energies

MDPI

Article

Assessment of the Renewable Energy Recovery Potential from Municipal Solid Waste: A Polish Case Study

Emilia den Boer [1,*], Kamil Banaszkiewicz [1], Iwona Pasiecznik [1], Jan den Boer [2], Hongzhi Ma [3], Elias Hakalehto [4,5] and Łukasz Kowalczyk [6]

1 Faculty of Environmental Engineering, Wrocław University of Science and Technology, 50-370 Wrocław, Poland; kamil.banaszkiewicz@pwr.edu.pl (K.B.); iwona.pasiecznik@pwr.edu.pl (I.P.)
2 Faculty of Life Sciences and Technology, Wroclaw University of Environmental and Life Sciences, 50-375 Wrocław, Poland; jan.denboer@upwr.edu.pl
3 School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing 100083, China; mahongzhi@ustb.edu.cn
4 Department of Agricultural Sciences, University of Helsinki, 00014 Helsinki, Finland; elias.hakalehto@gmail.com
5 Finnoflag Oy, 70101 Kuopio, Finland
6 K35 Usługi Przyjazne Środowisku Łukasz Kowalczyk, 63-040 Komorze, Poland; biuro@k-35.pl
* Correspondence: emilia.denboer@pwr.edu.pl

Abstract

This study investigates whether the optimal utilization of the biomass potential contained in municipal solid waste (MSW) can support the implementation of circular economy (CE) principles and contribute to climate policy objectives, particularly the reduction in greenhouse gas (GHG) emissions in the waste management sector. The analysis evaluates whether waste-to-energy recovery can support the objectives of the European Green Deal, including a 55% reduction in GHG emissions by 2035 and the achievement of climate neutrality by 2050. The assessment was conducted for two MSW streams generated in a Polish municipality: separately collected biowaste and residual MSW remaining after meeting European reuse and recycling targets. The study summarizes the results of detailed experimental investigations of the physicochemical and fuel properties of these waste streams. Proven and commercially available energy recovery technologies, including anaerobic digestion (AD) of biowaste and incineration of residual waste, were analyzed. GHG emissions were assessed using a life cycle assessment (LCA) approach, taking into account both direct emissions and avoided emissions resulting from the substitution of conventional energy and fertilizer production. The experimental results revealed significant variability in the biodegradability and energy potential of individual biowaste fractions, with the highest biogas yields observed for kitchen waste. Residual waste exhibited a considerable calorific value and a significant share of renewable energy due to its biomass content. The results indicate that the share of renewable energy in electricity generated from waste is expected to increase from 46.1% in 2025 to 49.9% in 2040. In relation to the total electricity demand of the analyzed city, energy recovered from waste accounts for 1.8 ± 0.3% in 2025 and 1.3 ± 0.2% in 2040. Scenario-based modeling demonstrated that the target system, maximizing energy recovery from both biowaste and residual waste, achieves a consistently negative GHG emission balance throughout the analyzed period (2025–2040), ranging from −72 ± 15 kg CO_2-eq/ton in 2025, through the most favorable value of −81 ± 17 kg CO_2-eq/ton in 2035, to −57 ± 12 kg CO_2-eq/ton in 2040, expressed per ton of total managed biowaste and residual waste.

Keywords: municipal solid waste; biowaste; residual waste; energy recovery; biomass content; renewable energy; circular economy

Check for updates

Academic Editor: Massimo Dentice D'Accadia

Received: 24 April 2026
Revised: 25 May 2026
Accepted: 29 May 2026
Published: 4 June 2026

1. Introduction

Energy demand is steadily increasing worldwide, while growing pressure is being placed on reducing greenhouse gas (GHG) emissions and limiting dependence on fossil fuels. Current European and global climate strategies aim to achieve climate neutrality (net-zero GHG emissions) by 2050, supported by ambitious intermediate emission reduction targets. Under the European Climate Law and the "Fit for 55" package, the European Union has committed to reducing net GHG emissions by at least 55% by 2030 compared with 1990 levels. Furthermore, the European Commission is currently discussing an additional intermediate target for 2040 corresponding to approximately 90% net emission reduction relative to 1990 levels [1]. Achieving these objectives requires a profound transformation of the energy, industrial, transport, and waste management sectors.

In this context, mixed or residual waste, i.e., waste remaining after material recovery processes, is increasingly recognized as an important locally available source of renewable and low-carbon energy, particularly for fractions that cannot be feasibly reused or recycled [2–6]. Life cycle assessment (LCA) studies demonstrate that properly designed waste-to-energy (WtE) systems, including incineration with energy recovery, gasification, anaerobic digestion (AD) and pyrolysis, can simultaneously reduce landfilling, replace fossil fuels and significantly decrease GHG emissions compared with conventional waste disposal and energy generation pathways [2,4–8]. Residual MSW is typically a heterogeneous mixture of biogenic components, such as food waste, paper and garden waste, together with fossil-derived materials including plastics and synthetic textiles. According to the IPCC guidelines, the proportions of biogenic carbon (C_{bio}) and fossil carbon (C_{nbio}) in municipal waste are among the key factors determining GHG emissions from waste treatment processes. As CO_2 emissions originating from the biogenic fraction of waste are generally considered carbon-neutral, a higher biomass content in municipal waste increases the share of recovered energy that can be classified as renewable.

At this point, it is important to acknowledge the ongoing scientific debate regarding the assumption of carbon neutrality for biomass combustion. In LCA studies, waste-derived biomass is commonly treated differently from biomass intentionally cultivated for energy production. Most waste-based LCA approaches apply the so-called "zero-burden" assumption, according to which waste enters the system without upstream environmental impacts associated with its generation. Consequently, only emissions related to waste collection, transport, treatment, and subsequent material or energy recovery are included in the system boundaries [9–12]. This approach is widely applied to municipal solid waste, food waste, and sewage sludge, which are generally considered by-products of other human activities rather than purpose-produced energy resources [9–12]. In contrast, when biomass is cultivated specifically for energy generation or bio-based products, LCA studies generally include upstream environmental impacts such as cultivation inputs, fertilizer use, land-use change and transport [13–16].

However, several studies have emphasized that this assumption may become problematic when waste-derived biomass has a significant economic value or competes with alternative material or energy uses [9,10,17]. Therefore, a broadly accepted approach within the research community is to apply the zero-burden assumption only to genuine waste or by-product biomass streams with low economic function, while fully accounting for upstream emissions in the case of purpose-grown biomass intended for energy recovery. Under this framework, waste-to-energy (WtE) systems characterized by a higher biogenic fraction may achieve more favorable GHG balances through the displacement of fossil fuel-based electricity and heat production [2,3,5,18–20].

https://doi.org/10.3390/en19112716

The IPCC Guidelines (2006) provide average values of biogenic carbon content for individual municipal waste fractions, on the basis of which the share of biogenic carbon in European MSW is estimated to range from approximately 33% to 50% [21]. Direct measurements conducted at Swedish waste incineration plants indicated that the average share of fossil carbon in combusted waste was approximately 47–48% [22], while in the Netherlands, the fossil carbon share in waste incineration is assumed to be approximately 51% [23]. However, the data currently applied in IPCC methodologies may be partially outdated due to changes in material production, packaging composition and consumption patterns. Moreover, the IPCC methodology does not provide detailed information regarding the biogenic carbon content in fine waste fractions (<20 mm), despite their potentially significant contribution to the overall waste stream. Therefore, reliable assessment of the renewable energy share and GHG emissions associated with waste treatment requires detailed site-specific waste characterization studies. In particular, determination of biomass content and its chemical energy potential in residual MSW remains essential for accurate estimation of renewable energy recovery and climate impacts [24–28].

In addition to residual waste, separately collected municipal biowaste represents another important source of waste-derived renewable energy. Source-separated kitchen waste, food waste, garden waste and other biodegradable fractions are particularly suitable for AD processes leading to biogas and/or biomethane production [29–31]. The energy recovery potential of such waste streams depends strongly on their biodegradability, as it is directly linked to methane generation potential, which is commonly evaluated through biogas or methane potential tests [31,32]. Easily degradable fractions, such as food waste, generally exhibit substantially higher methane yields than lignocellulosic or structurally complex materials such as garden waste, which are often more suitable for thermochemical conversion technologies [31,32]. Consequently, both the quantity of separately collected biowaste and its material composition, particularly the share of easily biodegradable organic matter, determine the actual renewable energy potential of this stream [17,18,30–32].

Waste management is recognized as a significant contributor to global GHG emissions; therefore, assessment of current emissions and evaluation of mitigation potential under future management scenarios are essential. A recent global LCA study estimated average emissions from municipal waste management at 89.70 kg CO_2-equivalent per ton of waste handled, ranging from 49.27 kg CO_2-eq/ton in high-income countries to 128.11 kg CO_2-eq/ton in low-income countries [33]. Open dumping was identified as the dominant source of emissions, contributing nearly 70% of total GHG emissions, followed by collection and transport, unmanaged landfills, sorting operations, controlled landfills, sanitary landfills and composting. In contrast, recycling of recoverable fractions and energy recovery through AD and waste incineration may provide substantial environmental benefits and emission reductions.

Recent EU scenario modeling demonstrated that highly integrated waste management systems may even transform the MSW sector into a net carbon sink [34]. The lowest net GHG emissions were estimated for Austria (−490 kg CO_2-eq/ton), whereas the highest values were reported for Greece (539 kg CO_2-eq/ton), with an average value of 49 kg CO_2-eq/ton, consistent with the findings of [33]. In these systems, GHG emissions are primarily associated with landfilling, incineration and recycling operations, with landfilling contributing up to 74% of total emissions. Conversely, GHG savings are mainly associated with material and nutrient recovery (15–64%), as well as energy recovery processes (0–22%). However, most existing large-scale studies are based primarily on literature data, national statistics and databases such as Eurostat, and therefore involve a relatively high level of generalization. As a consequence, they often do not adequately account for local conditions, including specific waste composition, collection efficiency or the operational performance of waste treatment facilities. In the context of increasing climate-related challenges, there is a growing need for more detailed local analyses capable of accurately estimating current GHG emissions and forecasting the effects of future waste management scenarios.

Therefore, this study presents an approach for assessing GHG emissions associated with municipal waste management in a city in Poland, taking into account both residual MSW and separately collected biowaste streams. The main objective of the study is to perform a detailed analysis of actual waste composition and waste characteristics in order to provide more accurate data regarding the energy recovery potential of the analyzed waste streams. Furthermore, the study aims to evaluate the potential contribution of these streams toward achieving climate policy objectives, including a 55% reduction in GHG emissions by 2035 and climate neutrality by 2050. Accordingly, the study includes analyses of waste quantity and composition, fuel properties, and renewable energy potential, which together determine the overall environmental performance of the waste management system. Finally, future waste management scenarios are evaluated in terms of energy recovery potential, renewable energy share, and associated GHG emissions, with reference to long-term climate neutrality targets.

2. Materials and Methods

The study addressed three key areas relevant to the evaluation of waste management systems: (i) morphological composition of selectively collected and residual municipal waste; (ii) biomass content and biodegradability of waste, including residual MSW, selectively collected biowaste; and (iii) fuel properties and renewable biomass content in residual MSW.

2.1. Study Location

The research was conducted in a Polish municipality with approximately 650 thousand residents and nearly 1 million inhabitants in the metropolitan area. The waste samples were collected over 12 months throughout 2023 to account for significant seasonal fluctuations in waste composition and technological properties.

2.2. Sampling

Samples were collected from fresh municipal waste delivered to a waste treatment facility. An approach of stratified sampling was used, with stratification based on the city's typical residential areas: (1) single-family housing, (2) multi-family estates, and (3) city center areas. Both residual waste and biowaste samples were collected directly after unloading from collection vehicles representing different collection routes (from the above-mentioned 3 typical residential areas). A composite sample (~100 kg) was prepared by combining ten subsamples (10 kg each) collected from evenly distributed sections of a ~0.5 m high waste pile, according to the method described in den Boer et al. [35].

2.3. Granulometric and Morphological Composition

The morphological composition of mixed municipal waste was analyzed using a methodology recommended by the Polish Ministry of Environment for waste characterization in projects funded by the National Fund for Environmental Protection [35–38]. The sampling scheme is shown in Figure 1. The research included granulometric analysis using 80 mm, 40 mm, 20 mm, and 10 mm sieves, morphological analysis of the >40 mm fraction, and physicochemical analysis of combustible material fractions with granulation of >40 mm (individually for each material) and fractions 20–40 mm (separation to biodegradable and non-biodegradable components), 10–20 mm, and <10 mm.

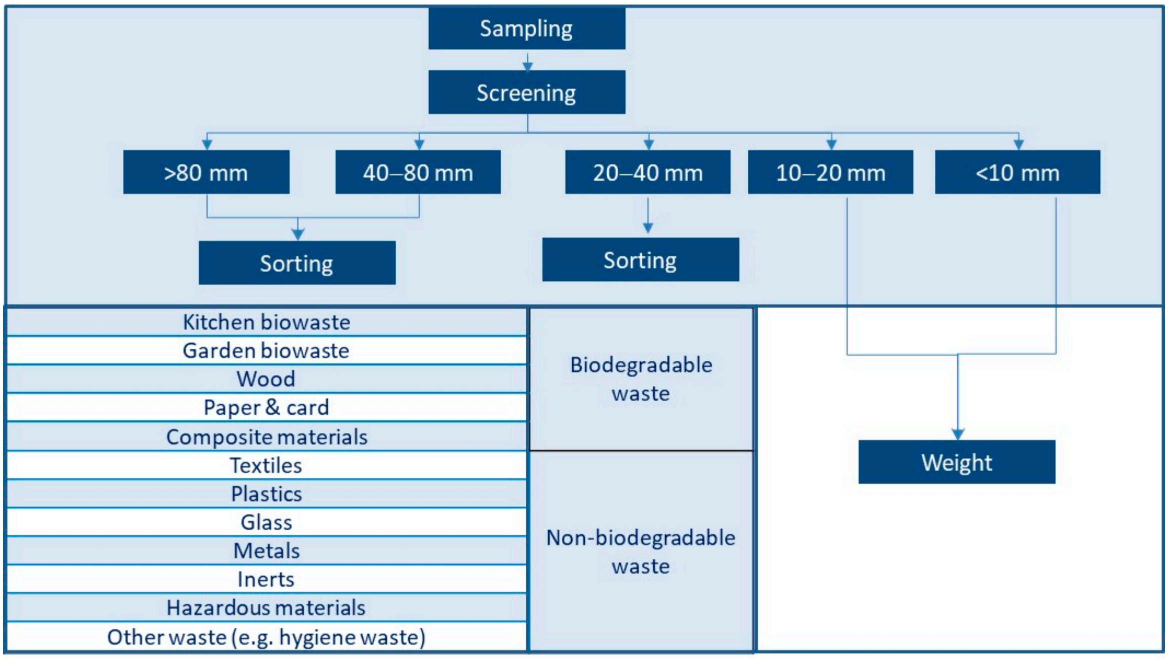

Figure 1. Sampling schedule of sorting analyses (modified from [35]).

2.4. Physicochemical Characterization

Most physicochemical analyses were conducted at the Laboratory of Water and Wastewater Treatment and Waste Management at the Wrocław University of Science and Technology using standardized PN-EN and PN-ISO methods and calibrated analytical equipment. All analyses were performed in accordance with standard methods commonly applied in waste characterization. Prior to analysis, waste was shredded and homogenized with the RETSCH SM 2000 cutting mill.

Standard analytical procedures were applied. Moisture content was determined by the oven-drying method (PN-EN 15934:2013 [39]). Loss on ignition (LOI) was measured according to PN-EN 15935:2013. Ash content was determined at 550 °C (PN-EN 15403:2011 [40]) and 815 °C (PN-ISO 1171:2002 [41]). The biomass content analyses were performed using the selective dissolution method (PN-EN 15440:2011 [42]). The scheme of analyses according to PN-EN 15440:2011 method is shown in Figure 2.

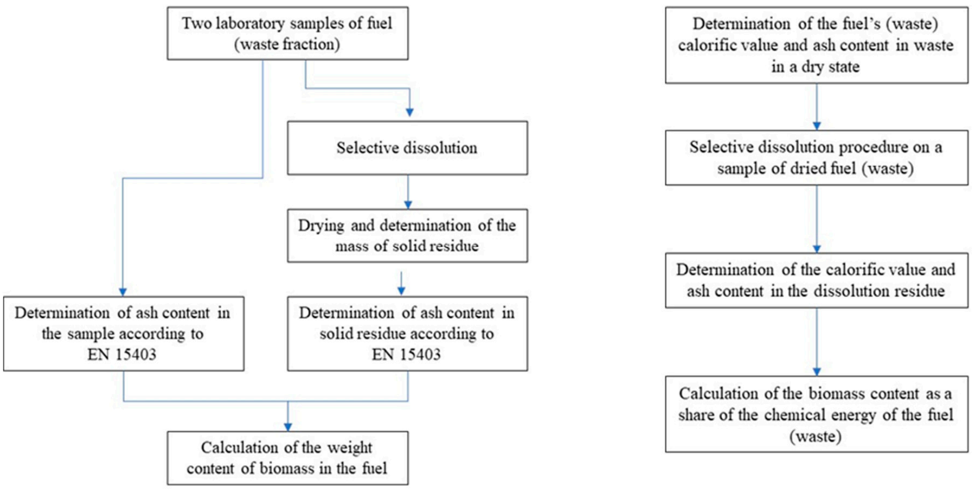

Figure 2. Procedure for determining the biomass content by weight (left) and the chemical energy content in the biodegradable and non-biodegradable fraction (right) using the selective dissolution method (PN-EN 15440:2011).

Biodegradability/biogas potential tests. Biogas potential (GB21) was determined according to VDI 4630 (2016) [43] by measuring biogas production over 21 days in eudiometers at 35 °C. Results were normalized to standard conditions and expressed per unit of dry mass. Additional experiments were conducted in a 20 L pilot-scale bioreactor (BFB 20, ROTAMETR, Gliwice, Poland) under controlled conditions (mixing 20 rpm, pH 6.5–7.0, temperature 35 °C). Biogas production and composition (CH_4, CO_2, H_2S, O_2) were monitored using a portable analyzer (MRU OPTIMA, Fuchshalde, Germany), with the following accuracies: ±0.3 vol. % absolute or 3% reading, both for CH_4 and CO_2; ±2 ppm H_2S absolute or 5% reading and ±0.2 vol. % O_2 absolute, or ±2% reading. The reactor was operated in fed-batch mode, with tests running for 21 days, excluding the initial lag phase. Approx. 1.5 kg biowaste samples were inoculated with 10 L of sewage sludge digestate and filled with distilled water (approx. 8 L). Net biogas production from biowaste was calculated by subtracting the biogas potential of the digestate.

Fuel properties and biomass content. Fuel properties (calorific value, ash, elemental composition) were determined according to PN-EN standards using a bomb calorimeter. Biomass content was assessed by selective dissolution (PN-EN 15440:2011), including drying, acid digestion, filtration, and ash determination. Results were expressed as mass and energy shares of biodegradable and non-biodegradable fractions.

2.5. Quality Control

To address the heterogeneity of municipal waste, measurements were performed in triplicate, and the obtained results are presented as mean values with standard deviations. Seasonal variability was addressed by determining the physicochemical properties for samples collected in four seasons and calculating annual average values together with variability ranges.

3. Results and Discussion

The following section presents the results of our investigations on the energy recovery potential of municipal waste generated in a selected Polish city, taking into account two waste streams: residual waste and separately collected biowaste.

3.1. Waste Composition

The energy potential of residual MSW depends on waste composition and fuel properties of individual waste fractions. In the following, the results of the yearly waste sorting analyses are presented. On an annual average, the highest share in the mass of waste is recorded by kitchen biowaste (17.0 ± 4.4%), plastics (14.4 ± 3.4%), paper and cardboard (13.4 ± 3.9%) and the 20–40 mm fraction (12.9 ± 4.1%), which mostly contains kitchen biowaste. The share of biowaste in fraction >40 mm is 18.2 ± 4.0%. However, the fines fraction also comprises significant shares of biowaste. Sorting of fraction 20–40 mm to biodegradable and non-biodegradable materials revealed very strong uniformity of this fraction, as the biodegradable materials' share was (97.8 ± 8.4%). Moreover, as sorting of the <20 mm fraction was not possible due to its high visual homogeneity, the overall biowaste content in this fraction was based on its organic matter content, amounting approx. to 50% (the exact data is presented in the following sections). Thus, the overall biowaste share amounts to approx. 35.9 ± 6.1%.

Waste composition shows significant fluctuations across seasons. Seasonal changes result primarily from different consumption patterns and vegetation growth, which are related to weather conditions. Thus, for the purposes of further assessment and to improve the clarity and comprehensiveness of data interpretation, the morphological composition and fuel properties of the waste were averaged across the four seasons. Figure 3 presents the seasonal composition of residual MSW. Summer months can be characterized by the highest shares of material categories comprising beverage packaging (plastics—16.1 ± 3.8%, glass—7.5 ± 2.7% and composite materials—6.5 ± 2.2%), which is associated with higher temperatures and greater beverage consumption compared to other seasons. Moreover, it is accompanied by the highest paper and card share (15.9 ± 4.7%) and the lowest kitchen waste share (13.6 ± 3.6%). The latter may be attributed to the fastest biodegradation and disintegration of this fraction, which already takes place during waste collection. The other seasons show generally lower dry recyclables contents and higher kitchen waste shares, which strongly influence the energy content of residual MSW across seasons.

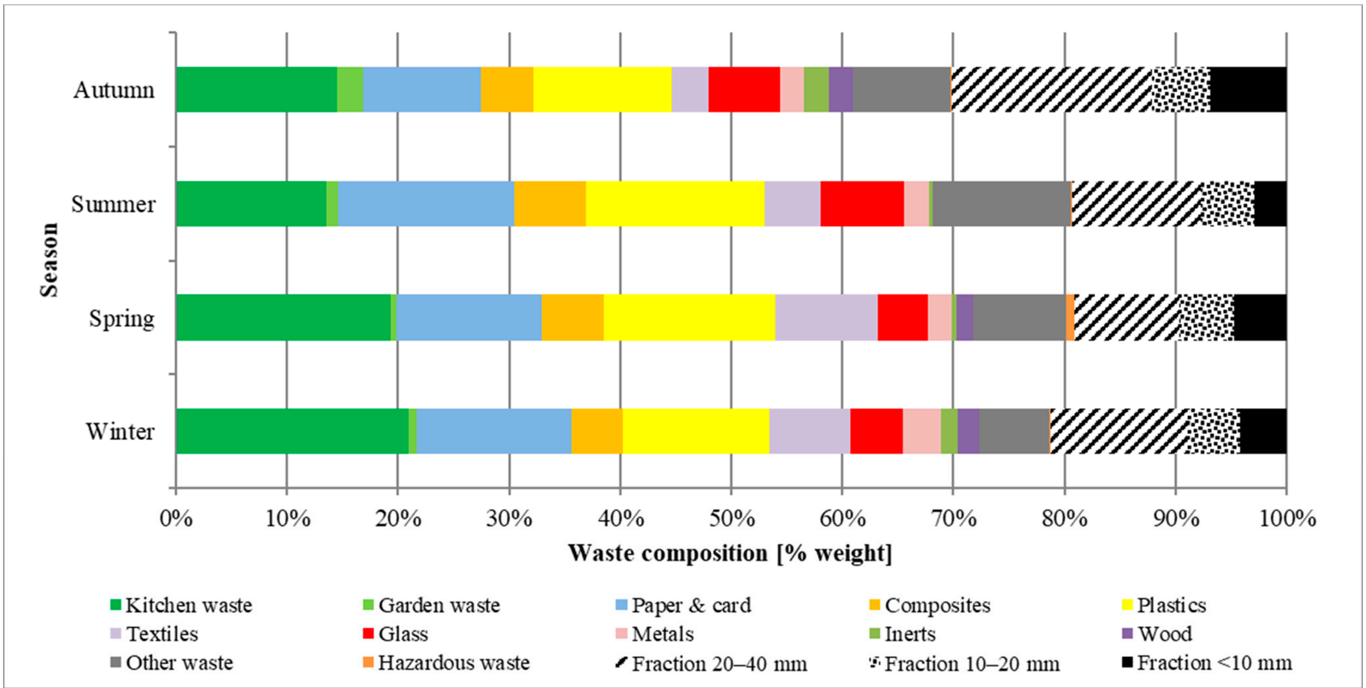

Figure 3. Variability of the morphological composition of mixed (residual) municipal waste.

The data presented in Figure 3 represent aggregated results derived from a more detailed analysis of individual granulometric fractions, as shown in Figure 4. Figure 4 illustrates the seasonal variability of the morphological composition of residual waste in the >80 mm and 40–80 mm fractions, as well as the mass share of sieve fractions below 40 mm. The >80 mm and 40–80 mm fractions were analyzed separately due to the intended applicability of the results for future prognostic and scenario analyses. The >80 mm fraction accounted for 52.9–57.0% of the total residual waste mass, with an average share of 54.7 ± 1.9%. This fraction was dominated by combustible materials, primarily plastics, paper and cardboard, and kitchen biowaste. As discussed in the following sections, the physicochemical properties of materials contained in this fraction are generally more favorable for energy recovery compared with the corresponding properties of the 40–80 mm fraction. However, the share of the >80 mm fraction in residual MSW is expected to decrease with increasing efficiency of separate waste collection systems and material recycling. Therefore, from a prognostic perspective, determination of the contribution of individual granulometric fractions is essential for predicting future changes in the energy recovery potential of residual waste streams.

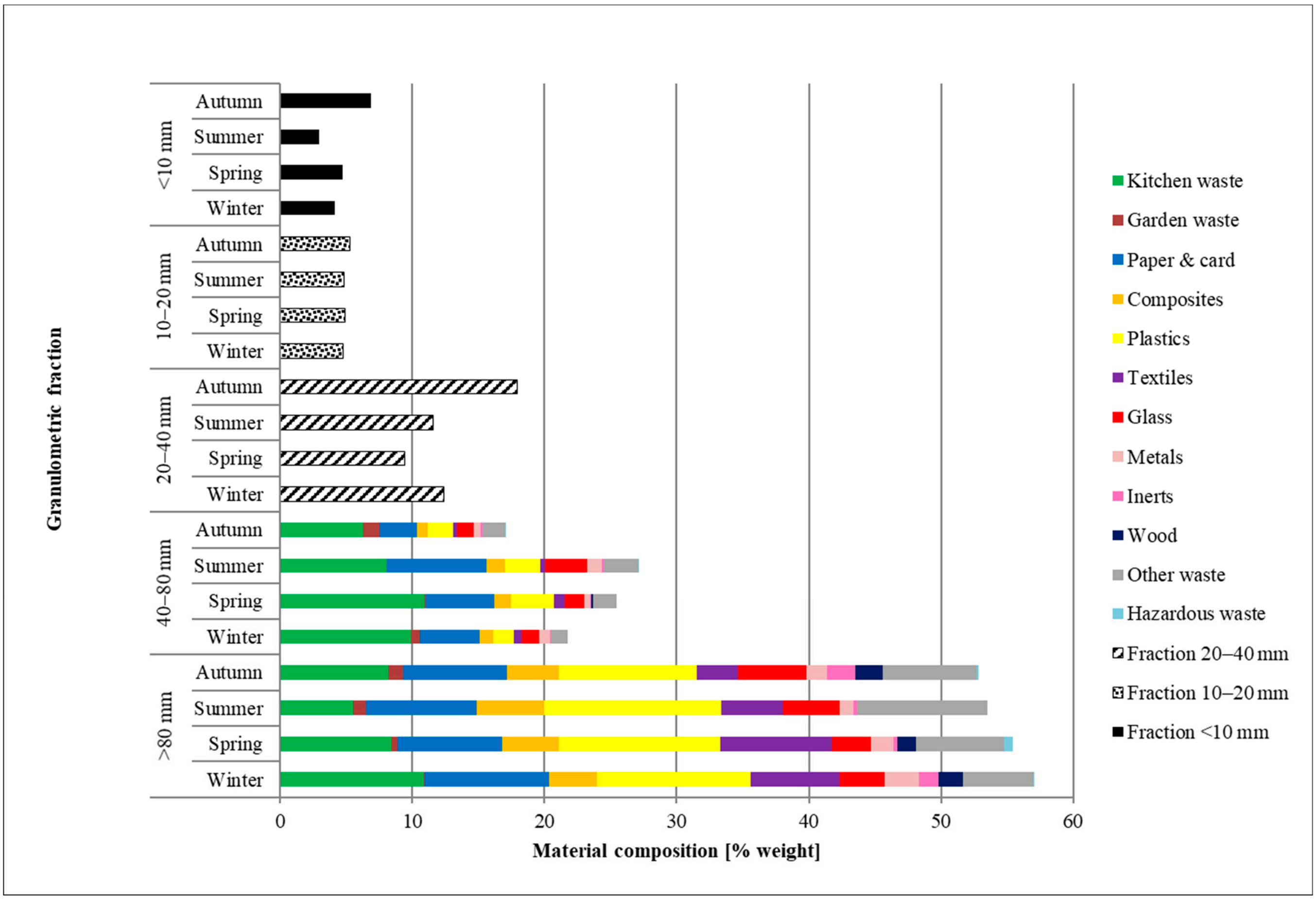

Figure 4. Variability of the material composition of the >80 mm and 40–80 mm fractions of residual waste.

The 40–80 mm fraction constituted between 17.0 and 27.2% of the waste mass, with an average share of 22.8 ± 4.5%. This fraction consisted mainly of kitchen biowaste, paper, and cardboard. The share of the 20–40 mm fraction ranged from 9.4% in spring to 17.9% in winter, with an annual average of 12.8 ± 3.6%. The 10–20 mm fraction accounted for 4.9 ± 0.2% of the waste mass, while the <10 mm fraction represented 4.7 ± 1.6%. As expected, the fine fraction content was lowest in summer (2.9%) and highest in autumn (6.9%).

3.2. Waste Properties

In addition to waste composition, the variability of the technological properties of waste was also evaluated. To enable further prognostic analyses and scenario development, the technological properties were determined separately for each morphological material category and granulometric fraction. It can be expected that in the future the composition of residual MSW will change due to, inter alia, higher separate collection and recycling rates, as stipulated by the CE goals. The determined physicochemical properties of individual morphological/granulometric fractions will be used to estimate the properties of residual waste characterized by different morphological compositions, thereby enabling simulation and forecasting of waste properties under projected future waste management scenarios. Figure 5 presents the calorific values (lower heating values, LHV) of granulometric waste, averaged across the seasons.

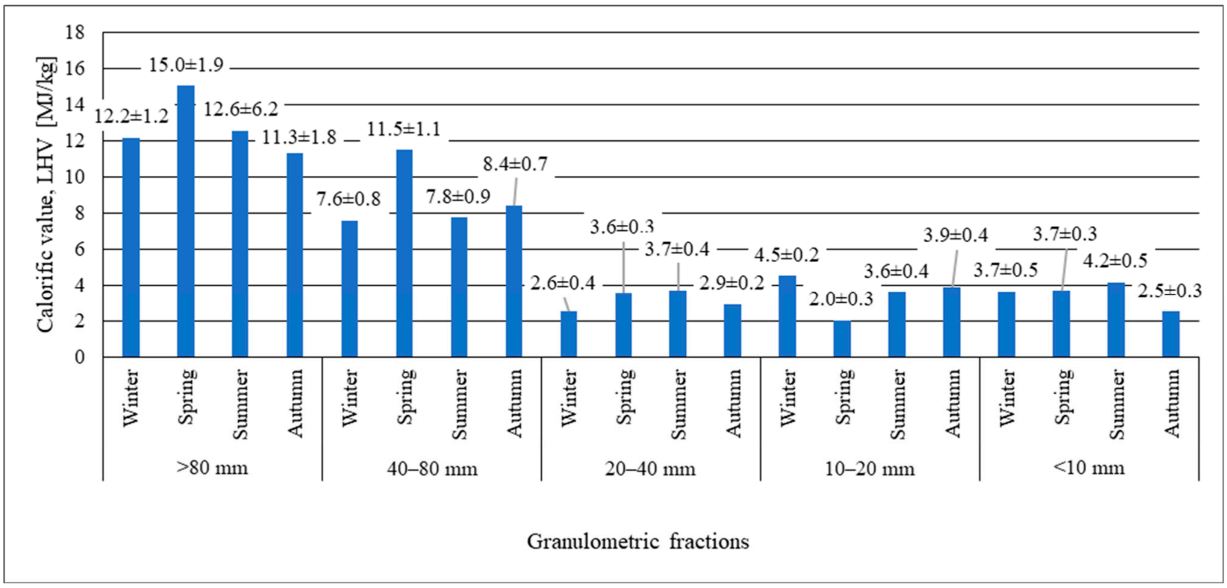

Figure 5. Seasonal changes in the calorific value of the granulometric fraction of residual waste during the year.

Overall, the >80 mm fraction exhibited the highest calorific value, ranging from 11.3 to 15.0 MJ/kg, with an average value of 12.8 ± 1.6 MJ/kg. This fraction consists predominantly of combustible and recyclable materials; therefore, its composition and fuel properties are expected to change with the further development of separate collection systems and increasing recycling rates of municipal solid waste (MSW). The 40–80 mm fraction showed an average calorific value of 8.8 ± 1.8 MJ/kg, ranging from 7.6 to 11.5 MJ/kg, indicating that this fraction also possesses significant energy recovery potential. Its lower calorific value compared with the >80 mm fraction is primarily associated with a lower content of high-calorific materials, such as plastics and composites, as well as higher moisture content. Fractions below 40 mm exhibited substantially lower calorific values, generally below the threshold for autothermal combustion (5.8 MJ/kg), mainly due to their relatively high moisture content. This results from a strong domination of these fractions by the biodegradable organics. In the current state, those fractions are not suitable for energy recovery. The overall calorific value of residual waste was highest in spring (11.8 ± 1.4 MJ/kg) and lowest in autumn (8.4 ± 0.9 MJ/kg), with an annual average value of 9.8 ± 1.5 MJ/kg. An important aspect of energy recovery from waste is the biomass content. The biogenic fraction in waste was determined using the selective dissolution method in accordance with PN-EN 15440:2011. The biomass content can be expressed as: mass share, energy share (calorific value or heat of combustion), and total carbon share. In this study, shares of biomass and energy from biomass fractions have been evaluated. Results of the selective dissolution of individual waste fractions are presented in Table 1.

Based on the results obtained, the shares of the biodegradable fraction in the dry mass (x_B) of waste and the shares of energy from the biodegradable fraction (X_B^{cal}—share of renewable energy) were determined. The mass shares of the biodegradable fraction are the highest for wood; kitchen and garden biowaste; fraction 20–40 mm and paper (89.1 ± 3.2; 85.8 ± 5.4; 85.7 ± 3.4 and 76.5 ± 1.2%TS, respectively), and the lowest for plastics (12.0 ± 12.7%TS). The share of the biodegradable fraction in plastics is related to the presence of biodegradable contaminants and packaging components (labels, adhesives). In the energy assessment, the highest shares of renewable energy sources are recorded by: wood; fractions 20–40 mm and <20 mm; paper; and kitchen and garden biowaste (99.1 ± 0.4; 92.0 ± 4.1 and 91.9 ± 4.1%). Similarly, the lowest value of the renewable energy source

(RES) index was found for plastics (6.7 ± 7.3%). The obtained results can be compared with literature data. Below, in Table 2, the commonly reported values for the mass and energy share of biomass in respective materials are provided.

Table 1. Energy characteristics of biodegradable components present in fractions >40 mm of residual waste, in accordance with PN-EN 15440:2011.

Parameter	Share of Biomass Fraction	Calorific Value of Non-Biomass Fraction	Calorific Value of Biomass Fraction	Share of Energy from Biomass (RES Index)
Norm-based designation	x_B	$q_{NB,daf}$	$q_{B,daf}$	X_B^{cal}
Unit	%TS	MJ/kg VS	MJ/kg VS	%
Kitchen and garden biowaste	85.8 ± 5.4	40.5 ± 2.5	17.7 ± 1.5	91.9 ± 4.1
Paper and card	76.5 ± 1.2	24.8 ± 3.4	17.4 ± 1.7	92.0 ± 4.1
Composites	62.4 ± 2.4	38.1 ± 3.2	14.3 ± 2.7	47.1 ± 10.3
Plastics	12.0 ± 12.7	39.0 ± 1.1	17.6 ± 0.5	6.7 ± 7.3
Textiles	68.4 ± 5.1	39.8 ± 1.9	20.9 ± 0.6	57.5 ± 11.6
Wood	89.1 ± 3.2	19.1 ± 1.8	19.1 ± 0.8	99.1 ± 0.4
Other waste	51.4 ± 6.0	34.7 ± 4.2	16.4 ± 0.6	41.7 ± 8.6
20–40 mm	85.7± 3.4	3.4 ± 0.6	17.6 ± 1.6	97.8 ± 2.1
<20 mm	51.5 ± 2.1	2.8 ± 0.3	17.5 ± 1.9	96.9 ± 4.5

TS—total solids; VS—volatile solids; daf—dry, ash free.

Table 2. Reported mass and energy shares of biomass in waste components.

Fraction (Examples)	Share of Biomass Fraction—X_B (%TS)	Share of Energy from Biomass X_B^{cal} (%)	Source
Kitchen/garden biowaste, wood	86–89	92–99	[17,44]
Paper and card	77	92	[45,46]
Plastics	12	7	[47–49]
Textiles, composites, other waste	51–68	42–58	[47–49]

High shares of biomass and energy from biomass for kitchen waste, paper and wood are consistent with their mainly biogenic origin and high degradable organic carbon content [17,45,46]. Plastics show low biomass share and very low renewable energy share, matching studies where plastics dominate the fossil fraction in mixed fuels [47–49]. Intermediate values for textiles, composites and "other waste" reflect mixtures of biogenic (e.g., cotton, wood) and fossil (e.g., synthetic fibers, plastics) materials [47–49].

Similar ranges for overall waste-derived fuels (around 40–50% biomass energy share) are reported when comparing selective dissolution (SD) and radiocarbon (^{14}C) methods, though SD can overestimate biomass in some cases [47–49].

Figure 6 presents the average calorific values of residual waste components and the energy shares of the biomass fraction (RES) in the analyzed MSW, which can be used to calculate the fuel properties and RES share for waste of various compositions.

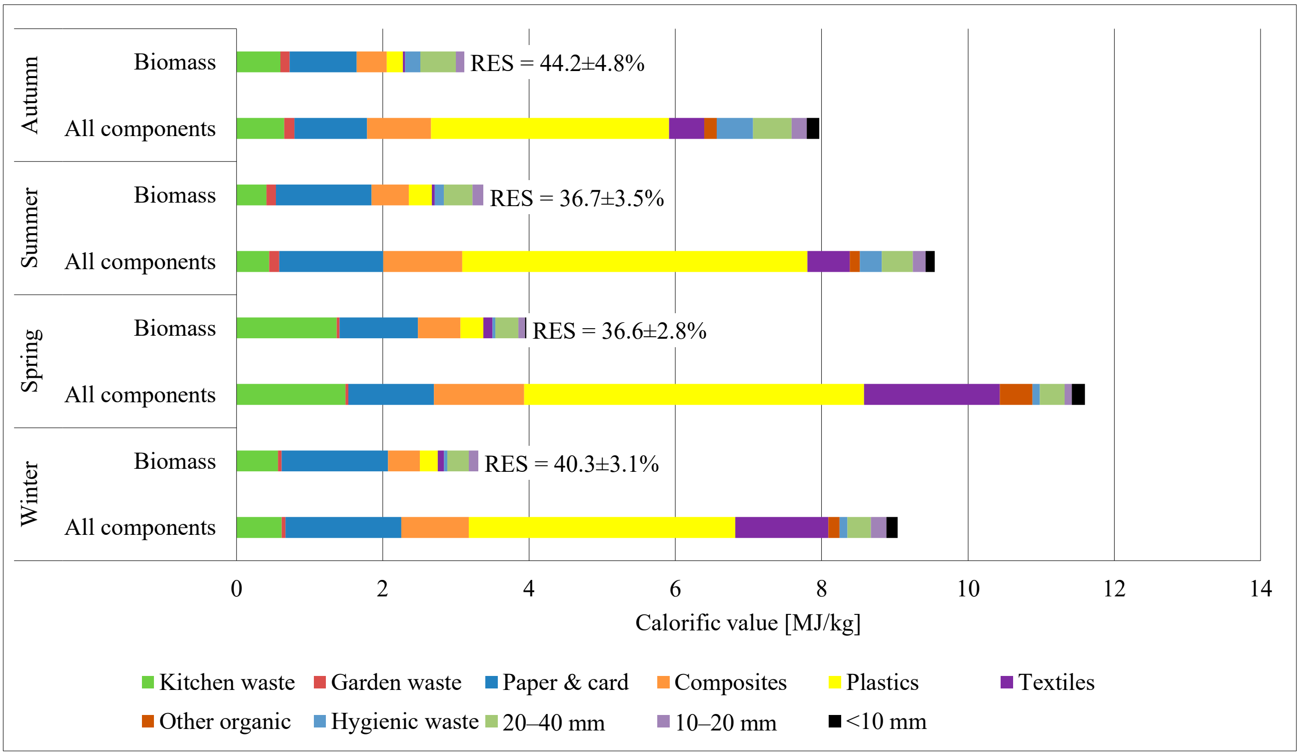

Figure 6. Variability of calorific values and renewable energy content in residual waste from a city.

The share of renewable energy sources (RES) in the evaluated residual municipal waste ranged from 36.6 ± 2.8% in spring to 44.2 ± 4.8% in autumn, with an annual average of 39.5 ± 3.6%. The RES content in residual waste is of key importance in the context of climate protection and GHG reduction targets. Based on the presented research results, a forecast of the renewable energy share generated through thermal recovery processes from residual waste will be developed, taking into account changes in the material composition of this waste stream.

3.3. Energy Recovery from Biowaste

Another important source of energy is separately collected biowaste. Biowaste can generally be considered biomass, except for contaminants, which are predominantly plastics. AD is the most common process used for energy recovery from biowaste, with the resulting digestate subsequently applied for land fertilization. In contrast to composting, this option enables not only the closure of the organic matter cycle but also provides an additional benefit in the form of renewable energy production. However, AD is also associated with certain environmental impacts, resulting, inter alia, from excessive feedstock pretreatment as well as unavoidable methane emissions. The determination of RES potential from separately collected biowaste differs from the assessment of residual waste intended for incineration, as energy in this case is recovered through microbial conversion processes. To establish the overall energy balance of AD systems, data on the biogas potential of biowaste is required. The following section therefore presents the results of the biogas potential assessment of municipal biowaste.

The properties of selectively collected biowaste were determined using samples collected after transportation to the treatment facility. However, observations made during the sampling campaign indicated that, at that time, only garden waste was being separately collected to a significant extent. Although the collection of kitchen waste together with garden waste had already been implemented, it had not yet resulted in a noticeable change in the composition of the collected biowaste stream. Most kitchen waste was still found in the residual waste fraction. Therefore, the following section primarily presents the characteristics of green waste. Nevertheless, it is expected that the share of kitchen waste in the separately collected biowaste stream will gradually increase in the future. To obtain data representative of the future biowaste stream potential, kitchen biowaste used for the analyses was additionally separated from residual waste. At the time the research was conducted, this was the only feasible approach to obtain data on the kitchen biowaste stream. However, these data should be interpreted with caution, as they may involve a certain degree of bias. Nevertheless, this approach enabled the inclusion of kitchen waste in the subsequent scenario modeling, assuming that the separately collected biowaste stream would also contain this fraction in the future.

The seasonal variability of the properties of selectively collected biowaste throughout the year is illustrated in Figure 7. The figure presents the moisture content, organic matter content, and biogas potential determined during the 21-day test (GB21). Clear seasonal trends in moisture content can be observed, with the lowest water content recorded in summer (27.6 ± 1.1%) and the highest in autumn (57.6 ± 3.6%). The loss on ignition of green waste ranged from 70.4 ± 2.6% VS in winter to 78.15 ± 2.8% VS in summer. Interestingly, these results do not directly correspond to the observed biogas potential, which was highest in spring (165.7 ± 11.3 dm^3/kg TS) and lowest in winter (62.3 ± 7.2 dm^3/kg TS). This can be explained by the different composition and characteristics of garden waste during the vegetation season, when the biomass consists mainly of fresh grass and other green plant material, in contrast to the relatively dry and partly decomposed plant residues dominating in the autumn and winter periods. Consequently, the biogas yield per unit mass is substantially lower in autumn and winter than in the spring and summer seasons. The average annual biogas yield from garden biowaste was 111.4 ± 35.5 dm^3/kg TS, with an average methane content of 63.8 ± 1.2%.

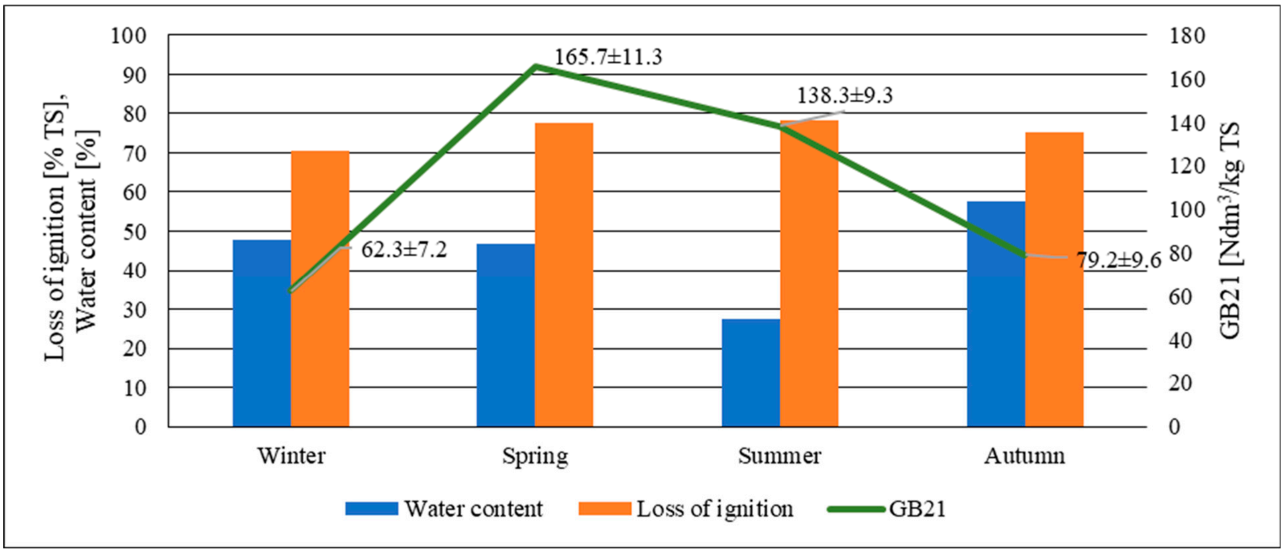

Figure 7. Variability of technological properties of collected garden waste depending on the season.

In the case of kitchen waste, the average technological properties exhibited lower seasonal variability. The moisture content ranged from 56.1 ± 4.1% to 74.2 ± 3.1% (Figure 8). The loss on ignition was lowest in summer (72.9 ± 4.1%TS) and remained relatively stable during the other seasons, ranging from 84.9 ± 2.1%TS to 86.8 ± 1.9%TS. Biogas production was highest in winter (377.0 ± 12.1 Ndm^3/kg TS) and lowest in autumn (277.2 ± 11.8 Ndm^3/kg TS). The average annual biogas yield from kitchen biowaste was 317.9 ± 42.7 Ndm^3/kg TS, with an average methane content of 68.3 ± 1.3%.

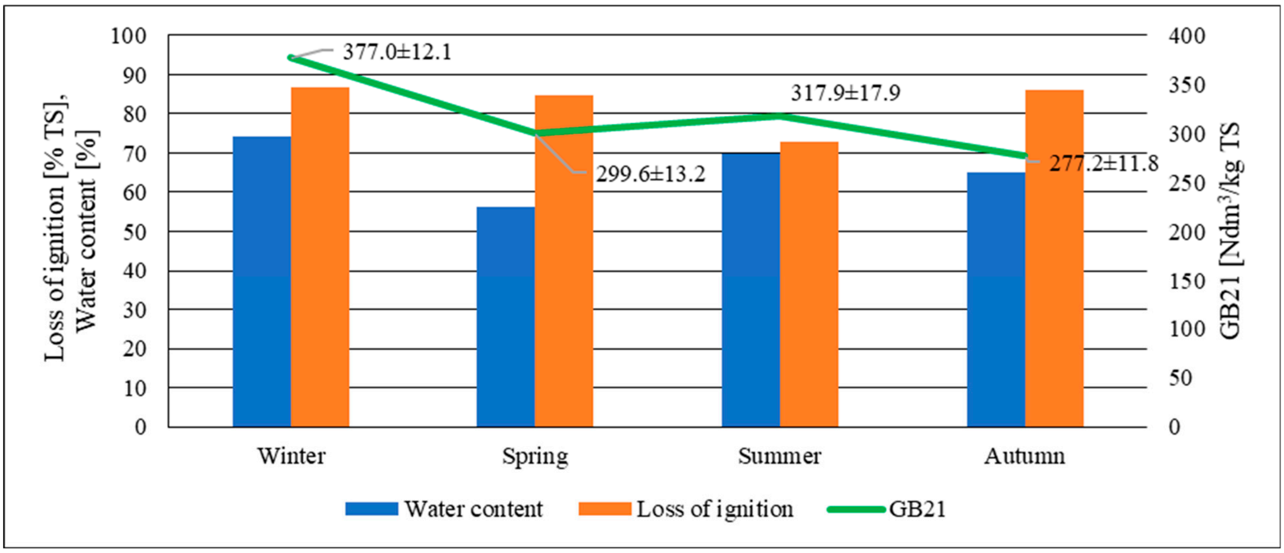

Figure 8. Variability of technological properties of collected kitchen waste depending on the season.

Overall, it should be emphasized that kitchen waste exhibits an average annual biogas production potential (317.9 ± 42.7 Ndm^3/kg TS) nearly three times higher than that of green waste (111.4 ± 35.5 Ndm^3/kg TS). This makes kitchen waste significantly more suitable for energy recovery through biogas production via AD.

The overall energy potential of waste was evaluated for a selected municipality in Poland, taking into account the current quantities of separately collected biowaste and residual waste. In forecasting future waste quantities, it was assumed that, in order to meet the European CE targets, increasing amounts of waste materials will be diverted to material recycling in order to satisfy the 2035 65% MSW recycling target. Consequently, the residual waste stream is expected to decrease significantly (Figure 9). This quantitative forecast was combined with a projected change in waste composition, representing a worst-case scenario in terms of energy recovery. However, many uncertainties remain regarding whether such a scenario is realistic and achievable in practice. From the current perspective, it may be considered an idealized scenario reflecting the full implementation of CE objectives.

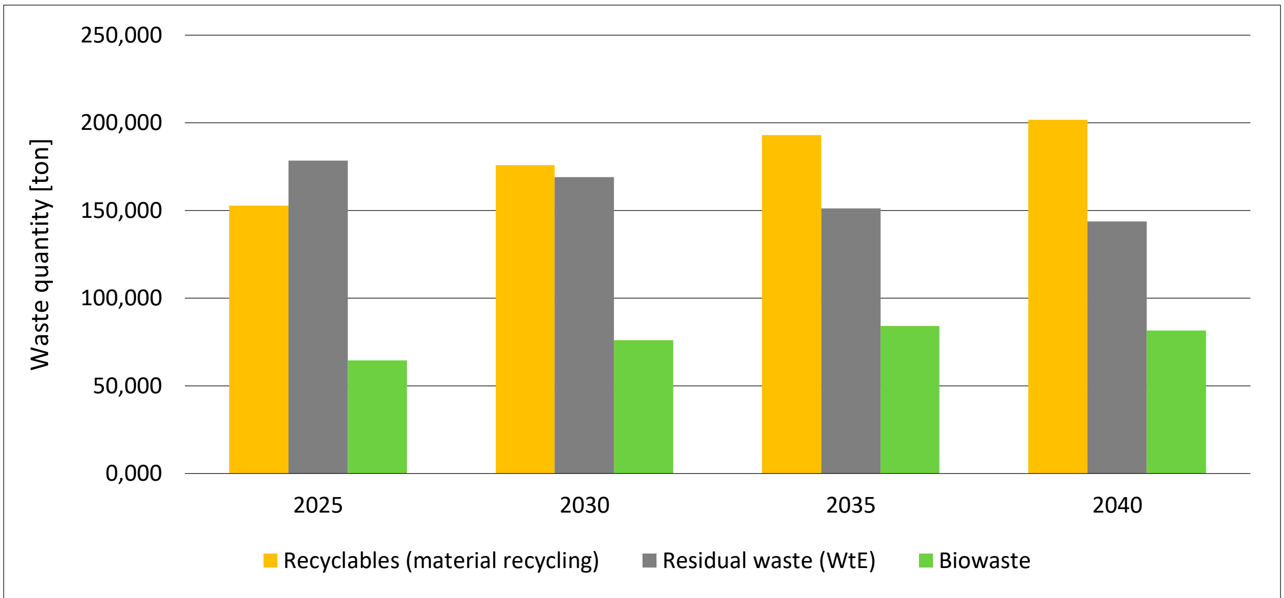

Figure 9. Waste streams available for material recycling and energy recovery.

The main results of these analyses are presented below in order to place the obtained analytical data on energy potential into a broader context. The efficiency coefficients applied for the energy recovery operations were based on literature data from existing AD plants operating in Germany and Poland [31,50].

Based on previously established waste energy potentials and taking into account the average efficiencies of energy recovery, the total energy balance was calculated for the given scenario. Figure 10 presents the share of RES in electricity generated from waste in the years 2025–2040, which overall increases from 46.1 ± 3.9% to 49.9 ± 4.1%. In relation to the total electricity demand for the analyzed municipality, energy from waste accounts for 1.8 ± 0.3% in 2025 to 1.3 ± 0.2% in 2040.

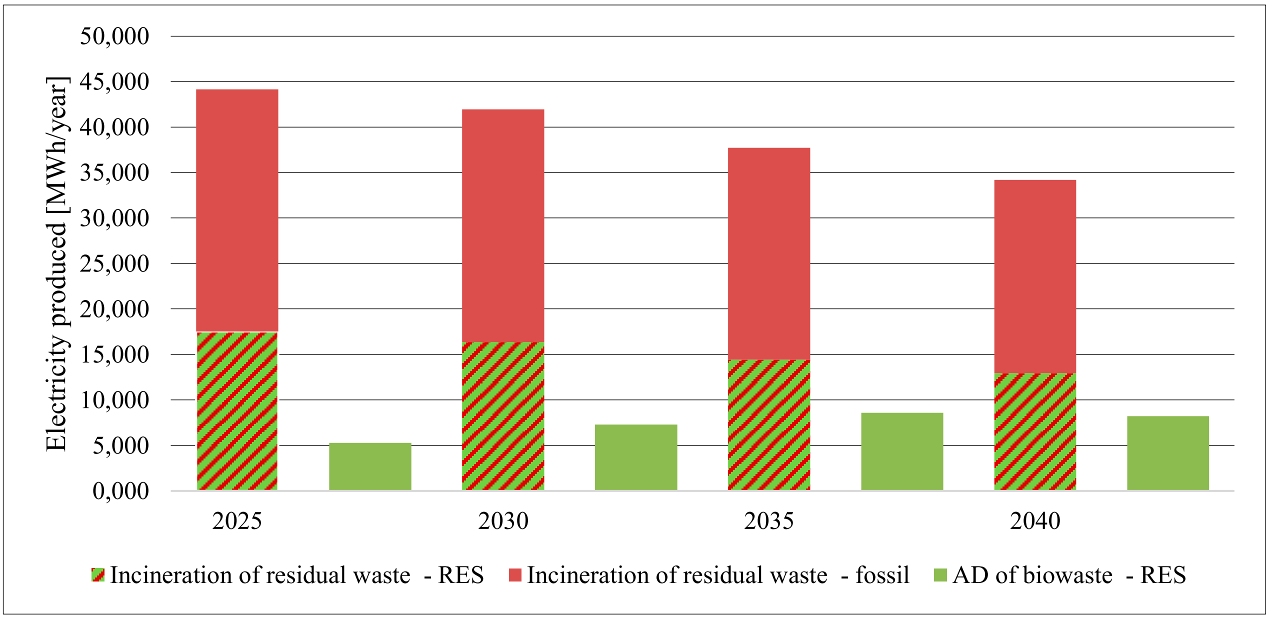

Figure 10. Prognosis of net electricity production in the waste-to-energy scenario in 2025–2040.

The total amount of electricity that can be extracted in 2025 is 49,413 ± 345 MWh, with 89.3 ± 3.1% coming from residual MSW. Subsequently, a gradual decline to 42,429 ± 328 MWh is forecast by 2040. During this period, the share of electricity generated through AD increases (from 10.7 ± 1.3% in 2025 to 19.4 ± 2.2% in 2040). All energy generated through AD comes from renewable energy sources. In the case of an incineration plant, this depends on the share of energy from biomass in the final energy balance. Based on the residual waste composition prognosis, the share of renewable energy in residual waste changes during this period from 39.7 ± 3.3% in 2025 to 37.8 ± 2.9% in 2040.

In the case of heat production, the situation is quite similar. In 2025, the amount of heat that can be recovered from waste is the highest, at 199,7 ± 12.8 MWh, decreasing to approximately 167.3 ± 10.8 MWh by 2040. The share of heat generated by the WtE is even slightly higher than that of electricity, accounting for 92.1% in 2025 and 85.1% in 2040 of the total amount of heat recovered from waste. In this case, the total share of heat from renewable energy sources ranges from 44.5% in 2025 to 47.0% in 2040. The total heat demand for the city that can be substituted by energy from waste is very similar to that of electricity, ranging from 1.9% in 2025 to 1.2% in 2040.

3.4. Carbon Footprint of Energy Recovery from Municipal Waste (Residual Waste and AD of Biowaste)

Figure 11 shows the GHG emission balance for the analyzed residual waste and biowaste management options. These data do not include emissions related to the recycling of raw materials selectively collected and separated from residual waste, as these processes were assumed to be the same for both options and are not included in the analysis. The obtained results present a comparison of the emission balance calculated according to the IPCC methodology under the assumptions described previously, without taking into account avoided emissions from substituted fossil energy sources. The results are presented as an overall waste management system and as unit emission per ton of treated waste. The base year (1988) was based on the sole landfilling of all waste without any separate biowaste collection. Overall, GHG emissions from the waste management system decreased from 767 ± 42 kg CO_2-eq/ton to 415 ± 23 kg CO_2-eq/ton when the energy recovery system was included. This is a result of changes introduced in waste management over the last three decades—particularly the requirement to process the entire waste stream before landfilling. The emission forecast from the analyzed waste management options indicates the possibility of achieving further reductions. Total projected emissions are 87.823 ± 4729 ton CO_2-eq/year (390 ± 21 kg CO_2-eq/ton) in 2040, representing a 37.6% reduction compared to the base year. In this scenario, the thermal process generates by far the highest emissions.

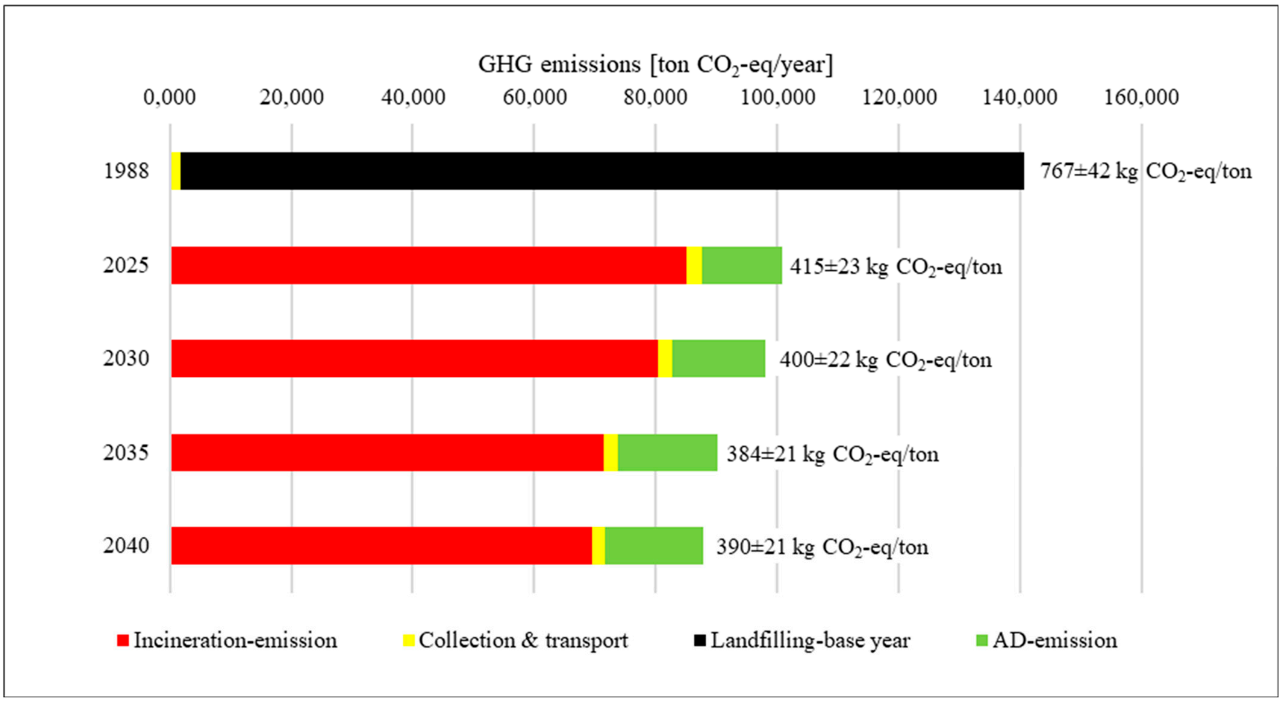

Figure 11. Cumulative and specific GHG emissions when implementing energy recovery from residual MSW and biowaste.

According to the IPCC methodology, the GHG balance includes emissions generated during the analyzed processes but does not include credits from avoided products such as energy or fertilizers. This methodology was developed to balance global emissions, not individual subsystems. Generally, products obtained from waste have a positive impact on a global scale by replacing conventional processes (e.g., energy production), which contributes to reducing total GHG emissions. The LCA methodology, in accordance with the standard (ISO 14044:2006, 2006) and its application guidelines, allows for the inclusion of benefits associated with the generation of by-products and services in the analyzed system. If the waste management system produces additional products (e.g., fertilizer or electricity), the credits related to these should be taken into account as environmental benefits resulting from replacing conventional processes for producing these products in the economy, in the form of so-called "avoided emissions" referred to as "credits". These are calculated in amounts proportional to the amount of "recovered" materials or energy (ISO 14044:2006, 2006). Figure 11 considers only emissions associated with each waste management option. In Figure 12, avoided emissions associated with replacing artificial fertilizers with compost and liquid digestate resulting from AD of biowaste are also taken into account. Furthermore, the replacement of electricity and heat by energy recovered from waste is also taken into account, both in the AD plant and in the incineration plant. In the latter case, avoided emissions resulting from the recycling of metals from slag are also taken into account. The total GHG emission balances, after taking into account avoided emissions, are negative, meaning that the replaced emissions exceed the actual GHG emissions from the analyzed waste management processes. Overall, net GHG emissions in the waste-to-energy variant are −17,534 ± 3682 ton CO_2-eq/year in 2025, and then the benefits are reduced to −12,829 ± 2694 ton CO_2-eq/year in 2040, which is associated with a reduction in the stream of residual waste directed for energy recovery. The unit emission factor is most favorable for 2035 (−81 ± 17 kg CO_2-eq/ton) and becomes reduced to −51 ± 12 kg CO_2-eq/ton, due to assumed diversion of waste to material recycling. Nevertheless, over the entire 2025–2040 period, the waste-to-energy system demonstrates a negative emission balance, so it is beneficial in terms of climate protection goals.

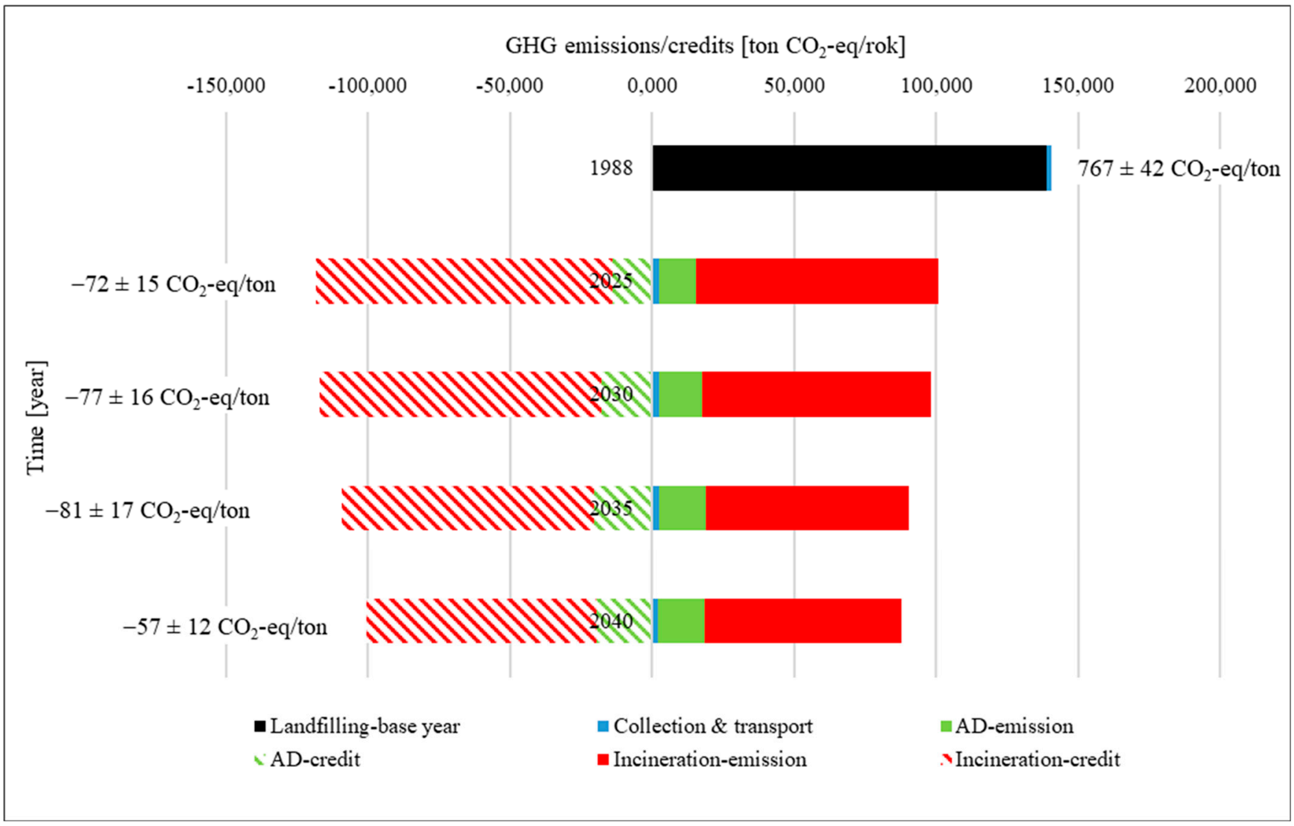

Figure 12. Cumulative and specific GHG emission balance when implementing energy recovery from residual MSW and biowaste.

These findings can be confronted with the global LCA study reported in [33], which estimated average emissions from municipal waste management in high-income countries at 49.27 kg CO_2-eq/ton of waste handled, while also emphasizing the substantial environmental benefits associated with recycling and energy recovery processes. The present study similarly confirms that recovery-oriented waste management strategies may substantially reduce net climate impacts, and the results may be more beneficial due to assumed high energy recovery efficiencies from residual MSW, which are related to the relatively new WtE infrastructure in Poland.

The obtained results are also in general agreement with the EU scenario modeling study [34], which demonstrated that highly integrated waste management systems may potentially transform the MSW sector into a net carbon sink. The unit emission factors obtained in the present analysis fall within the range reported for European countries, although they are less extreme than the lowest value estimated for Austria (−490 kg CO_2-eq/ton). Nevertheless, in the current study, only two waste streams were considered, and primarily for energy recovery purposes. If material recycling were also included, the overall emissions would have been even lower.

At the same time, the present results provide additional insights into the temporal change in the role of WtE systems under CE conditions. Similar to the conclusions of [34], the reduction in residual waste quantities resulting from increased recycling leads to a gradual decrease in the climate benefits associated with energy recovery. As more recyclable fractions are diverted from residual waste streams, the energy potential of the remaining waste decreases, reducing the magnitude of avoided emissions. This explains the observed reduction in net GHG savings between 2025 and 2040. Nevertheless, despite lower waste quantities and lower energy recovery potential, the system maintained a negative emission balance throughout the entire analyzed period, indicating that WtE may continue to provide complementary climate benefits even in highly recycling-oriented waste management systems.

Although energy recovery from waste is not a priority within the CE, it is a desirable option for managing waste that cannot be recycled. Biowaste and residual waste constitute the largest waste streams that can be used to produce energy. At the same time, due to their biomass content, they are partially considered climate-neutral. The overall yearly average calorific value of residual waste indicated in this study is 9.8 ± 1.5 MJ/kg. The prognosis results show that throughout the analyzed period, residual waste, despite being separated into a raw material waste stream for recycling, has a calorific value that allows it to be subjected to energy recovery processes. In the case of selectively collected biowaste, the biogas potential of kitchen waste shows an average annual biogas production potential (317.9 ± 42.7 Ndm^3/kg TS), being nearly three times higher than that of green waste (111.4 ± 35.5 Ndm^3/kg TS). This makes kitchen waste significantly more suitable for energy recovery through biogas production via AD, which is beneficial in terms of the predicted growth of the separate collection efficiency of this particular stream.

All energy generated in the AD process comes from renewable energy sources. In the case of incineration, this depends on the share of energy from biomass in the final energy balance. Based on waste collection results in 2025, 89.3 ± 3.1% of the total energy recovery balance consists of energy obtained from residual MSW. Considering the development of separate collection and recycling levels, and subsequent energy recovery from biowaste and residual MSW, the total share of renewable energy in electricity generated from waste between 2025 and 2040 increases from 46.1% to 49.9%. By 2040, the projected share of electricity generated in the AD process will increase to 19.4 ± 2.2%. It demonstrates the relation of both streams in terms of energy potential. Despite an increase in biowaste separate collection, the energy potential of residual MSW remains much higher. Based on the study results, the share of renewable energy from residual MSW changes over this period from 39.7% ± 3.3% in 2025 to 37.8 ± 2.9% in 2040.

Relative to the city's total electricity demand, energy from waste accounts for 1.8 ± 0.3% in 2025 and 1.3 ± 0.2% in 2040.

The study verified the feasibility of reducing GHG emissions by 55% by 2030 compared to 1990 and, in the longer term, contributing to achieving complete climate neutrality in waste management. The unit GHG emission factor (related to one ton of total managed biowaste and residual waste) is negative throughout the period 2025–2040, ranging from −72 ± 15 kg CO_2-eq/ton in 2025, through the most favorable value of −81 ± 17 kg CO_2-eq/ton in 2035, to −57 ± 12 kg CO_2-eq/ton in 2040. This means that the environmental benefit of recovering energy from waste is significant, and the waste management system generates negative emissions. In this context, the waste management system already meets the European Green Deal targets, both by 2030 and for climate neutrality in 2050.

However, it should also be underlined that despite a positive role of waste-to-energy in mitigating GHG emissions, air pollutant emissions—including PM, acid gases, heavy metals, dioxins/furans—remain as central environmental concerns associated with waste incineration [51–53]. While modern emission controls have reduced many regulated pollutants to low levels in developed countries [54], challenges remain regarding the following:

- Emerging contaminants: New toxic organics are being discovered that may not be fully regulated or understood in terms of health impact [53];
- Ash management: Fly ash remains a hazardous by-product requiring careful stabilization/disposal due to its heavy metal/dioxin content [54,55];
- Socio-political aspects: Public opposition persists due to perceived health risks and environmental justice concerns—especially where plants are sited near marginalized communities or where regulatory enforcement is weak [56].

This should be carefully taken into consideration when planning waste management strategies.

4. Conclusions

The study demonstrated that both residual MSW and separately collected biowaste constitute significant and complementary sources of renewable energy, supporting the role of WtE systems in the transition toward a circular and climate-neutral economy. Despite increasing recycling rates and separate collection efficiency, residual waste will remain the dominant energy carrier in the analyzed period due to its substantial calorific value, while kitchen biowaste shows particularly high suitability for renewable biogas production through AD. The analyzed waste management system achieved a consistently negative GHG emission balance throughout 2025–2040, confirming that optimized energy recovery from waste can substantially contribute to the European Green Deal objectives, including the reduction in GHG emissions and the achievement of climate neutrality. At the same time, the relatively limited contribution of WtE to total city electricity demand indicates that its strategic importance lies primarily in sound waste management, renewable energy substitution, and emission mitigation rather than large-scale energy supply. Nevertheless, environmental and social concerns related to waste incineration, including pollutant emissions, hazardous ash management, emerging contaminants, and public acceptance, must remain key considerations in the planning and development of future waste management systems.

Author Contributions: Conceptualization and methodology, E.d.B.; validation, J.d.B.; investigation, E.d.B., K.B. and I.P.; resources, E.H. and H.M.; data curation, Ł.K. and H.M.; writing—original draft preparation, E.d.B.; writing—review and editing, J.d.B., K.B. and I.P.; visualization, Ł.K. and E.H.; supervision, E.d.B.; funding acquisition, E.d.B. All authors have read and agreed to the published version of the manuscript.

Funding: Waste sorting analyses were performed with the support of municipal funding.

Data Availability Statement: Dataset available on request from the authors.

Conflicts of Interest: Elias Hakalehto was employed by Finnoflag Oy, 70101 Kuopio, Finland. Łukasz Kowalczyk was employed by K35 Usługi Przyjazne Środowisku Łukasz Kowalczyk, 63-040 Komorze, Poland. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Regulation (EU) 2021/1119 of the European Parliament and of the Council of 30 June 2021 Establishing the Framework for Achieving Climate Neutrality and Amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'). Available online: https://eur-lex.europa.eu/eli/reg/2021/1119/oj/eng (accessed on 1 March 2026).
2. Liu, B.; Rajagopal, D. Life-cycle energy and climate benefits of energy recovery from wastes and biomass residues in the United States. *Nat. Energy* **2019**, *4*, 700–708. [CrossRef]
3. Vasileiadou, A. From Organic Wastes to Bioenergy, Biofuels, and Value-Added Products for Urban Sustainability and Circular Economy: A Review. *Urban Sci.* **2024**, *8*, 121. [CrossRef]
4. Lawal, I.; Ndagi, A.; Mohammed, A.; Saleh, Y.; Shuaibu, A.; Hassan, I.; Abubakar, S.; Soja, U.; Jagaba, A. Proximate analysis of waste-to-energy potential of municipal solid waste for sustainable renewable energy generation. *Ain Shams Eng. J.* **2023**, *15*, 102357. [CrossRef]
5. Lombardi, L.; Castaldi, M. Energy Recovery from Residual Municipal Solid Waste: State of the Art and Perspectives within the Challenge to Climate Change. *Energies* **2024**, *17*, 395. [CrossRef]
6. Yaman, C.; Anıl, I.; Alagha, O. Potential for greenhouse gas reduction and energy recovery from MSW through different waste management technologies. *J. Clean. Prod.* **2020**, *264*, 121432. [CrossRef]
7. Sardarmehni, M.; Levis, J. Life-cycle modeling of nutrient and energy recovery through mixed waste processing systems. *Resour. Conserv. Recycl.* **2021**, *169*, 105503. [CrossRef]
8. Ryu, C. Potential of Municipal Solid Waste for Renewable Energy Production and Reduction of Greenhouse Gas Emissions in South Korea. *J. Air Waste Manag. Assoc.* **2010**, *60*, 176–183. [CrossRef]
9. Davis, T.; Mahmud, R.; McNaul, S.; Jamieson, M.; Lewis, E. A Comparative Analysis of Waste-as-a-Feedstock Accounting Methods in Life Cycle Assessments. *Hydrogen* **2025**, *6*, 74. [CrossRef]
10. Aldama, D.; Grassauer, F.; Zhu, Y.; Ardestani-Jaafari, A.; Pelletier, N. Allocation methods in life cycle assessments (LCAs) of agri-food co-products and food waste valorization systems: Systematic review and recommendations. *J. Clean. Prod.* **2023**, *421*, 138488. [CrossRef]
11. Hosseinzadeh-Bandbafha, H.; Nizami, A.; Kalogirou, S.; Gupta, V.; Park, Y.; Fallahi, A.; Sulaiman, A.; Ranjbari, M.; Rahnama, H.; Aghbashlo, M.; et al. Environmental life cycle assessment of biodiesel production from waste cooking oil: A systematic review. *Renew. Sustain. Energy Rev.* **2022**, *161*, 112411. [CrossRef]
12. Sfez, S.; Meester, S.; Vlaeminck, S.; Dewulf, J. Improving the resource footprint evaluation of products recovered from wastewater: A discussion on appropriate allocation in the context of circular economy. *Resour. Conserv. Recycl.* **2019**, *148*, 132–144. [CrossRef]
13. Wang, Z.; Huang, W.; Wang, H.; Gao, J.; Zhang, R.; Xu, G.; Wang, Z. Research on the improvement of carbon neutrality by utilizing agricultural waste: Based on a life cycle assessment of biomass briquette fuel heating system. *J. Clean. Prod.* **2024**, *434*, 140365. [CrossRef]
14. Wiloso, E.; Heijungs, R.; Huppes, G.; Fang, K. Effect of biogenic carbon inventory on the life cycle assessment of bioenergy: Challenges to the neutrality assumption. *J. Clean. Prod.* **2016**, *125*, 78–85. [CrossRef]
15. Weihs, G.; Jones, J.; Ho, M.; Malik, R.; Abbas, A.; Meka, W.; Fennell, P.; Wiley, D. Life cycle assessment of co-firing coal and wood waste for bio-energy with carbon capture and storage—New South Wales study. *Energy Convers. Manag.* **2022**, *273*, 116406. [CrossRef]
16. Gaffey, J.; Collins, M.; Styles, D. Review of methodological decisions in life cycle assessment (LCA) of biorefinery systems across feedstock categories. *J. Environ. Manag.* **2024**, *358*, 120813. [CrossRef]
17. Moretti, P.; De Araujo, M.; De Castilhos, B.; Buffière, P.; Gourdon, R.; Bayard, R. Characterization of municipal biowaste categories for their capacity to be converted into a feedstock aqueous slurry to produce methane by anaerobic digestion. *Sci. Total Environ.* **2020**, *716*, 137084. [CrossRef]
18. Marciniuk-Kluska, A.; Kluska, M. Energy Recovery from Municipal Biodegradable Waste in a Circular Economy. *Energies* **2025**, *18*, 2210. [CrossRef]
19. El-Fawal, E.; Naggar, A.; El-Zahhar, A.; Alghandi, M.; Morshedy, A.; Sayed, H.; Mohammed, A. Biofuel production from waste residuals: Comprehensive insights into biomass conversion technologies and engineered biochar applications. *RSC Adv.* **2025**, *15*, 11942–11974. [CrossRef]
20. Kalak, T. Potential Use of Industrial Biomass Waste as a Sustainable Energy Source in the Future. *Energies* **2023**, *16*, 1783. [CrossRef]

21. Johnke, B.; Hoppaus, R.; Lee, E.; Irving, B.; Martinsen, T.; Mareckova, K. *Emissions from Waste Incineration: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*; Intergovernmental Panel on Climate Change (IPCC): Geneva, Switzerland, 2001.
22. Mohn, J.; Szidat, S.; Zeyer, K.; Emmenegger, L. Fossil and biogenic CO_2 from waste incineration based on a yearlong radiocarbon study. *Waste Manag.* **2012**, *32*, 8. [CrossRef] [PubMed]
23. Palstra, S.; Meijer, H. Carbon-14 based determination of the biogenic fraction of industrial CO_2 emissions—Application and validation. *Bioresour. Technol.* **2010**, *101*, 10. [CrossRef]
24. Ilmas, B.; Dongbei, Y.; Khalid, S.; Mir, K. Characterization and energy potential evaluation of urban municipal solid waste of Pakistan. *Carbon Manag.* **2021**, *12*, 581–591. [CrossRef]
25. Martinez, C.; Rocha, E.; Carneiro, A.; Gomes, F.; Batalha, L.; Vakkilainen, E.; Cardoso, M. Characterization of residual biomasses from the coffee production chain and assessment the potential for energy purposes. *Biomass Bioenergy* **2019**, *120*, 68–76. [CrossRef]
26. Morales-Máximo, M.; López-Sosa, L.; Alvarado-Flores, J.; Alcaraz-Vera, J.; García, C.; Álvarez-Jara, M.; Rutiaga-Quinones, J. Multifactorial Assessment of the Bioenergetic Potential of Residual Biomass of *Pinus* spp. in a Rural Community: From Functional Characterization to Mapping of the Available Energy Resource. *Fire* **2023**, *6*, 317. [CrossRef]
27. Matheri, A.; Ntuli, F.; Ngila, J.; Seodigeng, T.; Zvinowanda, C.; Njenga, C. Quantitative characterization of carbonaceous and lignocellulosic biomass for anaerobic digestion. *Renew. Sustain. Energy Rev.* **2018**, *92*, 9–16. [CrossRef]
28. Rolewicz-Kalińska, A.; Lelicińska-Serafin, K.; Manczarski, P. The Circular Economy and Organic Fraction of Municipal Solid Waste Recycling Strategies. *Energies* **2020**, *13*, 4366. [CrossRef]
29. Pavlas, M.; Dvořáček, J.; Pitschke, T.; Peche, R. Biowaste Treatment and Waste-To-Energy—Environmental Benefits. *Energies* **2020**, *13*, 1994. [CrossRef]
30. Sarangi, P.; Srivastava, R.; Singh, A.; Sahoo, U.; Prus, P.; Sass, R. Municipal-Based Biowaste Conversion for Developing and Promoting Renewable Energy in Smart Cities. *Sustainability* **2023**, *5*, 12737. [CrossRef]
31. Seruga, P.; Krzywonos, M.; Seruga, A.; Niedźwiecki, Ł.; Pawlak-Kruczek, H.; Urbanowska, A. Anaerobic Digestion Performance: Separate Collected vs. Mechanical Segregated Organic Fractions of Municipal Solid Waste as Feedstock. *Energies* **2020**, *13*, 376. [CrossRef]
32. Bayard, R.; Benbelkacem, H.; Gourdon, R.; Buffière, P. Characterization of selected municipal solid waste components to estimate their biodegradability. *J. Environ. Manag.* **2017**, *216*, 4–12. [CrossRef]
33. Oo, P.; Prapaspongsa, T.; Strezov, V.; Huda, N.; Oshita, K.; Takaoka, M.; Ren, J.; Halog, A.; Gheewala, S. The role of global waste management and circular economy towards carbon neutrality. *Sustain. Prod. Consum.* **2024**, *52*, 498–510. [CrossRef]
34. Albizzati, P.; Foster, G.; Gaudillat, P.; Manfredi, S.; Tonini, D. A model to assess the environmental and economic impacts of municipal waste management in Europe. *Waste Manag.* **2023**, *174*, 605–617. [CrossRef]
35. den Boer, E.; Jedrczak, A.; den Boer, J.; Butrymowicz, T. Factors affecting the reproducibility of waste sampling and composition analyses. *Environ. Eng. Manag. J.* **2018**, *17*, 2755–2766. [CrossRef]
36. Jędrczak, A.; Szpadt, R. *Określenie Metodyki Badań Składu Sitowego, Morfologicznego i Chemicznego Odpadów Komunalnych, Zielona Góra, Kamieniec Wrocławski*; Polish Ministry of Environment: Warsaw, Poland, 2006.
37. Pietrzyk, J.; Rackiewicz, I.; Leoniewska-Gogola, J.; Pochwała, M. *Wytyczne dla Jednostek Samorządu Terytorialnego, Dotyczące Realizacji Badań w Zakresie Analizy Składu Morfologicznego Odpadów, Właściwości Fizycznych i Chemicznych Odpadów Oraz Weryfikacji Wyników Badań*; Atmoterm S.A.: Opole, Poland, 2018.
38. Hryb, W.; Wandrasz, A.J. Research on the Morphological Composition and Recovery Possibilities of Selectively Collected Plastics and Metals—A Case Study. *Appl. Sci.* **2025**, *15*, 11227. [CrossRef]
39. *PN-EN 15934:2013*; Sludge, Treated Biowaste, Soil and Waste—Calculation of Dry Matter Fraction After Determination of Dry Residue or Water Content. Comite Europeen de Normalisation: Brussel, Belgium, 2013.
40. *PN-EN 15403:2011*; Solid Recovered Fuels—Determination of Ash Content. Comite Europeen de Normalisation: Brussel, Belgium, 2011.
41. *PN-ISO 1171:2002*; Solid Mineral Fuels. Determination of Ash Content. Polish Standard, Polish Committee for Standardization: Warsaw, Poland, 2002.
42. *PN-EN 15440:2011*; Solid Recovered Fuels—Methods for the Determination of Biomass Content. Polish Committee for Standardization: Warsaw, Poland, 2011.
43. *VDI 4630 (2016)*; Fermentation of Organic Materials—Characterization of the Substrate, Sampling, Collection of Material Data, Fermentation Tests. Verein Deutscher Ingenieure: Düsseldorf, Germany, 2016.
44. Matteo, U.; Nastasi, B.; Albo, A.; Garcia, D. Energy Contribution of OFMSW (Organic Fraction of Municipal Solid Waste) to Energy-Environmental Sustainability in Urban Areas at Small Scale. *Energies* **2017**, *10*, 229. [CrossRef]
45. Narožnova, I.; Møller, J.; Scheutz, C. Characterisation of the biochemical methane potential (BMP) of individual material fractions in Danish source-separated organic household waste. *Waste Manag.* **2016**, *50*, 39–48. [CrossRef]

46. Muir, G.; Hayward, S.; Tripney, B.; Cook, G.; Naysmith, P.; Herbert, B.; Garnett, M.; Wilkinson, M. Determining the biomass fraction of mixed waste fuels: A comparison of existing industry and (14)C-based methodologies. *Waste Manag.* **2014**, *35*, 293–300. [CrossRef] [PubMed]
47. Ariyaratne, H.; Melaaen, M.; Tokheim, L. Determination of biomass fraction for partly renewable solid fuels. *Energy* **2014**, *70*, 465–472. [CrossRef]
48. Staber, W.; Flamme, S.; Fellner, J. Methods for determining the biomass content of waste. *Waste Manag. Res.* **2008**, *26*, 78–87. [CrossRef]
49. Schnöller, J.; Aschenbrenner, P.; Hahn, M.; Fellner, J. Sample preparation and determination of biomass content in solid recovered fuels: A comparison of methods. *Waste Manag. Res.* **2014**, *32*, 1024–1029. [CrossRef]
50. Daniel-Gromke, J.; Liebetrau, J.; Denysenko, V.; Krebs, C. Digestion of bio-waste—GHG emissions and mitigation potential. *Energy Sustain. Soc.* **2015**, *5*, 3. [CrossRef]
51. Wang, W.; Xu, Y.; Zhang, S.; Xu, Z.; Xue, X. Bibliometric insights into pollution research: Trends, geographic disparities, and emerging environmental challenges. *Environ. Res. Commun.* **2025**, *7*, 075026. [CrossRef]
52. Delkash, M. Air Emissions from Combustion and Incineration Processes: Insights into Air Quality and US EPA Regulations. *Water Air Soil Pollut.* **2025**, *237*, 104. [CrossRef]
53. Liu, Y.; Zhu, G.; Yu, Z.; Li, C.; Lin, B.; Liu, G.; Jin, R.; Zheng, M. Priority Organic Pollutant Monitoring Inventory and Relative Risk Reduction Potential for Solid Waste Incineration. *Environ. Sci. Technol.* **2024**, *58*, 18356–18367. [CrossRef]
54. Luo, Y.; Ye, M.; Zhou, Y.; Su, R.; Huang, S.; Wang, H.; Dai, X. Assessing the Environmental Impact of Municipal Waste on Energy Incineration Technology for Power Generation Using Life Cycle Assessment Methodology. *Toxics* **2024**, *12*, 786. [CrossRef] [PubMed]
55. Tait, P.; Salmona, J.; Sandhu, M.; Guscott, T.; King, J.; Williamson, V. Economic, Environmental, and Sociopolitical Aspects of Waste Incineration: A Scoping Review. *Sustainability* **2025**, *17*, 5528. [CrossRef]
56. Zhao, C.; Zhao, Y.; Lin, K.; Wang, Z.; Zhou, T. Comprehensive assessment of thermal characteristics, kinetics and environmental impacts of municipal solid waste incineration fly ash during thermal treatment. *Process Saf. Environ. Prot.* **2023**, *175*, 619–631. [CrossRef]