 27.4% on a dry matter basis. The obtained results are slightly lower than the parameters specified in the Regulation of the Minister of Agriculture and Rural Development (Journal of Laws 2008 No. 119, item 765), which requires organic fertilizers to contain at least 30% organic matter. The slightly lower organic matter content necessitates changes in the process of preparing the mixture of biodegradable substances.

Variations in the organic carbon content of compost can be caused, among other aspects, by the type of waste being composted. Since municipal organic waste is not homogeneous but consists of a mixture of green waste (e.g., grass, flowers, shrubs), fruit, vegetables, etc., the organic carbon content in the final product—compost—can vary. In biodegradable waste, this content may differ depending on its composition, which affects the

organic carbon content in the compost. Additionally, process parameters such as the temperature and moisture content can also potentially affect the organic carbon content in the compost.

Their high calcium content gives these composts valuable properties, including creating favorable conditions for the development of soil bacteria, reducing soil acidity, and improving the air and water conditions in the soil. Composts and soil improvers can be used in field crops, orchards, and vegetable gardens, as well as ornamental plants, lawns, and permanent grasslands [127]. The condition for the sale of compost is that it meets the quality requirements for an organic soil improver, confirmed by an appropriate administrative decision issued by the Minister of Agriculture and Rural Development. A review of the available and innovative technologies for the treatment of municipal organic waste collected selectively in urban areas, carried out in [138,139], indicates aerobic composting as one of the processes that allows for the production of high-quality products for the implementation of a circular economy. Other researchers, presenting the results of their work [140] in the field of sustainable municipal organic waste management, conducted studies during composting in static piles with mechanical aeration. The results of their research confirmed that the compost obtained was an organic fertilizer that met the quality and sanitary requirements for use in agriculture. As an alternative to commercial facilities for the treatment of municipal organic waste collected separately in households, the authors in [141] conducted research on compost produced in composters in individual households. The results of their research showed that the content of heavy metals and microelements was below the permissible limits specified by national requirements, which allowed the compost to be used in domestic conditions.

Figure 8 shows the fertilizing properties of six selected composts in terms of compliance with legal requirements.

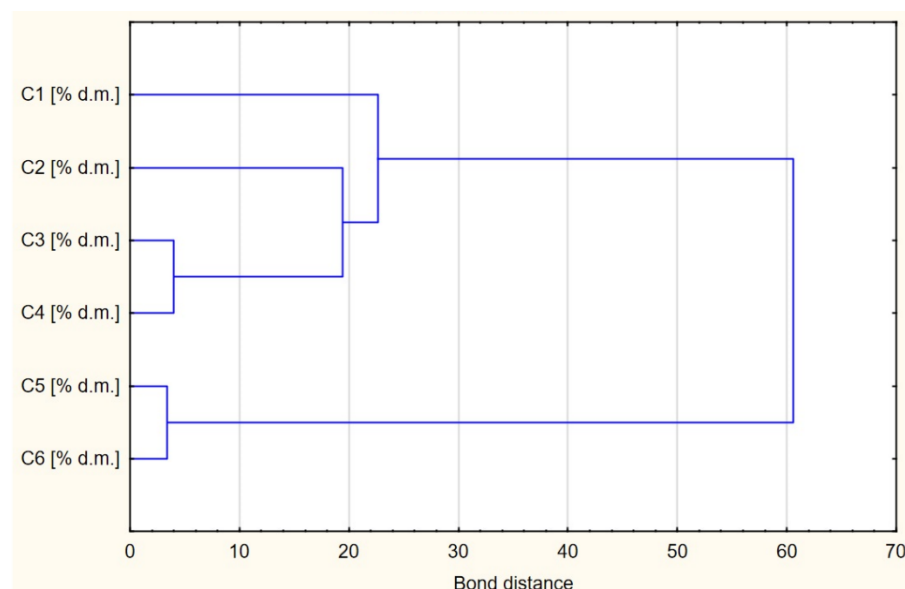


Figure 8. Dendrogram of bond distances for the fertilizing properties of composts.

An analysis of the effectiveness of the aerobic processing of selectively collected organic waste in relation to the required parameters showed that the objects form three clusters; see Figure 8. The smallest distance between clusters occurs at the level of the first cluster, containing the parameters for composts C5 and C6. The agglomeration distance for the first cluster is $x = 3.30$; $y = 1.51$. The second cluster contains the parameters for composts C3 and C4. The agglomeration distance for the second cluster is $x = 4.13$; $y = 3.48$. The third cluster consists of compost samples C1 and C2, with a bond distance of $x = 22.65$;

$y = 5.15$. All clusters are connected by a bond with parameters $x = 60.66$; $y = 3.27$. This state of the bonds within the dendrogram indicates a difference in the distance between the first and third bonds. Despite the differences in bond distances, the composts presented meet the quality requirements for an organic fertilizer or soil conditioner, with the exception of the organic matter content for composts C5 and C6. The quality testing of composts and their uses are the subject of research and analysis by many researchers around the world. The use of composts in urban areas to determine the effectiveness of fertilizers as a means of improving soil quality—and, in particular, reducing the runoff volume and improving runoff quality—was presented by the authors of [142]. The results of their study showed an increase in vegetation growth on disturbed sandy clay soil and a reduction in the volume of surface runoff of rainwater, which is crucial in densely built-up urban areas. The results of the study published in [143] concerned the impact of using mulch compost in greenhouse vegetable cultivation, using various types of irrigation. Composts produced from plant waste from parks and recreational areas demonstrated very high fertilizing value. This was due to the frequent fertilization and mowing of the grass, resulting in high nutrient content in the compost feedstock, which distinguished them from industrial composts. Composts from urban green spaces located along transportation routes were found to have higher levels of heavy metals and polycyclic aromatic hydrocarbons. Their concentrations were approximately one and a half times higher in composts from green spaces located along transportation routes. The results of the study showed that the use of compost significantly improved the plant height, root length, and biomass moisture content. In addition, the compost increased nutrient retention and soil moisture by buffering the salinity thanks to its ability to exchange carboxyl groups and cations. The possibility of mixing municipal organic waste with sewage sludge is another direction for the processing of this waste stream. The authors of [144] used kitchen waste generated by a canteen and excess sludge from a sewage treatment plant to convert the waste into compost through vermicomposting. The results of the study showed a reduction in total organic carbon, the largest increase in total nitrogen, increased cellulose degradation, and stronger interactions between bacteria.

The research and analysis of the results of testing compost that was a product of the aerobic processing of selectively collected organic waste show the presence of heavy metals, the permissible values of which are regulated by relevant legal acts. The samples (S1 to S8) were taken by the authors of [90–94] from biological treatment plants and consisted of the following: S1 to S5— aerobic treatment (compost piles) of green waste selectively collected from households; S6 to S8— aerobic processing of green waste from households and green areas using aerobic technology in closed bioreactors (intensive) and in piles (maturation). Table 8 presents the results of tests of selected parameters of the final product, i.e., compost, based on eight different samples taken from different composts based on the literature data.

Table 8. Heavy metal content in selected composts [mg/kg d.m.].

Parameter	S1	S2	S3	S4	S5	S6	S7	S8
Chromium	10.85	10.22	10.14	24.0	20.6	36.74	28.53	22.45
Cadmium	2.62	2.92	3.33	1.7	1.43	3.51	1.04	4.12
Nickel	38.12	35.12	33.82	23.0	6.71	47.58	22.82	11.34
Lead	51.25	59.10	53.15	107.0	36.0	44.98	37.86	101.22
Copper	80.51	84.28	81.61	87.0	51.0	82.90	36.31	42.73

The results of the compost sample tests for heavy metal content showed that the requirements were met for all samples. Figure 9 shows the fertilizing properties of the eight

selected composts in terms of compliance with the legal requirements for heavy metal content.

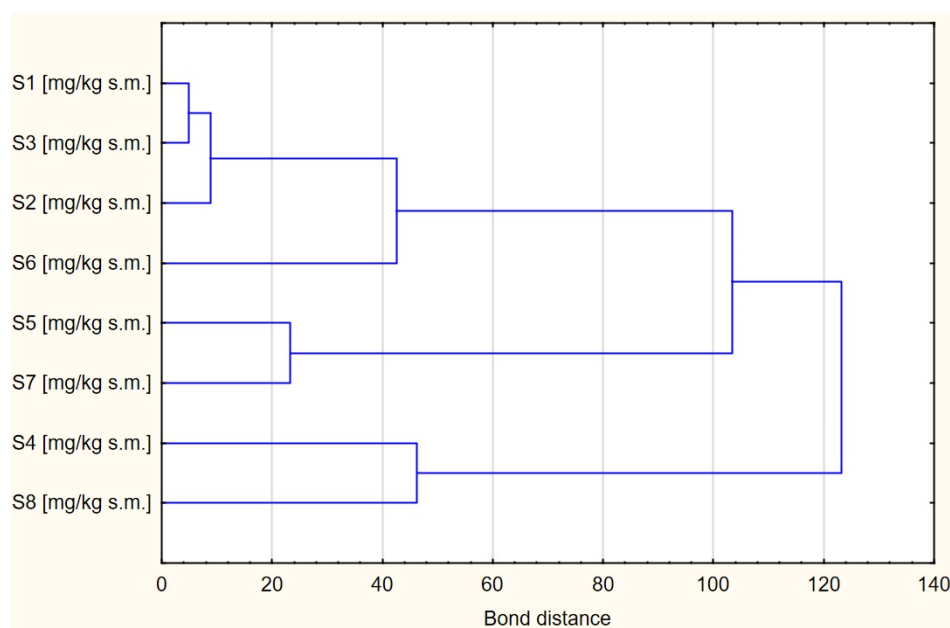


Figure 9. Dendrogram of bond distances for the fertilizing properties of composts in relation to heavy metal content.

An analysis of the effectiveness of the aerobic processing of selectively collected organic waste in terms of heavy metal content showed that the objects form four clusters; see Figure 9. The smallest distance between bonds occurs at the level of the first cluster, containing the results of heavy metal tests for samples S1, S2, and S3. The agglomeration distance for the first bond is $x = 9.03$; $y = 6.78$. The second cluster contains the parameters for compost samples S5 and S7. The agglomeration distance for the second bond is $x = 23.44$; $y = 3.52$. The third cluster is compost sample S6, with a bond distance of $x = 42.76$; $y = 5.89$. The fourth cluster contains compost samples S4 and S8, with an agglomeration distance of $x = 46.40$; $y = 1.54$. All clusters are connected by a bond with parameters $x = 103.40$; $y = 4.71$. This state of the bonds within the dendrogram indicates a difference in the distance between the first and fourth bonds. Despite the differences, the heavy metal content meets the requirements for organic fertilizers and soil conditioners. The researchers in [145] undertook the management of green waste from urban areas and proposed the production of compost-based pellets for fertilization purposes. The results of the study showed that the pellets had the highest mechanical strength and contained the highest concentrations of nutrients (N, P, K). Importantly, regarding the quality of the compost, no exceedances of the permissible standards for heavy metal content were found. This confirms the usefulness of compost-based pellets as an alternative to mineral fertilizers, in line with the principles of the circular economy. The use of compost to increase the effectiveness of soil phytoremediation in order to reduce heavy metal content has been presented in [146]. The results of the study emphasize the role of organic additives, including compost fertilizers, in the effective removal of heavy metal contaminants from the soil. Proposed scenarios for future solutions in this area should focus on optimizing organic and microbiological methods. The composting of municipal organic waste is a form of organic recycling that converts waste into a product. Aerobic and anaerobic processes enable the production of compost, which, depending on how it is used, can be supplemented with appropriate additives that constitute waste. The addition of ash to compost

was described in the study in [147], which found that this additive increased the concentrations of fertilizers in compost and caused the slower release of the components into the aqueous solution. Municipal organic waste obtained from urban areas may contain heavy metals, which can potentially appear in compost. Research in this area was carried out in [148]. The authors evaluated compost for its safe use in agriculture. The direct application of compost to the soil in the case of vegetable crops led to an improvement in the physicochemical properties of the soil, including organic matter. They concluded that the use of organic fertilizers is a suitable alternative to chemical fertilizers but recommended further research into the accumulation of heavy metals by plants. The effectiveness of removing heavy metals from the soil, including zinc, lead, and cadmium, using compost as an organic fertilizer, was described in [149]. The results of the study showed that compost had very good sorption potential for heavy metals, with the highest effectiveness in removing lead. The use of organic fertilizers is part of integrated waste management and the circular economy.

The results of the research carried out in the study and their analysis showed that organic waste collected selectively and processed in aerobic installations meets the requirements for the final product resulting from the applicable legal acts. The composts tested meet the requirements for organic fertilizers and soil conditioners in solid form.

4. Conclusions

Any product that is not used and has no specific purpose acquires the properties of waste. The priority task in waste management is to reduce the stream of biodegradable organic waste sent for disposal, including landfilling. The biological treatment of organic waste, which involves the microbiological conversion of organic matter into useful products such as compost, allows the products of this process to be returned to the natural cycle in terms of a circular economy. The composting process involves the intensive decomposition of pollutants present in organic waste, including persistent organic pollutants, and can therefore also be used as a method of pollutant disposal, involving their permanent stabilization in the material.

The biological treatment of selectively collected municipal organic waste is carried out under aerobic and anaerobic conditions. The product of these processes is compost, which is an organic fertilizer or soil improver, and they constitutes organized activities in which organic waste becomes a potential biological material at the moment of its management. In the case of anaerobic processes, biogas is produced, which is a source of renewable energy that, once purified, can be used to produce electricity and heat.

Organic waste contained in mixed municipal waste and separated in the MBT installation undergoes the same processes as selectively collected waste. However, due to the low organic fraction content and the presence of contaminants, the final stabilized waste will not meet the criteria for an organic fertilizer. This type of waste, with code 19 05 99, known as other wastes not otherwise specified, will constitute a “stabilizer”, i.e., a stabilized organic fraction. Once it meets the quality requirements, this waste can be safely stored in landfills, thermally converted in energy recovery facilities, or used for the reclamation of degraded areas.

Organic waste, especially that separated from mixed municipal waste, may contain organic contaminants such as polychlorinated aromatic hydrocarbons, pesticide residues, nonylphenols, and phthalates. The biological treatment of organic waste means that, during the composting process, some of these pollutants are broken down into harmless products. Polychlorinated aromatic hydrocarbons are bound to the organic fraction of the compost and are therefore unavailable to plants and soil organisms. Therefore, in this process, it is necessary to control and assess the safety of the end product, both in terms of compost as a fertilizer and the “stabilizer” as waste in relation to legal requirements.

The biological treatment of organic waste in installations using the best available techniques, and the end products of these processes, such as organic fertilizers and stabilized waste, is in line with the concept of sustainable development. This results from planned and undertaken activities in which waste becomes a product (organic fertilizer, soil improver, biogas, energy). Such activities represent the harmonious coexistence of environmental protection, social equality, and economic growth, with the aim of meeting the needs of current generations without limiting the possibilities of future generations.

The implementation of the separate collection of municipal organic waste supports its controlled collection and treatment and may reduce the risk of uncontrolled disposal. Diverting biodegradable waste from direct landfilling to biological treatment can reduce the amount of organic waste deposited in landfills and the associated potential for methane generation, although the magnitude of these effects depends on the collection and treatment system [127,150,151]. In addition, the anaerobic treatment of organic waste enables the recovery of biogas as a renewable energy carrier [120,126]. When recovered biogas is used to generate electricity, heat, or transport fuel, it may partially substitute energy derived from fossil fuels and provide potential greenhouse gas benefits. However, the magnitude of these benefits depends on the feedstock, process performance, energy use pathway, and management of the resulting digestate [152].

The separate collection of municipal organic waste and its biological treatment through aerobic and anaerobic processes support biodegradable waste management by enabling the recovery of materials, nutrients, and energy. These pathways are consistent with circular economy principles and may contribute to climate change mitigation by diverting organic waste from landfilling and enabling compost and biogas production [121,153]. Greenhouse gas emissions and avoided emissions were not quantified in the present study; therefore, the climate-related effects should be interpreted as potential implications supported by the literature. The biological treatment of municipal organic waste also supports circular economy objectives by conserving resources and enabling the production of compost, soil improvers, biogas, and energy. At the European Union level, circular economy policy promotes waste prevention, resource recovery, and more sustainable production and consumption systems [154]. Controlled waste treatment may also have indirect relevance to public health protection by reducing potential environmental exposure associated with uncontrolled emissions and leachate. However, the present study did not assess pollutant exposure, morbidity, or other health outcomes. Therefore, no direct or measurable improvement in human health can be inferred from the results presented in this study [155–157].

The results directly demonstrate differences in the physicochemical characteristics, biological stability, and potential management pathways of products derived from the two analyzed municipal organic waste streams. The study did not quantify greenhouse gas emissions, avoided emissions, fossil energy substitution, or health outcomes. Consequently, the possible contributions of biological treatment to climate change mitigation and public health protection should be regarded as broader potential implications supported by the literature, rather than as effects directly measured in this study. Further research based on lifecycle assessment, installation-level emission measurements, and energy balance calculations is required to quantify these effects.

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