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Management of the Municipal Waste Stream: Waste into Energy in the Context of a Circular Economy—Economic and Technological Aspects for a Selected Region in Poland

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Abstract: The goal of this paper is the research and analysis of municipal waste stream management in rural areas, potentially designed for energy purposes in thermal treatment systems. The research section includes granulometric, morphological, and physicochemical analyses to determine waste parameters. Studies have indicated that the calorific value for mixed municipal waste ranged between 6.5 and 9.5 MJ·kg, while following mechanical treatment for the oversize fraction over 80 mm ranged between 11.6 and 12.7 MJ·kg. The biodegradable fraction content analysis of waste—granulation 10 to 20 mm—demonstrated its presence at the level of 80%, which may be used to produce biogas. Studies have shown that the humidity level of waste generated in rural areas is in the range of 32.9 to 40.9%, which does not disqualify it from energy use in the production of refuse-derived fuel. Implementing a circular economy in the municipal waste sector aims at minimizing the use of raw materials, limiting municipal waste generation and greenhouse gases emissions, and increasing the level of energy use. Implementing new municipal waste management models is crucial to achieve a balanced, low-emission, waste-free, and competitive economy. The results are a significant research input for a group of municipal wastes generated in rural areas, such as refuse-derived fuel.

Keywords: waste management; fuel from waste; waste to energy; circular economy; municipal waste

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1. Introduction

Municipal waste generated throughout the centuries from human activity has always been an environmental and social issue. In this area of economic and social activity, waste should be processed per the waste processing hierarchy, so that the process poses a limited threat to humans and the environment. The need of continuously managing generated waste originates from the need to spare resources, limiting the space necessary to dispose of and search for new energy sources [1,2]. At present, when some countries in the world are particularly concerned about municipal waste management, taking into account the condition of the environment, safe and proper municipal waste disposal have a completely new meaning. The foregoing mainly applies to the impact of waste processing plants on the natural environment, in particular, its basic components, such as atmospheric air, surface water, underground water, and soil [3,4].

The European Union perceives the natural environment protection policy as an indispensable element of advocating for balanced and sustainable development. Further economic growth of the Member States as well as the wealth of their inhabitants—including care over their health—requires constant care regarding the condition of the environment and taking all the actions possible to protect it against degradation. Environmental protection programs are an essential element of the EU policy [5,6]. The definition of municipal waste in the Act on Municipal Waste states that municipal waste shall be construed as household-generated waste as well as waste containing no hazardous waste originating from other manufacturers, which, owing to its nature or composition, is comparable to household-generated waste [7]. Municipal waste disposed in previous years on landfill sites is a source of landfill gas (LFG), which should be caught and managed in a human-friendly and environmentally friendly manner. Energy use in cogeneration systems stands as an example of an optimum form of disposal. Such a solution makes landfill, being a system, an energy producer. Energy may be used for the landfill's needs as well as distributed to external power grids or district networks [8,9].

Taking into consideration dispersed sites of municipal waste generation and the whole process of its generation, collection, transportation, and methods of processing, it is advisable to apply appropriate tools to optimize the processes [10]. The above applies to mathematical modeling and GIS application that allow forecasting the pollutant distribution and the impact of integrated waste management on the environment at every identified process [11]. As regards GIS, a series of spatial analyses are carried out based on a thematic maps model (basic maps for design purposes, topographic maps, hydrogeological maps, sozological maps, etc.). This allows overlaying various layers, each of which concerns a different action [12,13]. Municipal waste generated mainly by household, infrastructural facilities are of different morphologies and have different properties, which are affected by many factors. The most important ones include inhabitants' standards of living, seasons of the year, building or flat heating methods, type of structure, and the application of raw material recycling by the inhabitants [14].

The characteristic feature of municipal waste generated in urban and rural areas is its varied morphology. Waste generated in rural areas and in the suburbs tends to show a higher mineral fractions content compared to urban agglomerations. Biodegradable waste dominates the waste composition in urban areas [15,16]. At present, municipal waste may be subject to varied disposal processes, which should be understood as subjecting the waste to biological, physical, thermal, or chemical transformation processes in order to process the waste into such a form that it poses no threat to human life and health or the environment, while, at the same time being capable of becoming, e.g., a source of energy [17,18]. Hansen states that effective waste management should start with an education on conscious shopping habits, avoiding waste generation, and correct waste segregation at the source. Waste management is considered an important area impacting climate change, in particular, as regards emissions released into the air [19]. Waste disposal in landfill sites is the least desired disposal manner. Landfill sites are used in multiple countries worldwide, being the easiest and cheapest method of municipal waste disposal. Yet, the results of such actions are a time bomb that will explode at some point [20,21].

Waste incineration depends on the country and region. Industrial countries in Europe as well as Japan, the USA, China, and Canada present a high rate of incinerated waste (over 90%). The majority of developing countries give preference to landfill sites as the more common municipal waste disposal technique. At present, over 500 waste-to-energy plants can be found in Europe, approx. 400 in China and 76 in the USA—they are based on efficient technology and advanced air pollution control systems [22]. Municipal waste thermal disposal predominantly takes place in systems equipped with a grate system, individually pyrolysis and gasification are observed, or a mixture of those processes. The majority of thermal systems convert waste in incineration processes, generating steam used for generating electricity and heat energy in cogeneration. Municipal waste incineration results in emissions into the air (mainly CO_2, N_2O, NO_x, NH_3, and C_{org} measured as total), which requires integrated emission size and purification efficiency monitoring systems [23].

Denmark deems waste generation and its environmental impact a crucial social issue. Non-recyclable waste must be disposed of in an environmentally friendly manner. The Danish thermal waste disposal system in incineration plants uses generated energy to produce heat energy and electricity. Thus, incineration plants are important electricity and heat suppliers in the Danish energy system. Dated 1st January 1997, Denmark completely prohibited municipal waste landfill sites, should the waste properties allow incineration. The goal of waste to energy is to ensure maximum energy retrieval in technological processes. Electricity is supplied to the public power grid, while heat is supplied to the district heating system [24]. Based on the statistical data, 13.4 million tons of municipal waste was generated in Poland in 2022, which on average means 355 kg per capita. Mixed municipal waste prevailed as regards the collected and generated municipal waste, accounting for 60% of the above. More than half (61.1%) of the generated municipal waste was sent for recovery, while over 2.7 million tons of municipal waste (20.2%) were directed for recovery in the form of thermal treatment with energy recovery. Disposal processes were applied in the case of over 5.2 million tons of municipal waste, where 5.1 million tons (38.1% of the municipal waste generated in total) were subject to landfilling. Compared to the leading EU states, the rate of waste sent for landfilling constitutes a huge challenge in the years to come [25].

2. Literature Review

2.1. Technical Aspects

Municipal waste incineration aimed at energy generation not only involves some technological requirements, but also material ones as regards the resistance to long-term thermal burden. The selected elements composed of a system performing the process of thermal treatment and waste conversion into energy entail the use of special construction materials. This applies mainly to waste conveyors, heat exchangers, steam transporting pipes, turbines, and grates. Municipal waste incineration components operate in hard conditions. The physical parameters of the operation to be performed are reflected in the structure and materials used. Subassemblies operate under many harmful factors. Some of them include temperature and its variability; working agent high pressure; varied waste composition and structure, including non-flammable fractions or aggressive pollutants; and elements that create an unfavorable environment for components, especially (Cl^-) and (SO_4^{2-}) ions. The steam temperature range in the turbines reaches 566–593 °C and the pressure is in the range of 25–30 MPa [26]. Diffusion coatings are commonly applied to enrich the surface with Al, Cr, or Si, thus ensuring appropriate resistance to oxidation and corrosion in high temperatures. Inconel 740H or Reno80 [27], CCA617, or Haynes 282 [28,29] coatings provide good results. The coating's resistance to high temperatures far exceeds the operating range of turbines and equipment in contact with steam, protecting its components against damage. Studies show that (Cl^-), (SO_4^{2-}), and (Na^+) ions in water used in steam turbines are corrosion-generating (e.g., pitting) [30]. The authors emphasize that the ions are conducive to the creation of acids, which accelerates the corrosion processes in turbines, thus resulting in their quick wear.

Heat exchangers, regardless of the technology applied (water or ammonia systems), require increased mechanical and anti-corrosion properties. One of the most frequently used materials resistant to thermal conditions and adverse factors conducive to the subassemblies' wear in furnaces is austenitic 316L stainless steel (1.4404) [31]. The steel is applied to heat exchangers, pipelines, hydraulic systems, and ball valves components. A great number of components used in heat exchangers and furnace elements are produced from austenitic steel materials; yet, also chromium-based and molybdenum-based alloys are used [32]. Furnace elements susceptible to direct contact with high temperatures are made of special types of steel. Boiler steel is a product distinguished by its ability to operate at high temperatures. Its favorable thermal properties are impacted by the presence of elements such as chromium, molybdenum, or vanadium. Common types of boiler steel include 16Mo3 steel. This steel is resistant to high temperatures, suitable for both cold and hot forming. Its characteristic feature is its good machining properties, as well as its corrosion-resistance—regardless of steam's presence in the environment. It can be applied for equipment operating at temperatures up to 530 °C [33]. 13CrMo4-5 steel is also characterized by good plasticity and ductility characteristics, and, at the same time, is characterized by its resistance to high temperatures. It also presents increased resistance to hydrogen and steam corrosion. It can be used in equipment operating at temperatures of up to 530 °C, as well as in the manufacture of pressure vessel components operating at temperatures of up to 350 °C [34]. However, 10CrMo9-10 is a boiler steel. It is heat-resistant and corrosion-resistant in steam environments at temperatures of up to 590 °C. It is also resistant to hydrogen at temperatures of up to 500 °C and pressure above 9.8 MPa, and up to 600 °C at a lower pressure [35]. P250GH steel is a high-quality stainless steel resistant up to temperatures reaching 480 °C. P250GH is suitable for welding components used in the manufacture of steam boilers and pressure vessels [36]. As regards low-alloy boiler steel, P265GH is weldable steel used for boiler and pressure vessel components, which are exposed to increased temperatures and high pressures [37]. Selecting suitable materials intended for use in municipal thermal treatment plants depends, to a large extent, on the energy content of the waste, the technology used, and the technological regime for meeting air emission standards.

Municipal waste thermal treatment technologies used in Poland meet the rigorous requirements for such systems, especially with regard to gases emission and ash emission standards. The systems are plants with energy recovery and flue gas treatments, processes control, checking, and monitoring. A municipal waste processing plant is a complex technical facility, and a high rate of composition change in incinerated waste results in the operator being forced to continuously control the operation and react to any deviations from the optimum parameters. The analysis of the municipal waste market in Poland undoubtedly shows the need to build subsequent thermal treatment plants incinerating calorific fractions over 80 mm generated in mechanical and biological processing systems. Such decisions should be preceded by profound economic, technical, environmental, and social analyses, taking into account the local dialog, including society's participation in consultations.

2.2. Economic Conditions

For municipal waste to constitute a stable fuel stream for waste incineration plants, relevant studies of its morphological composition must be carried out alongside an analysis of consumer behavior and financial inputs for the entire municipal waste management process. Eurostat data [38] show that there was an increase in waste generation in most countries in the period 2013–2021. The average amount of municipal waste in the EU in the period from 2013 to 2021 ranged between 479 and 530 kg per person. The value for Poland is slightly lower, ranging between 297 and 362 kg per person. Simultaneously, the largest amount of waste was generated in Denmark, the lowest in Romania [39]. Increasing amounts of waste require an efficient municipal waste management system compliant with the principles of sustainable development—which also generates costs and needs to be financed to ensure the best quality of waste collection, treatment, and final disposal. Regardless of local realities, the availability of financial resources is essential [40]. In Poland, keeping the region clean and in order are mandatory tasks of the municipality [41], which also translates into the fact that the municipality is obliged to organize the collection of municipal waste from the owners of properties located within its administrative boundaries. The Municipal Council regulates the municipal waste fees and the method of calculating the rate per the provisions of the Act, pursuant to which the maximum rate depends on the amount of monthly disposable income per one person in total for the previous year, and its amount varies depending on the method chosen by the municipality for calculating the fees [41]: per the number of people residing in the property, the amount of water consumed in the property, usable area of the household, the household itself, waste collection containers or bags, or the annual flat fee for a holiday home. The fees paid by the residents in a municipality are also influenced by factors such as the method of financing adopted, the costs of waste collection and management, the scope of the contract concluded between the municipality and the waste collection contractor, and the entity entrusted with municipal waste collection, including the use of the "in-house" model.

What is worth noting is the fact that the waste market is closely correlated with the rest of the economy, and the economic situation translates into the way municipal systems function, as well as the cost. In Poland, as well as in other countries, the responsibility for financing municipal waste management lies with the citizens, institutions, and companies through the payment of fees and taxes, and additional sources of financing may include subsidies from the municipal budget, revenues from the sale of materials and energy, and the revenue from extended producer responsibility programs [42]. An analysis of the municipal waste management levy system in different countries reveals the multiplicity of models used, with a strong preference for the use of a fixed and volume-based levy model. The former is easy to use and guarantees a constant flow of revenue, while the latter involves billing consumers based on the quantity and type of waste generated [43]. A modern approach to charging based on the quantity and quality of waste involves charging the users payments that are dictated by the aforementioned quantity and quality of waste delivered to the municipal waste management system [44]. Regardless of the charging system adopted by a country [39,45–47], a crucial role is played by shaping consumer awareness, which is supposed to lead citizens to engage in system efficiency improvement [45–48]. This is a widely discussed issue in the context of the fees incurred by, e.g., incentives to reduce waste and recycle more often [49], or, e.g., the “Pay As You Throw” (PAYT) weighted payment system [50]. This principle has become the subject of numerous scientific studies, some of which present the positive impact of the approach studied on waste reduction and some of which show the negative impact, identifying the drawbacks of this system. However, what should be noted is the fact that the role of users in municipal waste management, including the development of the recycling industry, translates into economic, social, and environmental sustainability. Simultaneously, it may increase the complexity of the municipal waste management system and thus require changes in legal regulations, user involvement, economic expenditure, and other resources [44]. Poland has recently observed a large increase in the costs of municipal waste management, which stems from increased costs of waste collection and transportation, as well as an increase in the costs associated with managing the municipal waste management system. The primary reason for increasing the costs of collecting and transporting municipal waste was a larger number of fractions to be collected by property owners, as well as an increase in fuel and salary costs. Yet, the increase in the cost of the municipal waste management system was caused by higher salaries, higher costs related to the operation of waste collection points, and an increase in the municipalities’ own responsibilities and tasks. Additionally, an increase was also observed, inter alia, in the cost of waste processing due to the increase in the cost of managing calorific waste, the adaptation to new standards, and no increase in the sale price of secondary raw materials collected selectively.

Municipal waste management fees per capita are supposed to cover the costs of system functioning. The highest share in the fees may be applied to the collection, transportation, recovery, and disposal of municipal waste. The waste management system assumes all the costs of collection and management to be covered by the inhabitants. The cost of the system may be reduced by the raw materials sales from waste income—both accepted at selected waste collection points and collected from the property. Statistical data concerning Poland show that, where municipal waste incineration plants function in towns/cities, the fees collected from the inhabitants are lower by approx. 10% compared to those without such plants. Yet, as regards the towns, where less waste is generated per capita, the fees are not lower. The fee depends on multiple factors, not only the amount of the waste generated, but also the specific nature of the region in terms of the social and economic conditions [51].

2.3. Managing Waste Disposal

Complex municipal waste management should be a crucial element to every country's environmental policy. As regards the European Union, its main objective is to use resources more efficiently and prevent waste generation. The current municipal waste hierarchy sets out a preferred program based on sustainable development priorities and gives preference to the application of integrated municipal waste management systems starting with collection, segregation, transportation, and treatment systems in terms of sustainability [52,53]. Taking this context into account, the main objective of waste management systems is the efficient management of waste disposal, recycling, reuse, or energy recovery processes through the control, collection, and treatment of waste, which should already be initiated at the waste generation stage [54]. The benefits of implementing integrated systems for municipal waste stream management include heterogeneous benefits for the economy and society, such as:

- Natural environment protection by decreasing the risks of soil, water, and air pollution [55];
- Using waste as a source of resources, including valuable elements [56], resulting in its independence from resource extraction. The above factors contribute to resource protection, while meeting the condition of the circular economy, the establishment of which provides further synergistic benefits, including a reduced demand for primary raw materials, energy saving, and reduced greenhouse gas emissions [54];
- Energy recovery, e.g., through the thermal treatment of waste [57] or its gasification;
- Minimizing waste storage space [58] by reducing its volume [59];
- Economic benefits, as the recycling and waste treatment industry creates jobs, stimulates the economy, and contributes to lowering the external effects (by-products) of industrial production;
- Reducing waste management costs by reducing the amount of waste in landfills [60];
- Stimulating public awareness of waste issues and the cooperation between different stakeholders, governments, local authorities, businesses, local communities, and citizens, to implement sustainable waste management practices, which ultimately contribute to a higher quality of life.

With a view of achieving the abovementioned goals, good municipal waste stream management should be characterized by adequate efficiency and effectiveness, which is usually observable in more developed countries. Ginevičius has observed that, along with the economic development of a country, the volume of municipal waste generated increases while the amount of waste in landfills decreases, which—inter alia—results from the higher efficiency of the functioning of management systems in more developed countries [61]. The main reasons for the lower efficiency of such management systems in less developed countries are financial, administrative, and managerial. A question arises—how should an efficient and effective municipal waste stream management system operate? The Waste Framework Directive, 2008/98/EC, of the European Union introduced the Waste Management Hierarchy System (WMHS), which obliges Member States to apply the hierarchy system as a priority in the waste prevention and management legislation and policy [62]. It classifies the proceedings hierarchically, from the most preferred actions to the least preferred ones, to be implemented in the EU countries as part of the waste management system. The WMHS distinguishes between waste prevention, preparing for re-use, recycling, other forms of recovery, e.g., energy recovery, and disposal, which includes incineration without energy recovery and landfilling. In this hierarchy, waste prevention is the most preferred action and disposal the least preferred [63]. The Directive assumes that waste management should be carried out, taking into account the principles of:

- The protection of human health and the environment;
- No risks to water, air, soil, plants, or animals;
- Does not cause a nuisance through noise or odors; and
- Does not adversely affect the countryside or places of special interest [62].

Sadeghi Ahangar et al. analyzed in their paper municipal waste management from the perspective of an integrated supply chain focusing on waste and its stakeholders. According to the aforementioned researchers, this chain includes waste generators, waste collectors and separators, and distribution centers and processors responsible for waste treatment or other uses, as well as those responsible for waste disposal. A well-functioning management system should be perceived as a whole and encompass the processes of waste collection, transportation, and disposal in an appropriate and economical manner. This involves its evaluation from economic, environmental, and social perspectives, so as to minimize the costs and pollution and maximize social aspects [64]. Luz et al. pointed out that the core of an efficient municipal waste stream management system is proper segregation and separation at the source [65]. Therefore, a well-functioning municipal waste management system should result in the increased recovery of collected waste in the households where it is generated [66]. Unfortunately, studies carried out, inter alia, in Poland, have demonstrated insufficient levels of municipal waste segregation [67,68], which may be related to the insufficient involvement of household inhabitants in this process. This prompts the need to revise the waste stream management systems' evaluation criteria, which typically evaluate these systems from the perspectives of cleanliness, speed and cost of collection, and transport, as well as disposal. Iwase and Dilokwanich pointed out that municipal waste management directly and indirectly engage various stakeholders. They include central governments, local governments, waste collection workers, households, businesses, non-profit organizations, mobile waste collectors, and waste management service providers and traders of waste and recyclables [69]. The researchers have proven that there is an insufficient involvement or a failure of the stakeholders in the municipal waste management system in fulfilling their responsibilities, which negatively affects its overall capacity and effectiveness. As a result, they proposed an appropriate allocation of capital within the system: financial, material (e.g., tools, machinery, equipment, and infrastructure), human (e.g., knowledge, skills, and motivation), social (enabling people to maintain and develop their own human capital by cooperating with others and gaining synergies through it), and natural (understood as any resource and energy flow providing valuable goods and services). Research by Iwase and Dilokwanich has shown that waste management systems allocate mainly financial and material capital, which is insufficient and does not ensure the efficiency of its stakeholders' actions. Additional human, social, and natural capital strengthening, e.g., through training, shaping environmental awareness, reuse, recycling, or recovery processes, contribute to the greater efficiency of the system's stakeholders and thus to a better and more sustainable operation [69].

The allocation of financial, material, human, social, and natural capital within a municipal waste management system should correspond to long-term and individualized action strategies, taking into account a holistic view of municipal waste management in a given area, its goals, and directions [70]. This demand is in line with the strategic management approach, which—as noted by Huebner and Flessa—means performing the right actions in the right way, paying attention to their long-term effects while taking into account the uncertainty and complexity of the operating conditions. The strategic management process is based on strategic thinking and not just on the implementation of its instruments [71]. A strategic approach within a municipal waste management system should involve and be shared by all its key actors. The beginning of the management process should be to specify the mission, vision, and long-term goals of a given municipal waste management system [72]. The next stage should involve a strategic analysis based on the analysis of the internal and external environments of the municipal waste management system, as well as the identification of its strengths, weaknesses, opportunities, and threats [73]. In their context, strategy options should be identified and the optimum one selected. This stage of management should verify the vision, mission, and strategic goals in terms of implementation possibilities. If they turn out to be unrealistic or inappropriate to the conditions, they need to be modified. Functional strategies and implementation plans for key system actors and the different levels of municipal waste management should also be defined in this phase [74]. This can be conducted using the balanced scorecard (BSC) or sustainability balanced scorecard (SBSC) methodologies, which are tools for integrating strategic planning with operational actions to improve performance in the short as well as the long run [75]. The balanced scorecard enables converting strategies into operational goals and bringing waste management in line with the strategy, making the actions of the individual actors in the waste management system compatible with it. The BSC makes it possible to parameterize and monitor the activities of the municipal waste management system in four areas: customers, internal processes, learning and improvement, and financial. The SBSC is an extension of the traditional balanced scorecard that integrates sustainability aspects into the BSC, taking into account social and environmental measures [76]. The next stage of strategic management is the implementation of the developed strategy in the tactical and operational activities of the waste management system through the implementation of basic management functions: planning, organizing, leading, and controlling. The final stage of the strategic management process is control that allows for monitoring and correcting the implementation of the strategy [77].

The strategic approach to waste disposal system management is supported by the complexity of the activities that are performed within it. This complexity results, inter alia, from the number of waste fractions dealt with by the system and the treatment technologies that can be implemented, as well as the number of its actors and stakeholders. This argues for the comprehensive management of the entire waste disposal process, including its interdisciplinary nature, which must take into account local conditions and their evolution. With reference to these facts, Thyberg and Tonjes proposed an interdisciplinary management framework that enables the planning implementation and maintenance of sustainable municipal waste management systems [77]. Their application enables: a proper definition of system components, complying with existing regulations, integrating the environmental, social, and economic perspectives into the system; collecting data and evaluating performance; as well as improving the system through changes and amendments to the system. The proposed framework has four superior components, where the individual steps to be followed for the system to be properly managed have been recommended. The first superior component of the framework for managing the municipal waste system is planning, which also distinguishes the need to:

- Define the system through its scopes, i.e., scale, timeframe, and boundaries, but also define the goals of the system in environmental, social, and economic dimensions, taking into account local conditions. The authors of the concept also highlighted the need for clear and precise definitions of the key terms that stakeholders will use within the system;
- Identify the environmental impact of planned activities;
- Identify stakeholders and their concerns about the system, and determine the method of communicating with them;
- Identify system performance indicators taking into account environmental, financial, regulatory, social, and stakeholder expectations;
- Select the best program option based on the above factors [77].

The next crucial framework component is implementation, which includes:

- Determining the specific goals as well as the time and measures to achieve them;
- Implementation;
- Systematic data collection.

Another superior framework element is evaluation, which should focus on:

- Diagnosing whether the goals specified at the planning stage are achieved and the reasons for the possible failures in the area;
- Evaluating the goals achieved from the perspective of requirements;
- Determining the challenges of the system.

The fourth main element of the municipal waste system management framework includes its improvements by:

- Introducing changes by defining the manner of the existing program's modification;
- Planning and implementing new action plans under the system;
- Goal reviews and modifications;
- Changes in other planning-stage elements;
- Iteratively moving through all the stages of the management framework to improve the system [73].

As Thyberg and Tonjes state, the framework can be applied to the whole waste management system or its specific elements, at different stages, from planning to evaluation and improvement. They can be used for both waste prevention and efficient waste management. They allow for the repeated planning of various options to facilitate optimum solution selection, and their general nature allows them to be applied to different systems and to take into account the local conditions [77], so they can be easily implemented in municipal waste stream management for energy recovery when aiming to achieve a circular economy.

Activities related to the optimization of municipal waste management in Poland are in line with the assumptions derived from the EU policy on circular economy, presented in the Communication from the Commission, the European Green Deal [78]. The circular economy action plan covers the entire life cycle of products, starting with the design, reducing the use of materials during production, and reusing waste in recycling processes. What is essential in the process is the production of reusable, durable, and repairable products, which will reduce the amount of waste generated. As regards municipal waste generated in different areas of residence and by economic activity, the organization of a stream management system is crucial. Such activities require the development of a waste management optimization model, dedicated to be applied in a given area in terms of the type of waste generated (morphological composition), the amount of waste, and its disposal [79].

Municipal waste collected through the waste management systems in place is subject to allocations to appropriate waste streams, which, owing to their morphological characteristics, will be subject to various recovery and disposal processes. Thermal municipal waste treatment plants—at the current level of waste treatment—are becoming an important element of waste management, being a key link in the disposal of mixed municipal waste (code 20 03 01). The remaining waste intended for thermal treatment is the residue from the mechanical waste transformation process in the form of the oversize fraction, which is the so-called pre-RDF, with code 19 12 12, and combustible waste (alternative fuel), with code 19 12 10, and is used in Polish cement plants to produce cement [80]. For thermal treatment systems to function properly, they must be supplied with waste fuel of an appropriate calorific value and an adequate stream to ensure the continuity of the thermal process. Therefore, such systems should be located close to large urban agglomerations and serve large waste management regions, ensuring an optimum amount of municipal waste [81]. One of the main objectives of the EU is pursuing sustainable development in waste management that ultimately leads to a decrease in waste generation and the highest possible rate of recovering precious raw materials. These goals may be achieved by the use of integrated management systems in municipal waste management. Poland is an EU state where municipal waste management is subject to continuous qualitative and quantitative optimizations. The crucial issue is to increase the waste segregation level at the source, thus increasing the recycling level.

3. Materials and Methods

This study involved research on the municipal waste generated in rural and sparsely urbanized areas (towns) to verify whether the waste generated has a sufficient energy value and may be used thermally, directly as mixed municipal waste or as fuel from waste. The subject matter of the study was mixed municipal waste generated in a small town (multi-family housing), including single-family houses, with a population of around 14,000, and a rural municipality with a population of around 24,000. For research purposes, the waste was divided into three groups based on the type of housing and heating systems, comprising multi-family housing (MF) from a town, single-family urban and suburban housing (SF) from a town, and single-family waste from a rural area (RA). Collected mixed municipal waste was supplied to the mechanical waste treatment plant, where a fraction was separated on the sorting line with a view of separating an oversize fraction (ballast) > 80 mm for the production of refuse-derived fuel (RDF) and a subsieve fraction < 80 mm for its biological processing.

As part of the study, the analysis covered three samples of municipal waste: the so-called raw waste (1, 2, 3 Bp—before mechanical treatment) before entering the system from three types of housing. In addition, tests examined three samples after a mechanical treatment process (1, 2, 3 Ap—after the process on a rotary sieve), also from three types of housing. Laboratory tests were carried out in an accredited laboratory, and granulometric composition analysis methodology and morphological analysis were used. PN-ISO 11465:1993 standard was applied for testing dry matter (moisture) [82] and roasting losses and ash content according to PN-EN 15035:2022-01 [83]. The content of biodegradable waste (biomass) and the heat of incineration and calorific value of the waste were specified. Total organic carbon (TOC) was specified with the use of the Tiurin method, while the sulfur (S) content and chlorine (Cl) content were determined using the turbidimetric method in a calorimetric bomb according to PN-EN 14582:2011 [84].

In order to identify particular waste samples taken for laboratory testing before and after processing from the three types of housing, the following steps were introduced:

- $MF1\_B_p$—raw (mixed) waste before processing on the sorting line, generated in a town, in multi-family housing;
- $MF1\_A_p$—waste after mechanical treatment on the rotary sieve of the sorting line, generated in a town, in multi-family housing;
- $SF2\_B_p$—raw waste before processing on the sorting line generated in single-family urban and suburban housing in a town;
- $SF2\_A_p$—waste after mechanical treatment on the rotary sieve of the sorting line, generated in single-family urban and suburban housing in a town;
- $RA3\_B_p$—raw (mixed) waste before processing on the sorting line, generated in single-family housing in rural areas of the municipality;
- $RA3\_A_p$—waste after mechanical treatment on the rotary sieve of the sorting line, generated in single-family housing in rural areas of the municipality.

This research included analyses of the granulometric (grain) composition with a separation of mass fractions, analysis of the morphological composition in granulometric fractions >80 and 20–80 mm, analysis of composition and physicochemical properties of waste, division of biodegradable parts in fractions of 10–20 mm, and physicochemical studies of samples with grain fractions of > 80 mm and <80 mm in terms of selected fuel parameters of waste, relevant to its thermal treatment. Sizes for granulometric compositions were selected based on the Regulation of the Minister of Climate and Environment of 28 December 2022 on the mechanical and biological processing of non-segregated (mixed) municipal waste. The sizes were set at the time of this study, and the study results as well as further municipal waste management methods were analyzed [85].

This study's results were subject to statistical analysis with the use of Statistica software version 14.1.0.4, in order to compare different fractions of municipal waste and analyze clusters, where Ward's method was applied. The method presents distances between clusters and uses the variance analysis approach, resulting in minimizing the sum of squares of deviations of any two clusters. Moreover, the Euclidean distance was used as the distance measure in this method. The analyses of the physical and chemical tests results of the waste covered the analyses for three XYZ variables presented in 3W diagrams [86].

4. Results and Discussion

4.1. Granulometric Analysis

Mixed municipal waste (raw) can be directly transferred to thermal treatment plants for energy recovery. The same mixed municipal waste can be subjected to mechanical treatment, such as on a sorting line, to separate fractions above 80 mm as a basic raw material for generating refuse-derived fuel. The remaining fraction of waste separated during mechanical treatment, producing fractions below 80 mm, can also be used for energy in anaerobic processes to produce municipal biogas. Therefore, each of these fractions can be a potential source of waste-derived energy.

The study's results of the granulometric composition of waste supplied to waste mechanical treatment systems are presented in Table 1.

Table 1. Granulometric composition of municipal waste supplied to the system.

Waste Fraction Size	Multi-Family Housing, Town MF	Single-Family Housing, Urban and Suburban, Town SF	Single-Family Housing, Rural Area of the Municipality RA
	MF1_Bp	SF2_Bp	RA3_Bp
	% of Waste Mass		
>80 mm	35.84	33.61	43.83
20–80 mm	49.15	52.42	33.85
10–20 mm	7.58	5.84	6.77
<10 mm	7.43	8.13	15.55

Granulometric analysis indicates that the largest fraction over 80 mm can be found in waste generated in rural areas, whereas the smallest fraction is found in single-family housing, in urban and suburban areas. A fraction below 10 mm also dominates in waste collected from rural areas. This particular municipal waste fraction size can be used to produce fuels from municipal waste. The share of the fraction above 80 mm to below 10 mm, including raw and mechanically processed waste, can be observed in Figure 1.

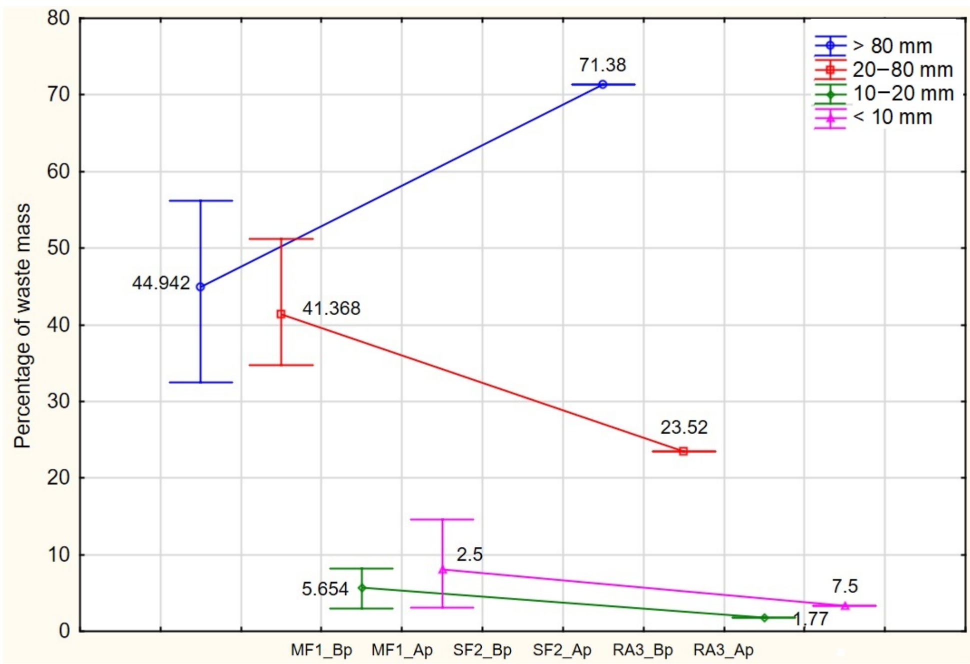

Figure 1. Pre- and post-mechanical processing percentage shares of selected waste fractions.

Studies have shown that, following mechanical treatment on a sorting line, the greatest granulation size was found in municipal waste generated in rural areas. As regards the 20–80 mm fractions, the greatest percentage share of the mass was related to municipal waste generated in urban and suburban areas in single-family housing. Figure 2 presents fraction contents over and below 80 mm for pre- and post-processing wastes, depending on the generation site.

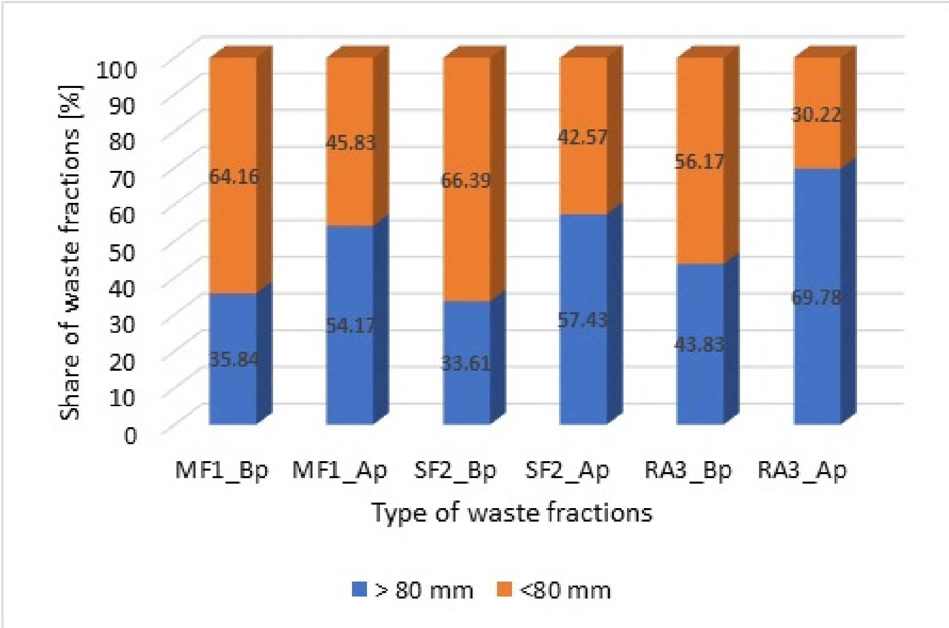

Figure 2. Fraction shares >80 mm and <80 mm in municipal waste per generation site.

The highest percentage of the <80 mm fraction was observed in raw waste collected from multi-family housing in urban areas. Yet, the lowest percentage was observed in mechanically treated waste generated in rural areas.

4.2. Morphological Analysis

The morphological analysis of municipal waste collected at three different generation sites was divided into 11 pre- and post-mechanical treatment fractions. The main group of material fractions (7 fractions) over 80 mm for pre- and post-mechanical treatment municipal wastes per generation site can be observed in Figure 3.

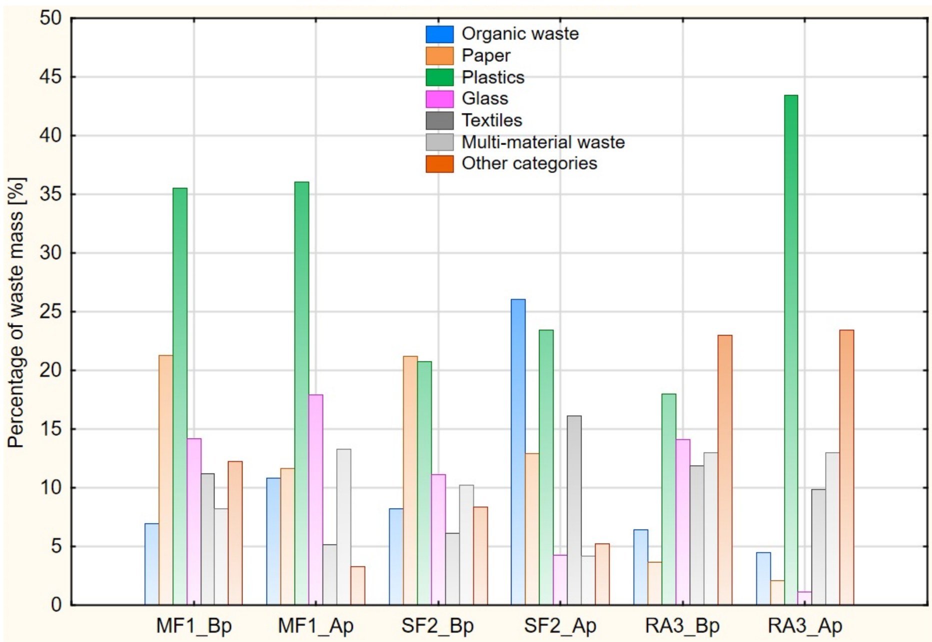

Figure 3. Morphological composition of municipal waste for the main fractions >80 mm.

The main material fraction of municipal waste over 80 mm is dominated by plastics from multi-family housing in urban areas. The second dominant fraction is paper waste in urban areas, while the least paper waste is found in rural areas. The remaining group of material fractions (4 fractions) over 800 mm for pre- and post-mechanical treatment municipal wastes per generation site can be observed in Figure 4.

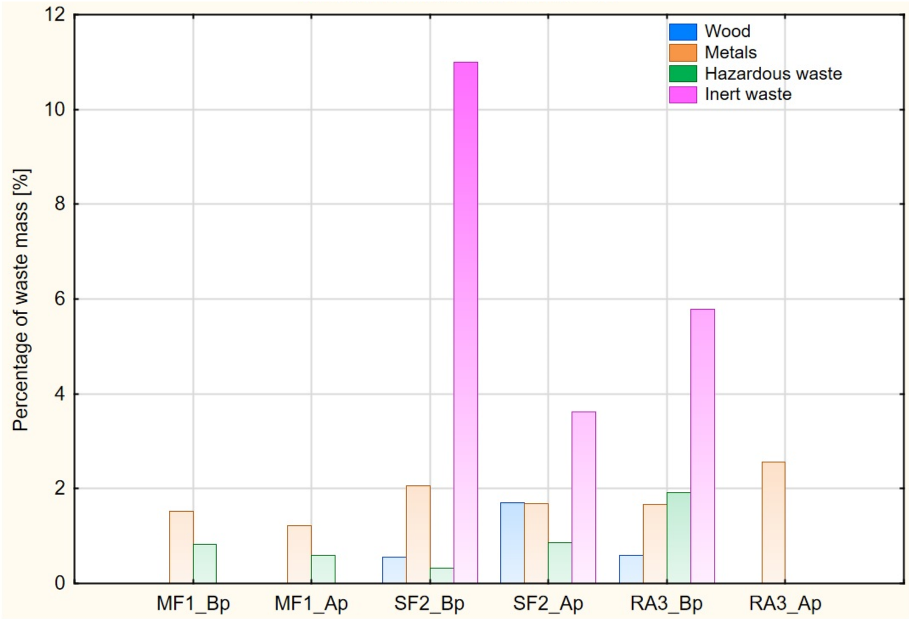

Figure 4. Morphological composition of municipal waste for the remaining fractions > 80 mm.

This remaining group of material fractions is dominated by inert waste (e.g., soil and stones) from the two areas representing rural and suburban single-family housing. This fraction is absent form waste in urban areas, and so is wood waste. Figure 5 presents the results of hierarchical grouping, a binary tree (dendrogram) for all material fractions over 80 mm separated from municipal waste, representing different generation sites and treatment methods.

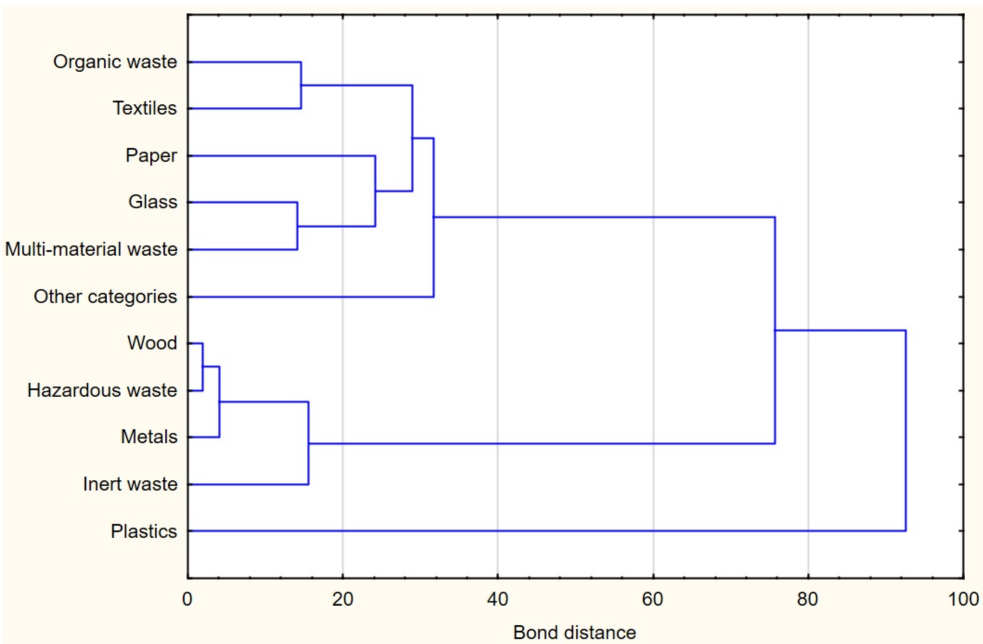

Figure 5. Dendrogram of fractions over 80 mm for particular municipal waste streams.

The analysis of the material fractions over 80 mm indicates that the objects form clusters creating three main groups. The first cluster contains waste fractions in the form of wood, hazardous waste, metals, and inert waste, which represent the smallest bond distance (y = 4.48÷15.67). This stems from the fact that the percentages between them are comparable, ranging from 0.0% to 10.6%. The second cluster contains six types of waste: organic waste, textiles, paper, glass, multi-material waste, and other. The range of bond distances for this group amounts to (y = 14.12÷31.94). The third cluster relates to plastics, which definitely stands apart from the others, for which the bond distance is (y = 92.67). Such a condition results from the predominant plastic content in municipal waste analyzed in the town. The dendrogram also presents a bond between the main groups (clusters one and two), which amounts to (y = 75.95).

The fraction of municipal waste with granularity less than 80 mm in municipal waste treatment systems, according to waste processing requirements, is directed to biological waste treatment processes to stabilize the biofraction under aerobic conditions and stabilized municipal waste production, or to processes exposed to anaerobic conditions to produce municipal biogas. To estimate the energy potential of fractions below 80 mm, a cluster analysis was performed as a potential source of biogas generation. Figure 6 presents the results of the hierarchical grouping, a binary tree (dendrogram) for all material fractions below 80 mm separated from municipal waste, representing different generation sites and treatment methods.

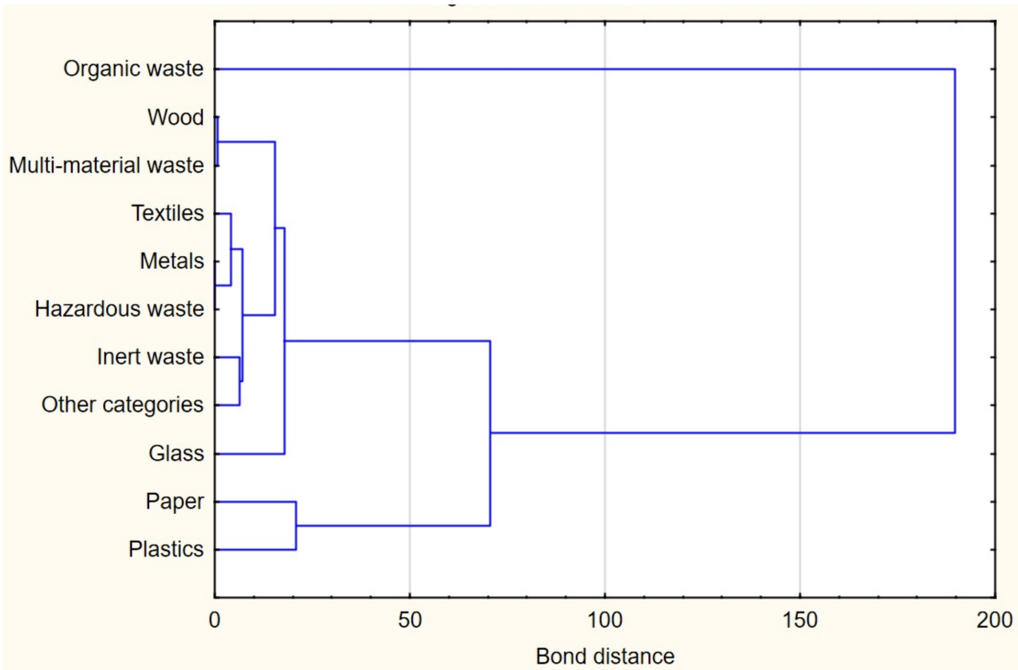

Figure 6. Fraction dendrogram (20–80 mm) for particular municipal waste streams.

The material fraction analysis of mixed municipal waste after being processed on the sorting line, with a granularity below 80 mm, showed that the objects form clusters resulting in four main groups. The first cluster contains waste fractions in the forms of wood, multi-material waste, textiles, metals, hazardous waste, inert waste, and other waste, which represent the smallest bond distance (y = 0.81÷15.44). This is due to the fact that the percentages for these fractions are comparable. The second cluster includes glass, with a bond distance of (y = 18.13). The third cluster is paper and plastic waste, with a bond distance of (y = 21.05). This condition is due to the significant content of paper and plastics in municipal waste surveyed from the town. The fourth cluster is the least similar to the other fractions and represents organic waste with a bond distance of (y = 198.73). Such a condition indicates the dominant content of biodegradable waste in all the waste products from the three types of housing. The dendrogram also presents a bond between the main groups (clusters one, two, and three), which is (y = 70.57).

In terms of the size of the waste fraction separated from the municipal waste stream after mechanical treatment, the analysis covered 10–20 mm fractions that can be thermally treated in waste incinerators or intended for the production of municipal gas in anaerobic processes. Owing to the specific nature of municipal waste with regard to the generation site, the biodegradable fraction in this granulation process will always be present, and its percentage content will depend on the waste generation site. The key parameter that determines the use of the above mentioned processes is the predominant presence of the biodegradable fraction in the 10–20 mm granulation. Figure 7 presents the biodegradable and non-biodegradable fraction contents in the separated 10 to 20 mm granulation sizes of mixed municipal waste and after mechanical treatment from three waste generation sites.

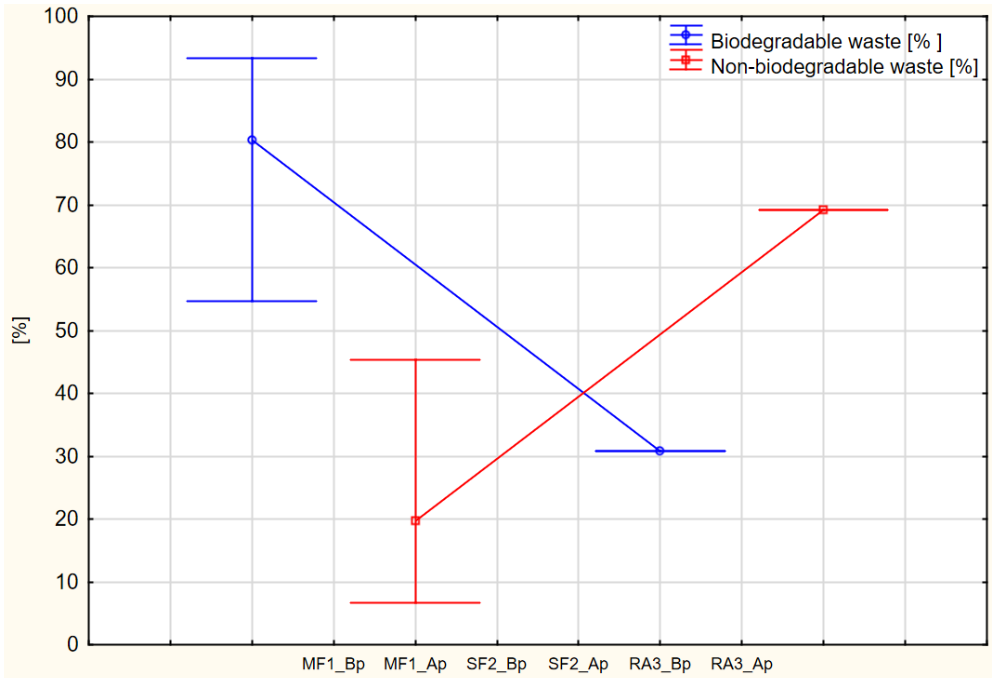

Figure 7. The percentage content of biodegradable and non-biodegradable fractions depending on the generation site and treatment method.

The content of the biodegradable fraction in waste with a granulation size of 10 to 20 mm presented the highest value for mixed municipal waste, showing a decreasing trend reaching the lowest value for waste generated in rural areas, after mechanical treatment. With regard to the non-biodegradable fraction, the trend is diametrically opposite and the maximum percentage value for this fraction amounts to approx. 70% for mechanically treated waste.

4.3. Physicochemical Analysis

In order to determine the parameters of the analyzed municipal waste streams in <80 mm and >80 mm fractions generated at three different sites, physicochemical analyses were performed to verify the energy value of the municipal waste stream. The selected fractions were also analyzed in terms of biomass content and moisture content as input parameters to classify the type of waste for a possible municipal biogas process. Figure 8 presents the relation between the calorific value, ash content, and waste moisture content depending on waste type and generation site.

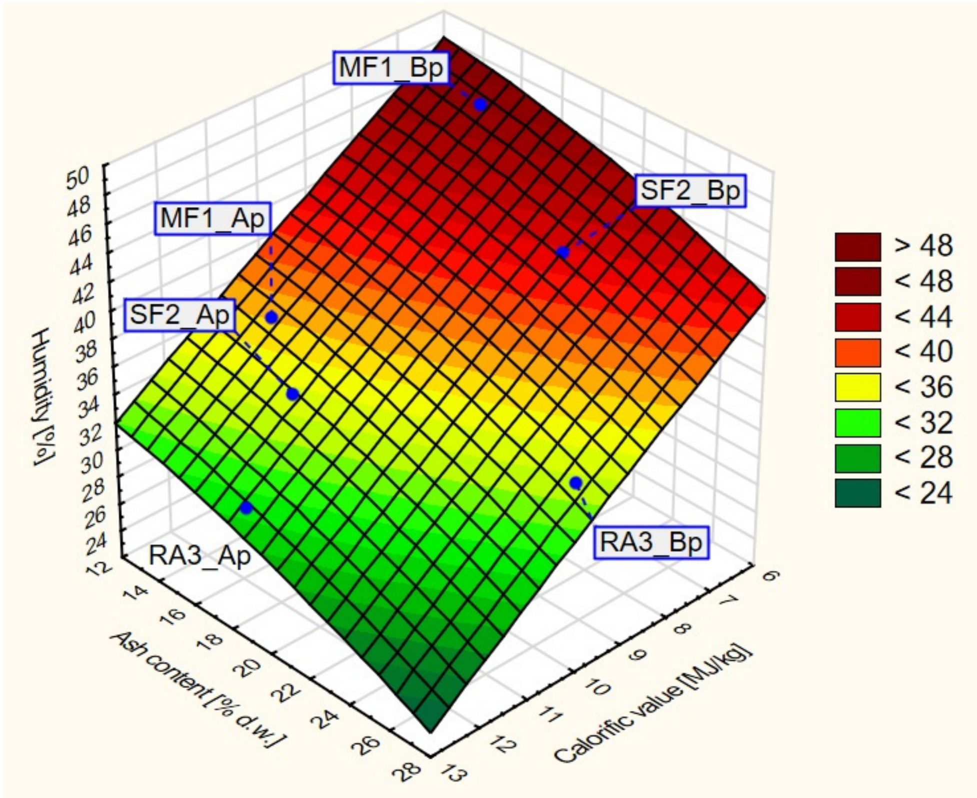

Figure 8. Relation between calorific value and ash content to waste moisture content.

In urban areas (multi-family housing), the calorific value of mixed (raw) municipal waste is an average value of 6 MJ·kg. This may result from the fact that biodegradable waste, textiles, plastics, paper, and rubber products are organized and separately collected in municipal waste systems. However, rural areas generate waste (mainly paper and plastics) that cause the waste stream to have a calorific value of approx. 12 MJ·kg. The above factors may be due to the low efficiency of waste segregation and ineffective selective collection of municipal waste in these areas. Figure 9 shows the correlation between the calorific value and the moisture content of waste depending on the generation site.

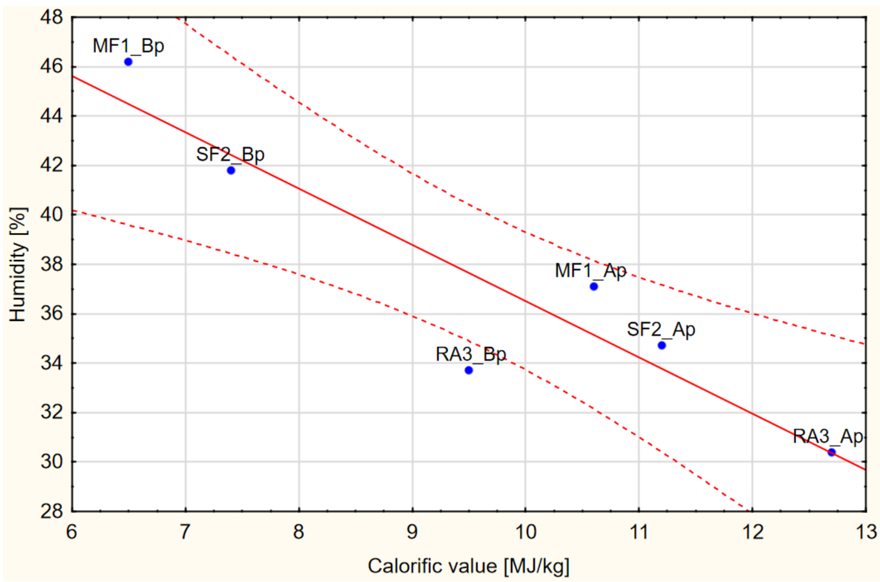

Figure 9. Correlation between calorific value and moisture content for individual waste streams.

The highest calorific value was recorded at the lowest moisture content for waste generated in rural areas (RA3_A_p), for fractions over 80 mm, following the mechanical treatment of waste. The opposite situation was observed in the case of mixed municipal waste generated in urban areas (RA34_B_p), which stands out the most from the regression line. Figure 10 presents the percentages of chlorine, sulfur, and total organic carbon in waste per generation site.

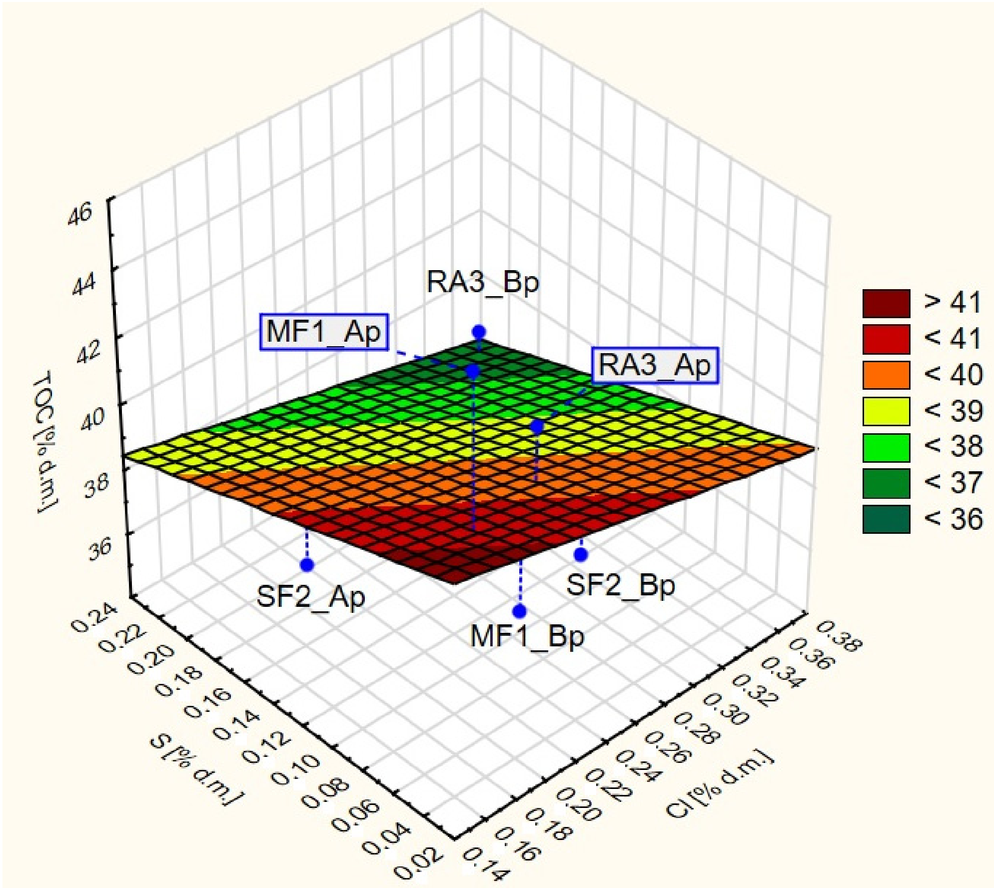

Figure 10. Sulfur content and total organic carbon content to chlorine values.

Physicochemical analysis of municipal waste generated in three different housing areas presented varied values of individual parameters. The analyses presented differences in the sulfur, chlorine, and total organic carbon content, among other things. The highest sulfur content was found in mixed municipal waste generated in rural areas, while the lowest sulfur content was recorded in waste generated in urban areas. An important parameter when municipal waste is incinerated is its chlorine content. Chlorine affects the technological aspect, but also the temperature required in the thermal process carried out. A high chlorine content in waste can lead to system corrosion. Therefore, the chlorine content should not exceed 1% in refuse-derived fuel. As regards the studied waste, the chlorine value fell within the range of 0.15 to 0.37% of dry mass. Figure 11 presents the relationship between the thermal value and the type of granulation and humidity of waste.

Municipal waste thermal value is impacted by, inter alia, highly calorific fraction content, e.g., plastic, paper, and wood. Moreover, increased humidity that may result from the manner of collection, transportation, and storage may lead to a decreased thermal value. The municipal waste generation site also impacts the thermal value, including the mineral (ashes) fraction and biomass content in the waste.

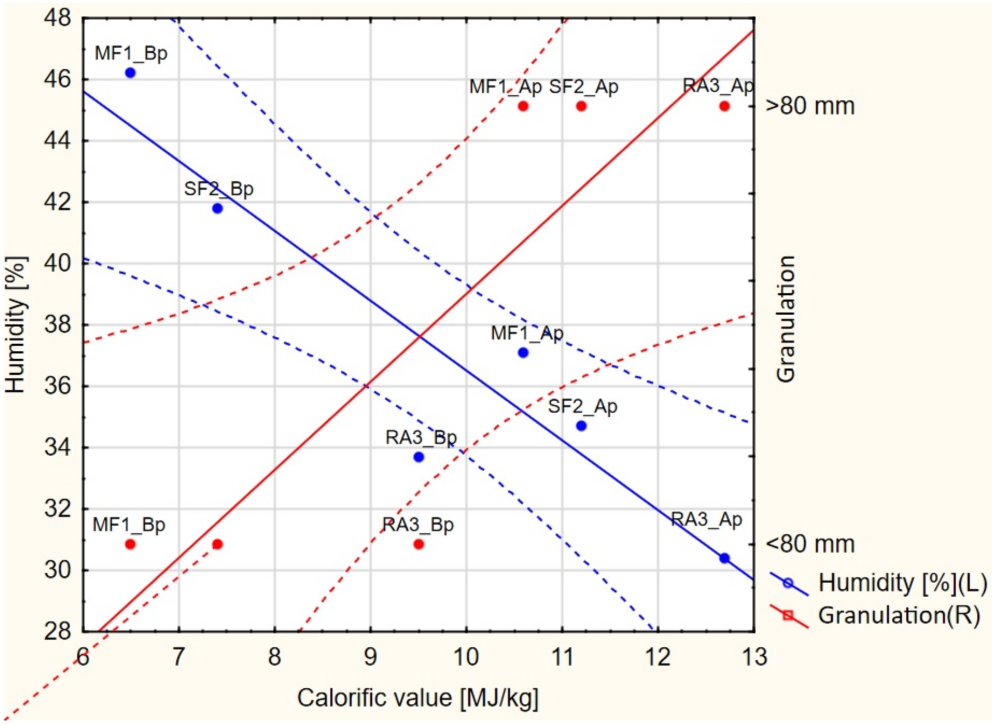

Figure 11. Relationship between thermal value and granulation and humidity.

The average calorific value of mixed municipal waste with code 20 03 01 generated in three different areas was 7.8 MJ·kg. As regards waste with a fraction >80 mm after being processed with a rotary sieve, waste is generated—code 19 12 12—(other waste, including mixed substances and objects from mechanical processing), with an average calorific value of 11.5 MJ·kg. This waste may be intended for direct incineration in a waste incineration plant or used as material for making refuse-derived fuel (RDF), with the waste code 19 12 10. Polish incineration plants mainly incinerate mixed municipal waste with waste code 20 03 01 and waste with code 19 12 12, 19 12 10. The analysis of the calorific value of mixed municipal waste incinerated in Poland proved that the value in 2021–2023 ranged from 7.8 to 8.4 MJ·kg. However, some incineration plants present a higher calorific value of 11 MJ·kg, which is due to the share of RDF. In Poland, there are 12 facilities for the thermal treatment of municipal waste and co-incineration of RDF, allowing for the thermal treatment of about 2 mL of Mg of municipal waste. The cement industry has the potential to use more than 1 mL of RDF in cement plants [87].

The issue of environmental efficiency in municipal waste management in the EU-28 has been the subject of research by Rios and Picazo-Tadeo, who defined in their paper indicators depending on how waste is processed. The most environmentally desirable methods of municipal waste treatment in the EU include recycling and recovery, Sweden being the leader in these processes. The lowest level of environmental performance with regard to waste treatment may be observed in Eastern European countries that joined the EU-28 in 2000, and some Mediterranean countries [88]. Research results presented in their paper demonstrated that municipal waste generated in rural areas—despite the tough conditions of collection and transportation, especially in winter—may be used as fuel for direct energy generation, with the thermal value ranging from 6.5 to 9.5 MJ·kg.

The permanent nature of changes and the necessity to adapt to changing conditions remain immanent features of every system, including municipal waste management. The search for the best solutions that will refer to the principles of sustainable development and place humans and the environment first also requires an appropriate approach to financing. The costs of operating the system generate expenses that should have clearly defined sources of financing (income). In Poland, these amounts (expenses and income) are included in the municipality's budget in a separate bank account and are classified according to the guidelines of regional accounting chambers. According to Kotlińska and Żukowska, the nationwide expenditures of the municipal waste management system in the period 2013–2021 were higher than the revenues of the system (but for the first two years) [39]. Taking into consideration the statistics showing an increase in the amount of waste generated, but at the same time an increase in the level of recycling municipal waste from 44.9% in 2015 to 49.6% in 2021 [38], solutions should be sought to improve the functioning of the system. The PAYT system (Pay As You Throw) is worth consideration; despite the indicated drawbacks [48], its undoubted advantage is the creation of an informed and more prudent citizen. The academic discourse indicates low citizen involvement as a drawback. Despite the numerous existing tools and technologies that can be used to improve the circular economy, the critical bottleneck is citizen involvement [42]. Drawing attention to consumers' roles and shifting the burden of responsibility for the waste generated in a well-designed system of fees paid, taking into account local conditions, may facilitate the efficiency of the system and provide a significant stimulus for the effective implementation of the waste hierarchy, where the key goal is waste prevention. What should be emphasized is the fact that the aforementioned approach should be supported by proper education from the earliest years. The study results based on a case study being a small town (multi-family housing), including single-family houses, with a population of around 14,000, and a rural municipality with a population of around 24,000 showed the need for selective collection optimization. The above factors stem from the fact that there is mainly packaging waste in the mixed municipal waste stream.

Changing legal, economic, and technological conditions, as well as growing environmental requirements force the optimization of the waste sector's operations, including changes in the management of the municipal waste stream generated in rural areas. Subject literature presents an assumption that the waste management system should be reliable, flexible, cost-effective, and environmentally friendly [89]. Scientific discourse on its optimization is carried out mainly in the technological–engineering, logistics, economic, and environmental areas. As regards technology, the possibilities of implementing various solutions for waste prevention, recycling, reuse, recovery, including energy, and waste disposal are considered. As far as prevention is concerned, the subjects include eco-design [90–92], cleaner production technologies [93], the creation of environmentally friendly packaging, and its minimization or reuse [94,95]. As regards recycling, the following solutions may be performed: mechanical recycling [96], high-temperature processing [97], solvolysis and pyrolysis, ultrasonic recycling, enzymatic recycling, etc. [98]. Recovery technologies include thermal treatment (incineration, pyrolysis, gasification, and plasma gasification), biochemical treatment (fermentation, anaerobic digestion, and landfills with gas capture and microbial fuel cells), and chemical treatment (esterification) [99]. In the field of logistics, the frequently addressed issues in the literature include: waste collection [100,101], waste transportation [102], waste processing and sorting [103], or system information management [104]. Another popular area of research related to waste management is economic considerations [105]. They focus on the issues of waste management financing [106], operating costs, sustainability, or infrastructure investment. There are also multiple considerations on the environmental impact of waste management [107,108], including topics such as greenhouse gas emissions, water and land pollution, and policy and regulatory issues. However, scientific discourse noticeably lacks considering the issue of waste management from a purely managerial perspective. Although ISO standards (e.g., ISO 14001 or ISO 14040 [109,110]) in waste management are referred to quite frequently, management methods and concepts that could improve the described waste management systems by creating synergistic benefits seems undervalued in the discourse. Management concepts worth considering that could be tested in waste management systems include: Lean Management and Lean Manufacturing, Knowledge Management, Smart Waste Management, Kaizen, and Benchmarking. The management and organizational optimization of waste management systems could synergize with technical and logistic modifications, contributing to an even greater efficiency and achieving the sustainable development goals. Humidity analysis of municipal waste generated, inter alia, in rural areas conducted in the study presented humidity to fall within the range of 32.9 to 40.9%. The value may be lower under the condition of facilitating the manner of waste collection, transportation to the processing plant, and storage prior to processing on the sorting line.

Approx. 1.8 million Mg of alternative fuels in Poland are currently consumed by the cement industry, which primarily includes RDF (refuse-derived fuel), which constitutes approx. 13% of the municipal waste generated in Poland in 2021. With the assumption of an increasing demand for cement, it may be concluded that cement plants are able to use up to 3 million Mg per year of alternative fuels for clinker production, i.e., contribute to "management" in an environmentally safe and economically beneficial way of about 2.5–2.9 million Mg of municipal waste. The cement industry, using RDF alternative fuels, is in fact a waste-free industry, and plays an important role in Poland's waste management system. Regulations governing waste management are subject to ongoing changes. The goals of the changes are, on the one hand, to reduce the risks (to people and the environment) that may result from improper waste management, and on the other hand, to enforce the maximum use of waste as a source of raw materials to replace those from natural sources. The European Union is and will be pursuing the idea of what has been termed as a circular economy [80,111]. Drawing conclusions from the study of municipal waste generated in poorly urbanized and rural areas, the conclusion should be that such types of mechanically processed waste may be used to generate refuse-derived fuel used in the cement industry.

What should be noted is that municipal waste incineration is only one of the available technologies for waste management. At the time of selecting this technology, it is important to pay attention to the economic and environmental costs when building and operating a thermal waste treatment system [112]. The technology is developing rapidly to meet increasingly stringent environmental standards. At present, the most challenging factor is the technologies that improve the efficiency of electricity and heat production and minimize the negative impact on the environment as a result of waste incineration. From all the types of incineration technologies, energy recovery is carried out by deriving thermal energy in the form of steam or hot water and recovering thermal energy from flue gases. Technical solutions are applied to that end—they make the processes' optimization feasible.

5. Conclusions

Municipal waste generated in different areas of human activity is characterized by different morphological compositions and different physicochemical parameters, which determines the choice of appropriate methods of processing. The hierarchy of municipal waste management in force determines its suitability for material, organic, or thermal recycling. Thermal treatment technologies used worldwide, including in Poland, guarantee the correctness of the process in terms of the use of construction materials. Structural materials function in harsh conditions and are exposed to harmful factors, such as high temperatures, high pressure of working agents, aggressive composition of incinerated waste, and unfavorable composition of working agents. To that end, Ni-based super alloys are used for boilers due to their exceptional mechanical properties and high thermal strength. Coatings commonly used to enrich surfaces with Al, Cr, or Si provide adequate resistance to oxidation and corrosion at high temperatures.

Municipal waste management is inextricably linked to economic aspects resulting directly from the costs associated with the collection and transportation of municipal waste and the cost of waste treatment. This condition results in a systematic increase in municipal waste management fees for the original waste generator.

The effectiveness of municipal waste management and the efficiency of the system are directly influenced by waste management models, and the resulting actions and decisions made with regard to the possible implantation of new waste treatment technologies. The application of innovative models makes it possible to correctly define the components of the system to ensure compliance with current legislations and applicable standards. What is of crucial importance is planning issues, including timeframes and boundaries, but also defining the goals of the system in environmental, social, and economic aspects, taking into account the local conditions.

Studies carried out in this paper have concluded that the municipal waste (waste code 20 03 01) collected in suburban areas of a town and rural areas is a potential source of energy for direct use as mixed municipal waste in the process of thermal treatment in waste incineration plants. As a result of mechanical treatment, e.g., on a rotary sieve, the separated fraction over 80 mm (waste code 19 12 12) can be intended for incineration in a waste incineration plant, or be an input fraction for the production of fuel from waste code 19 12 10 and used, for example, in a cement plant. Since mechanical treatment allows for the separation of an additional fraction, e.g., 10–20 mm, it can be intended for thermal treatment in incineration plants or, optionally, used in anaerobic processes to produce municipal gas, which is consequently a source of eclectic energy and heat. This study's results should indicate to waste owners—being municipalities—the potential ways of processing municipal waste, taking into account the selected technologies, ways of managing the waste stream, and the economic aspects that the waste owners should pay special attention to.

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