energies

MDPI

Article

Selection Path for Energy-Efficient Food Waste Management in Urban Areas: Scenario Analysis and Insights from Poland

Anna Rolewicz-Kalińska *, **Krystyna Lelicińska-Serafin** and **Piotr Manczarski**

Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, Nowowiejska 20 St., 00-653 Warsaw, Poland; krystyna.lelicinska@pw.edu.pl (K.L.-S.); piotr.manczarski@pw.edu.pl (P.M.)
* Correspondence: anna.kalinska@pw.edu.pl; Tel.: +48-502-353-496 or +48-22-234-74-83

Abstract: The problem of food being wasted in households has become an essential challenge in recent years. Food waste can be valorized in accordance with the principles of sustainable development, including as a source of energy. This study analyses the potential of anaerobic fermentation, pyrolysis, ethanol fermentation, incineration, and composting to treat food waste, focusing on its energy yield. This research considered two potential scenarios for generating food waste in Poland in both the near term (2030) and the long term (2050). Scenarios were proposed for regions with different levels of urbanization and demographic trends. The criteria for the selection of technologies for the energy-efficient processing of food waste from households in Poland were identified, taking into account the current state of these technologies, their prospective development, demographic changes, the nature of the regions, the trajectory of food waste generation, the spatial food waste generation rate, and the energy potential. Technologies like methane fermentation and thermochemical methods should be developed in densely populated areas with a high spatial food waste generation rate. Among the thermochemical processes, fast pyrolysis will provide the most significant energy benefits, followed by moderate pyrolysis and biocarbonization—at similar levels. Incineration is placed between carbonization and gasification. In less populated areas with lower spatial food waste generation rates, combining substrates with co-processing food waste and green waste should be considered. Biocarbonization systems can be integrated with composting in rural regions.

Keywords: food waste; anaerobic digestion; pyrolysis; incineration; energy potential

Academic Editor: Antonis A. Zorpas

Received: 16 December 2024
Revised: 2 January 2025
Accepted: 14 January 2025
Published: 17 January 2025

Citation: Rolewicz-Kalińska, A.; Lelicińska-Serafin, K.; Manczarski, P. Selection Path for Energy-Efficient Food Waste Management in Urban Areas: Scenario Analysis and Insights from Poland. *Energies* **2025**, *18*, 385. https://doi.org/10.3390/en18020385

1. Introduction

The issue of food waste (FW) represents a significant global challenge, contributing to environmental degradation, the emission of greenhouse gases, and the inefficient use of resources [1]. In recent years, there has been a growing emphasis on effectively managing food waste to minimize its environmental impact and recover valuable resources [2]. In urbanized areas with varying population densities, food waste processing technology selection is largely determined by the specific demographic, logistical, and infrastructural conditions present at the local level [3].

Understanding the specific characteristics of food waste enables the development of targeted strategies that align with the principles of the circular economy, emphasizing waste minimization and the valorization of bio-resources [4]. Garcia-Garcia et al. [5] propose the categorization of food waste based on the degree of processing (unprocessed, processed, and consumer-level), origin (plant, animal, or mixed), and stage of the supply chain (production, processing and manufacturing, distribution and retail, and consumption).

A similar food waste classification approach is proposed in several works [6–8]. The post-consumer food waste can be divided into four categories: unprocessed or minimally processed plant-based, processed plant-based, unprocessed or minimally processed animal-based, and processed animal-based. Unprocessed plant-based food waste includes raw fruits and vegetables, suitable for anaerobic digestion or composting, generating biogas and organic fertilizer [9]. Processed plant-based waste, like bread and cereals, is suited for alcoholic fermentation or incineration due to lower moisture and higher starch levels [10]. Unprocessed animal-based waste (meat scraps, bones) is rich in protein and fat, making it ideal for methane fermentation [11]. The last category, cooked and processed animal-based waste, is suited for incineration or anaerobic processes due to its high calorific value [12]. By categorizing food waste based on its processing level and origin, it is possible to apply the most appropriate methods for treatment. This not only improves the efficiency of waste management but also contributes to resource recovery [13]. Due to the method of collecting food waste from households in the municipal bio-waste system, it is usually impossible to separate individual categories of food waste. As a result, the collection system will usually receive waste of plant origin, with various degrees of processing and contaminated with, among others, plastics and paper [14,15].

In the European Union (EU), the quantity of food waste recorded for 2022 reached 59 million Mg, of which 32 million Mg were FW generated by households, representing 54% of the total [16]. According to Eurostat data and analysis by the Environmental Protection Institute, 4.5 million Mg of FW was generated in Poland in 2022, of which the most significant share—55.7%—came from households, accounting for 2.5 million tons [17]. Other sources of food waste include processing and manufacturing (12.2%), primary production (15.9%), retail and distribution (10.4%), and catering services (5.8%). According to Eurostat data, Poland's food waste generation rate in 2022 was 60 kg Inhabitant $(\mathrm{Inh})^{-1}\mathrm{year}^{-1}$ below the European average of 70 kg $\mathrm{Inh}^{-1}\mathrm{year}^{-1}$. The research [18] indicates that an area's degree of urbanization significantly affects food waste generation. Based on reports from Norway, Canada, and South Africa, the authors indicated that food waste rates are higher in urbanized households than in rural or suburban areas.

The revised Waste Framework Directive (2018) [19] is consistent with the zero-waste concept, emphasizing the prevention, reuse, and recycling of food waste at all stages of the food supply chain [20]. It recognizes the key role of energy recovery in achieving the Sustainable Development Goals. When prevention, reuse, and recycling are no longer viable options, energy recovery becomes a necessary step to extract value from unavoidable food waste by transforming it into electricity, heat, or biofuels [21]. Transforming food waste into energy is recognized as a feasible and sustainable option [22] and can play an important role in sustainable regional development. Biological methods, such as anaerobic digestion (AD), ethanol fermentation, and composting, as well as thermochemical methods and incineration, have been demonstrated to offer diverse pathways for FW treatment [23].

Dry AD is particularly suited for solid substrates with a high dry matter content (15–40%), as it minimizes water usage and maximizes methane production per unit of reactor volume [24]. This process operates as a single-stage process, with hydrolysis, acetogenesis, and methanogenesis occurring simultaneously under mesophilic (37–40 °C) or thermophilic (50–55 °C) conditions [25,26]. Thermophilic conditions are particularly effective for sanitizing food waste [27]. Compared to wet AD, dry AD presents several advantages, including reduced reactor volume, decreased heating and mixing energy consumption, and enhanced feedstock handling flexibility. With dry AD, organic material has fewer problems during pre- and post-processing [28]. Two primary methods are identified within the domain of dry AD: static methods, also called "garage systems," necessitate a feedstock moisture content of 60–75%, do not entail mechanical mixing, and simple methods of loading and unloading the reactor are used, most often using simple loaders. In this case, the digestate dewatering is usually unnecessary or only to a small extent. Dynamic methods, known as semi-dry systems, operate at a 75–85% moisture content [29,30]. Despite the advantages of dry AD, technical challenges are associated with achieving effective homogenization and mass transfer within the reactor [28]. Wet anaerobic digestion is the optimal process for feedstocks that exhibit a high moisture content (≥85%), including food waste, wastewater sludge, and agricultural residues. The operation of wet AD at mesophilic (35–40 °C) or thermophilic (50–55 °C) conditions facilitates efficient microbial access to substrates, thereby resulting in higher biogas yields per unit of organic material in comparison to dry AD [31]. However, the process requires a considerable input of water, which makes it less suitable for regions with limited water resources. Furthermore, the post-treatment of the liquid digestate is required to separate solids and manage excess liquid [32]. To address variability in food waste composition, pre-treatments such as the separation of impurities that could damage pumps and mixers, mechanical shredding, defibration (using pulpers), or enzymatic hydrolysis are usually employed in the case of AD. These processes enhance substrate accessibility, reduce retention time, and optimize biogas production [27].

Ethanol fermentation is a microbial process by which plant biomass containing sugars (e.g., sugar cane, wheat) or starch (e.g., corn, potatoes) is converted to ethanol and carbon dioxide. It can be effective for bakery waste, fruit pulp, and juice residues [33]. The principal product is bioethanol, a first-generation biofuel [33]. Fermentation efficiency is approximately 90%, based on the amount of fermentable sugars present [34,35]. The pre-treatment of lignocellulosic biomass before alcoholic fermentation is a complex process, necessitating a combination of chemical, physical (e.g., steam explosion), and biological methods [36–38]. This technology is particularly suited to food waste with a high sugar and starch content, such as fruit pulp or bakery waste, but requires a stable substrate of appropriate quality [38–40].

Composting is an aerobic process that breaks organic waste into a stable compost. Substrates with a 40–60% moisture content, such as kitchen and green waste, are optimal for composting [41]. However, incorporating structural materials is necessary at higher humidity levels [42,43]. The temperature may reach 70 °C in suitable conditions, facilitating optimal hygiene [44,45]. The advantages of this process include low costs and no need for thermal energy [46,47]. However, research indicates that this option has high energy consumption, contributes to GHG emissions, and does not produce renewable energy [48]. It is an attractive option for small-scale and community-based waste management [49]. However, the disadvantages include odor nuisance and limited efficiency when dealing with waste with a high water content [50]. There may also be problems with the management of the organic fertilizer produced. Composting is particularly useful for stabilizing digestate in methane processes and for bio-waste with a high C/N ratio (20–40) [51,52]. Pyrolysis is a thermochemical process of biomass degradation in the absence of oxygen, allowing biochar, bio-oils, and pyrolysis gas production. Slow pyrolysis produces 35% biochar, 30% liquid, and 35% gas, rendering it an optimal technique for converting lignocellulosic biomass, such as wood or straw. It is most often carried out at a temperature of 400–550 °C [53], sometimes also in the range of 300–950 °C [54]. Flash pyrolysis (up to 1000–1250 °C) generates up to 75% bio-oil, fast pyrolysis (850–1250 °C)—about 50% bio-oil, while moderate pyrolysis (300–450 °C) ensures a balanced share of products [54–56]. According to [57], intermediate (moderate) pyrolysis generates 35–50% of bio-oil, 25–40% of biochar, and 20–30% of syngas. This technology necessitates input with less than a 10% moisture content, which requires drying and grinding raw materials to 1–2 mm, thereby increasing pre-treatment costs [53,58]. Flash pyrolysis is a particular variant of fast pyrolysis, which is occasionally categorized as a separate type of pyrolysis process [59]. Fast or flash pyrolysis enhances gas or oil production [53,60]. In the fast pyrolysis process, the yield of liquid bio-oil ranges from 60 to 75% by weight, solid carbon products from 15 to 25%, and gaseous products from 10 to 20%. These figures depend on the type of raw material used [61]. Pyrolysis is employed in processing biomass with a high calorific value; however, its utility for food waste is constrained by the variability of its composition [62].

Incineration is an effective method for disposing of bio-waste with a high calorific value (e.g., dry plant waste), potentially yielding 0.3–0.7 MWh of energy per Mg of bio-waste [63]. Incineration is the most prevalent waste-to-energy method globally, reducing waste volume by 90% [64,65]. However, advanced exhaust gas purification is essential to prevent air pollution requirements [66,67]. Incineration is flexible and can be used for a diverse range of bio-waste, though it is less effective for wet or low-calorific waste [68–70]. However, within the circular economy framework, incineration should be regarded as a supplementary approach for managing non-recyclable food waste to enhance resource efficiency and reduce reliance on landfill sites [71,72]. Under typical conditions of the gasification process (temperature about 800 °C, long residence time), 5% of liquid products, 10% of biochar, and 85% of syngas are generated [73]. According to [74], the gas yield (the main product) equals 1.2 m^3 kg^{-1} DM of the feedstock. In this case, the feedstock requirements are lower.

The paper by Economou et al. (2024) [27] identifies methane fermentation and pyrolysis as the most energy-efficient food waste processing methods. In contrast, combustion and ethanol fermentation have moderate efficiency, and composting supports the goals of the circular economy despite the lower energy output.

The problem of food waste from houses has become an important challenge in recent years, especially in adapting technology to suit different regional conditions, such as population density and the possibility of technological implementation. The extant research tends to concentrate on individual technologies, yet frequently lacks the consideration of hybrid or region-specific solutions that consider demographic variations, spatial waste generation rates, and changes in this field, particularly in Poland. This article addresses these gaps by analyzing the technologies for using food waste from an energy perspective, both in the short and long term. The following methods were analyzed in detail: anaerobic fermentation, pyrolysis, composting, ethanol fermentation, and combustion. The study analyzed the potential future food waste generation scenarios (S1 and S2) in the short term (2030) and long term (2050) to propose strategies that are tailored to regions with different levels of urbanization and demographic trends. Identifying energy recovery strategies for food waste that align with urbanization trends and local waste generation patterns is essential to improving resource efficiency, reducing environmental impact, and supporting the well-being of both urban and rural communities.

This research aims to identify the most appropriate technology for energy-efficient FW processing in Polish households. The current state of these technologies and potential future developments will be analyzed to achieve this. In addition, the influence of demographic changes, the characteristics of different regions, and the generation of FW in different spatial contexts will be considered. This research will also assess the energy potential of FW generation.

2. Materials and Methods

2.1. Technology Selection Criteria

A selection of bio-waste processing technologies was identified for assessment in the context of the development of the bio-waste market in Poland. This was based on a review of selected publications, including the following [23,75–79] and previous works of the authors [14,80]. The technologies selected for analysis included those based on biological conversion in both aerobic (composting) and anaerobic conditions (methane and ethanol fermentation), thermochemical conversion (pyrolytic methods), and thermal conversion (incineration). A detailed division of the technologies, marked from T1 to T5, is presented in Figure 1.

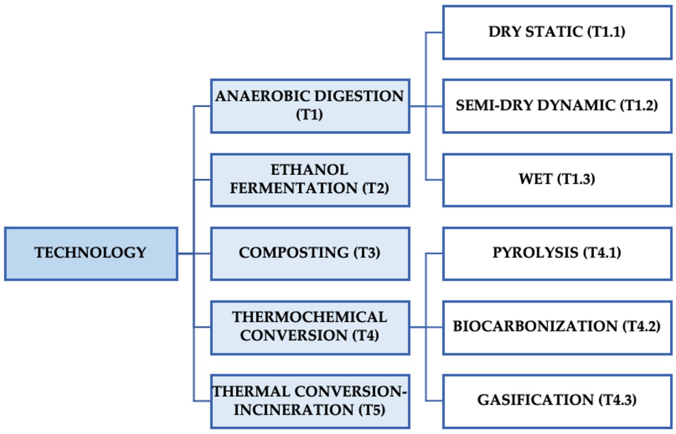


Figure 1. Technologies selected for the analysis.

2.2. Demographic Analysis and Classification of Areas

The demographic criteria for classifying areas may be based on the size of the population living in each area and on population density [81]. From the perspective of analyzing the needs for processing food waste, both parameters will be significant, influencing the demand for processing capacity and the criterion for selecting technologies (including in the context of their profitability) [82].

The analysis was conducted on a national level for Poland as a whole, as well as on a regional level for the individual voivodeships (Poland is divided into 16 administrative areas—voivodeships—as shown in Figure 2; in other countries, these are like regions, provinces) and for the five largest cities in Poland (Poznań, Warsaw, Łódź, Wrocław, and Kraków) [83]. Demographic trend scenarios were analyzed in the short-term (2030) and the long-term (2050) perspectives.

Figure 2. Administrative division of Poland into 16 voivodeships [84].

According to the DEGURBA classification (degree of urbanization), area categories are based on assessing the degree of urbanization of local administrative units (LAU2) and a typology based on a grid with a population density level of 1 km^2. The typology divides areas into cities, small towns, suburbs, and rural areas [85]. Cities are defined as densely populated areas comprising local administrative units where at least 50% of the population resides in urban centers and where the minimum population density is 1.500 inhabitants per km^2 (CAT 1). Small towns and suburbs are classified as areas with a medium population density, comprising local administrative units where less than 50% of the population lives in urban centers and where the minimum population density is 300 inhabitants per km^2 (CAT 2). Rural areas are local administrative units where more than 50% of the population lives in rural areas (CAT 3).

The Central Statistical Office (GUS) data for 2022 indicate that Poland comprises 8.5% urban areas, 15.7% small towns, and 59.5% rural areas, as delineated by the country's municipal divisions [86]. The work employs short- and long-term demographic forecasts, as provided by the Central Statistical Office [87].

2.3. Scenario Analysis

Food waste generation scenarios were analyzed in the short term (2030) and the long term (2050). The base year was 2023, for which quantitative data were available for analysis [88]. Two scenarios were developed to gain insight into the potential future trajectory of food waste generation in Poland, based on the demographic forecast for Poland (2.3) and assumed trends in waste generation rates (S1 and S2).

In Scenario S1, it is assumed that historical growth trends observed for the years 2018–2023 will be maintained. These trends indicate an annual increase of 1.31% in major cities and 1.93% for Poland and its voivodeships.

In Scenario S2, the implementation of activities aimed at reducing food waste and improving consumption patterns is assumed. In this scenario, the increase in waste generation is still positive but occurs at a slower rate than in Scenario S1. In Scenario S2, the annual increase is assumed to be half that observed in historical data (0.70% in major cities and 0.97% for Poland, respectively) for the short term due to implementing FW reduction strategies. Additional FW reduction strategies are introduced for the long term (2050), dropping the annual increase to 0.35% in major cities and 0.48% in Poland. An analysis of the available current and historical data on food waste generation suggests that the objective of a 30% reduction in household food waste by 2030, in accordance with the EU strategy, is unlikely to be achieved in Poland [89]. In this context, it was decided to develop scenarios based on historical data for analysis in this study. It should also be considered that food waste prevention strategies mainly apply to avoidable food waste, which represents 47% of household waste in Poland. This issue has been discussed in more detail in the authors' previous work [80].

2.4. Energy Potential Analysis

An energy potential analysis was performed, considering the properties of household FW and biological, thermochemical, and thermal conversion products used for energy recovery (in the combustion process), respectively, biogas, ethanol, bio-oil, biochar, and syngas. The parameters (average values) presented in Table 1 were considered.

Table 1. Parameters used in technological calculations.

Parameter	Values	Units	References
	Food Waste		
Water content (WC)	77	%	
Volatile solids (VS)	85.73	%	
Impurities	5.85	%	[14]
Biogas yield	389	m^3 Mg^{-1} VS^{-1}	
CH_4 share	57	%	
HHV	17.421	MJ kg^{-1} DM	[90]

Table 1. *Cont.*

Parameter	Values	Units	References
	Fast pyrolysis products		
bio-oil	60–75	%	[61]
biochar	15–25	%	
syngas	10–20	%	
	Moderate pyrolysis products		
bio-oil	35–50	%	[57]
biochar	25–40	%	
syngas	20–30	%	
	Carbonization products		
bio-oil	30	%	[54]
biochar	35	%	
syngas	35	%	
	Gasification products		
syngas	1.2	m^3 kg^{-1} DM	[74]
	Ethanol fermentation		
ethanol yield	107.58	g kg^{-1} DM	[91]
	Heat values		
biomethane	36.0	MJ m^{-3}	[92]
ethanol	21.6	MJ kg^{-1}	[91]
bio-oil	36.7	MJ kg^{-1}	[93]
biochar	23.6	MJ kg^{-1}	
syngas	17.0	MJ m^{-3}	

The biogas yield indicated in Table 1 is based on research conducted in Poland by the authors of this paper [14]. In the case of other regions, the results of the FW biogas yield may differ—the literature review indicates an extensive range of values of this parameter. In [94], the results of the biogas yield from German bio-waste were obtained in the range of 449.6–453.3 L kg^{-1} VS. According to [95], the methane yield of Malaysian food waste was 0.27–0.642 m^3 CH_4 kg^{-1} VS in the case of mono-digestion and up to 0.859 m^3 CH4 kg^{-1} VS for the co-digestion, and 0.396 m^3 CH_4 kg^{-1} VS for co-digested Korean FW. For FW produced locally in Oman [96], total gas production was found from 157 mL g^{-1} VS to 166 mL g^{-1} VS.

The following energy consumption in the process was assumed: for anaerobic digestion—10% of the energy produced, and for ethanol fermentation—0.6 kWh per gallon of ethanol produced [97]. In the paper by Fambri et al. (2024) [98], the energy consumption in pyrolysis processes was related to the total energy contained in the biomass (relative to the HHV of the feedstock). Based on the estimates in this paper, the energy consumption in slow, moderate, and fast pyrolysis processes and gasification was determined in the range of 25–40% of the feedstock HHV. Also, in the paper of Jerzak et al. (2022), the energy demand based on the relative share of HHV of the feedstock was determined [99]. Here, the shares are given at a lower level because the biomass with higher HHV values was used in the studies.

3. Results

3.1. The Current State of Food Waste Processing Technologies

Based on the literature review (Section 1. Introduction), the current state of investigated FW treatment technologies is summarized and compared in Table 2. The investigation included an analysis of anaerobic (T1, T2) and aerobic (T3) biological conversion, and thermochemical (T4) and thermal (T5) conversion. The analysis was carried out considering the following criteria: the purpose of the application, level of maturity, flexibility of the application, level of cost, optimal range of criteria, and emission level. As demonstrated in Table 2, the values given are illustrative cost ranges, which are subject to significant variation depending on the selected technology and local conditions, including the costs of selective collection. The costs are categorized as follows: investment costs (CAPEX), operating costs (OPEX), or alternatively, the total costs of processing the FW. The criteria were then taken into consideration in the evaluation of technologies for the energy-efficient treatment of FW from households in Poland.

Table 2. General characteristics of selected technologies T1–T5.

Criteria	T1: Anaerobic Digestion	T2: Ethanol Fermentation	T3: Composting	T4: Thermochemical Conversion	T5: Incineration
Purpose of application	Converting bio-waste into biogas and digestate	Converting bio-waste rich in sugars and starch into bioethanol	Aerobic stabilization of bio-waste to obtain compost	Decomposition of bio-waste into biochar, bio-oil, and synthesis gas under anaerobic conditions	Converting bio-waste into energy by direct combustion in the presence of excess oxygen
Maturity	Mature technology, widely used	New technology with limited commercialization	Mature technology, widely used	Developing technology. High level of innovation with potential for regional and global development	Mature technology widely used worldwide. innovations focus on emission control and energy efficiency
Flexibility of application	High flexibility, lower input requirements for dry AD, higher for wet AD	Low flexibility, significant feedstock requirements and complex pre-treatment	High flexibility, minimal pre-treatment requirements	Medium flexibility, depending on process parameters, special pre-treatment for higher efficiency, but no need to reject plastic ingredients	High flexibility, no complex pre-treatment required
Optimal criteria ranges	Anaerobic process Moisture: 60–75%—dry static 75–85%—dry dynamic >85/88%—wet, Biogas yield >100 m^3/Mg, Methane: >50% C/N = 10–30	Sugars: >30%, Starch: >20%	Oxygen process, from 5% to 15% O_2 in the air Moisture: 40–60%, Nitrogen: >0.3–1.5% Organic content: >20–40% TOC > 10%, C/N = 25–35	Cellulose: >30%, Lignin: >10%, Calorific value: >15 MJ kg^{-1}	calorific value: 8–10 MJ kg^{-1}, Contaminants: <5% Conditions for autothermal combustion: moisture content: <50%; ash content: <60% combustible mass: >25%
Sources	[24,100–103]	[10,39,40,104,105]	[106–109]	[110–114]	[114–121]
Emission level [a]	CH_4: 0.950–11.060 kg Mg^{-1} N_2O = 0.013–0.12 kg Mg^{-1} NH_3 = 0.024–0.72 kg Mg^{-1} CO_{2e} = 76–506 kg Mg^{-1}	CO_{2e} = 258–403 g L^{-1}	CH_4 = 4.060 kg Mg^{-1} N_2O = 0.055 kg Mg^{-1} NH_3 = 0.157 kg Mg^{-1} CO_{2e} = 78–118 kg Mg^{-1}	PM <4.7 mg Nm^{-3} HCl = 11.6 mg Nm^{-3} CO = 5.8 mol kg^{-1} CH_4 = 3.2 mol kg^{-1}	NO_x = 1.07–1.8 kg Mg^{-1} SO_2 = 0.096–1.36 kg Mg^{-1} NMVOC = 0.18–0.891 kg Mg^{-1} CO_{2e} = 386 kg Mg^{-1} SO_2 = 5.00 kg Mg^{-1} NMVOC = 0.89 kg Mg^{-1}
Sources	[101,122,123]	[123]	[101,122–124]	[125,126]	[127,128]
Cost estimation	CAPEX: 150–490 EUR Mg^{-1}; OPEX: 15–50 EUR Mg^{-1} Total treatment cost: 20–70 EUR Mg^{-1}	CAPEX: 145–189 EUR MWh^{-1} OPEX: 212 EUR MWh^{-1} Bioethanol production cost: 500–700 EUR m^{-3} bioethanol	CAPEX: 180–240 EUR Mg^{-1} OPEX: 16–65 EUR Mg^{-1}; Total treatment cost: 30–75 EUR Mg^{-1}	OPEX: 49–936 EUR Mg^{-1} (gasification) Bioproducts production cost: 0.45–2.76 EUR/kg/hydrogen (LCC approach); 400 EUR Mg^{-1} biocoal; 436–863 EUR Mg^{-1} biochar (conventional pyrolysis); 564- 979 EUR Mg^{-1} biochar (microwave pyrolysis); 75–300 EUR Mg^{-1} Oil 83–118 EUR MWh^{-1} (pyrolysis); 436–860 EUR MWh^{-1}	CAPEX: 350–760 EUR Mg^{-1} OPEX: 21–102 EUR Mg^{-1} Total treatment cost: 80–250 EUR Mg^{-1}
Sources	[129,130]	[131,132]	[129,130,133]	[134–138]	[129,139–141]

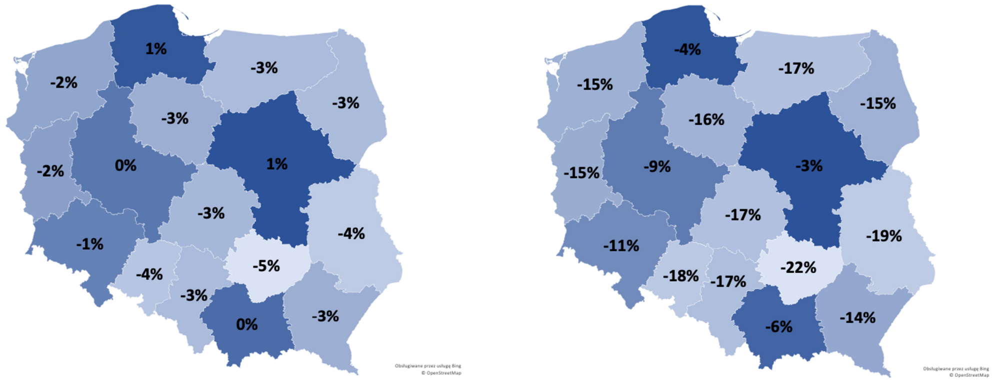
[a] emission from the process is taken into account, no net emission balance has been made (e.g., in the case of CO_{2e} emissions).

3.2. Demographic Changes in Poland

Changes in demographic trends in Poland are presented in Table 3 (for major cities) and Figure 3 (for voivodeships). In the short term, by 2030, the population of major cities such as Warsaw, Kraków, and Wrocław will increase by 3%, 3%, and 2%, respectively. An increase of 1% can also be observed in the Mazowieckie and Małopolskie voivodships. Regions with a lower population density, such as Warmińsko-Mazurskie and Podlaskie, already show a population decline. In other regions, the country's population is declining by an average of 2%. The largest demographic decline of 5% by 2030 will be observed in Świętokrzyskie and Łódzkie voivodships.

Table 3. Demographic trends for major cities in Poland in the short term—2030 and long term—2050.

City	2023–2030	2023–2050
Kraków	3%	4%
Warsaw	3%	2%
Wrocław	2%	−4%
Poznań	−2%	−16%
Łódź	−5%	−22%



(**a**) (**b**)

Figure 3. Demographic trends in Poland, individual voivodeships in the short term—2030 (**a**) and long term—2050 (**b**). Differences in color intensity reflect variations in demographic trends.

In the long term, Poland's population will decline by 12% by 2050. The largest population decreases will occur in the Łódzkie and Świętokrzyskie voivodeships (22% each), and Lubelskie (19%). Warsaw and Kraków's population will increase slightly in this period—by 4% and 2%, respectively. However, there will be significant decreases in Łódź and Poznań—22% and 16%, respectively.

3.3. Food Waste Generation in Poland

The analysis of historical data for the years 2018–2023 [88] showed that the growth trend of the generation rate increased during this period; for Poland as a whole, it amounted to an average of 1.93% per year, while for major cities, it amounted to 1.37% per year. Among the cities analyzed, the largest increase was observed in Poznań (an average of 5.8% per year), while a downward trend was observed in Wrocław (an average of −1.1% per year). Comparing the values of the generation rate for the years 2018 and 2023 for Poland, a 15% increase in value can be seen (from 325 to 357 kg Inh^{-1} year^{-1}), while in the major cities, this dynamic is slightly lower—an average increase in value of 11% between the years 2018 and 2023.

The value of the food waste generation rate for 2023 in Poland was 65.4 kg Inh^{-1} year^{-1} on average, ranging in individual voivodships from 44.7 kg Inh^{-1}year^{-1} (Podkarpackie voivodeship) to 76.0 kg Inh^{-1}year^{-1} (Lower Silesia voivodship)—a difference of 41%. In 2018, this difference was even greater and amounted to 49%, with the highest value in Lower Silesia (72 kg Inh^{-1}year^{-1}) and the lowest in Świętokrzyskie (36.9 kg Inh^{-1}year^{-1}). For the five major cities, the average value of the food waste generation rate in 2023 was 90.7 kg Inh^{-1}year^{-1}, ranging from 80.6 kg Inh^{-1}year^{-1} (for Łódź) to 104 kg Inh^{-1}year^{-1} (for Poznań). For 2018–2023, major cities (except Wrocław) show a clear increase in the waste generation rate. The growth dynamics in individual voivodeships are clearly differentiated. Regions with lower rates in 2018 have a greater potential for percentage growth, and significant changes were observed in them, i.e., in the Świętokrzyskie voivodeship, an increase in the waste generation rate from 36.7 to 52.0 kg $Inh^{-1}year^{-1}$ (by 41%) is observed. Voivodeships with a higher waste generation rate in 2018 (e.g., Pomorskie) show lower growth dynamics—an increase in the Pomorskie voivodeship from 64.8 to 68.1 kg $Inh^{-1}year^{-1}$ (a difference of 5%). The obtained values of the waste generation rate are lower than in [121]—98.2 kg $Inh^{-1}year^{-1}$, but similar to the results of the study conducted by Den Boer et al. in Opole, where the value of the FW generation rate in Opole was 61.7 kg $Inh^{-1}year^{-1}$ [142] and Eurostat value for Poland was 60 kg $Inh^{-1}year^{-1}$. A literature review for 2010–2020 showed that the average value of the food waste generation rate per capita in highly developed countries was 42.86 kg $Inh^{-1}year^{-1}$. In Europe, the rate was lowest, averaging 34.45 kg $Inh^{-1}year^{-1}$, while in the Asia-Pacific region, it reached the highest level, averaging 70.28 kg $Inh^{-1}year^{-1}$ [143].

Figure 4 compares food waste generation rates in Poland (voivodeships and individual cities) in 2018 and 2023.

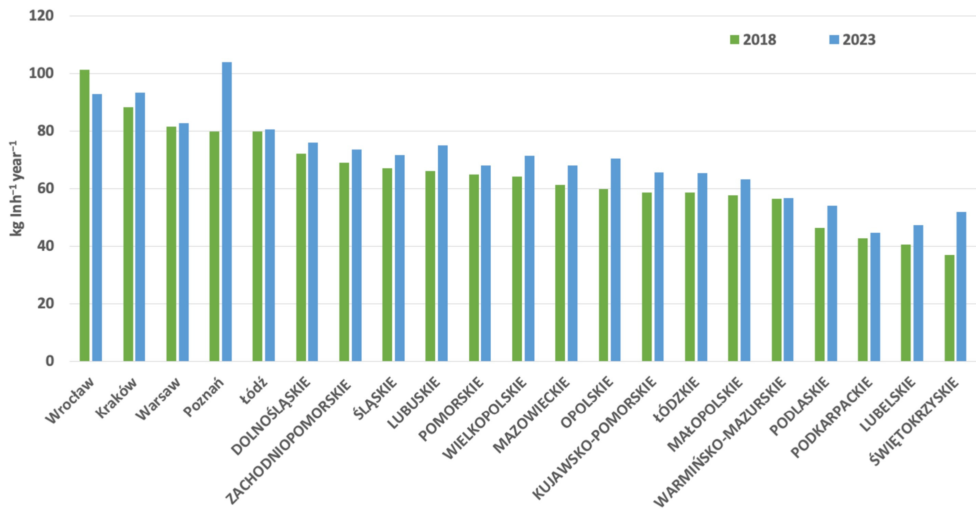
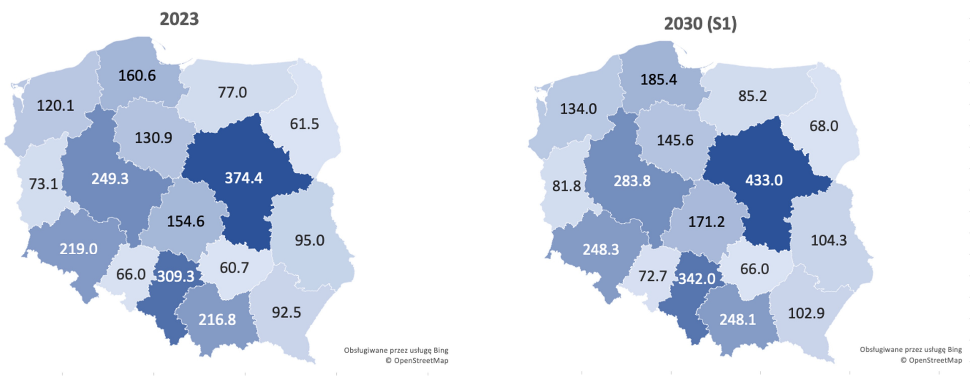


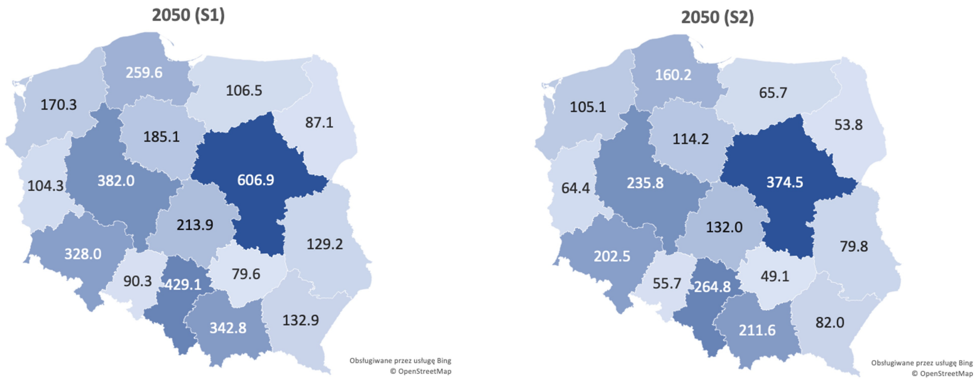
Figure 4. Comparison of the value of the food waste generation rates in Poland, voivodeships, and individual cities in 2018 and 2023.

The forecast of FW generated in Poland, in individual voivodeships and major cities in 2023, 2030, and 2050 for various scenarios is presented in Figures 5–7.



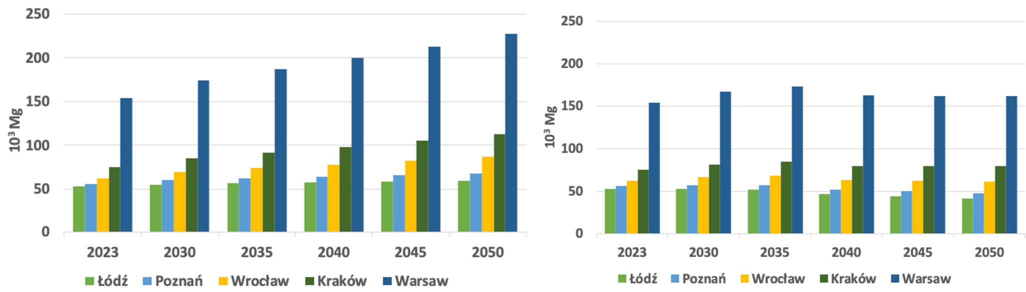
(**a**) (**b**)

Figure 5. *Cont.*



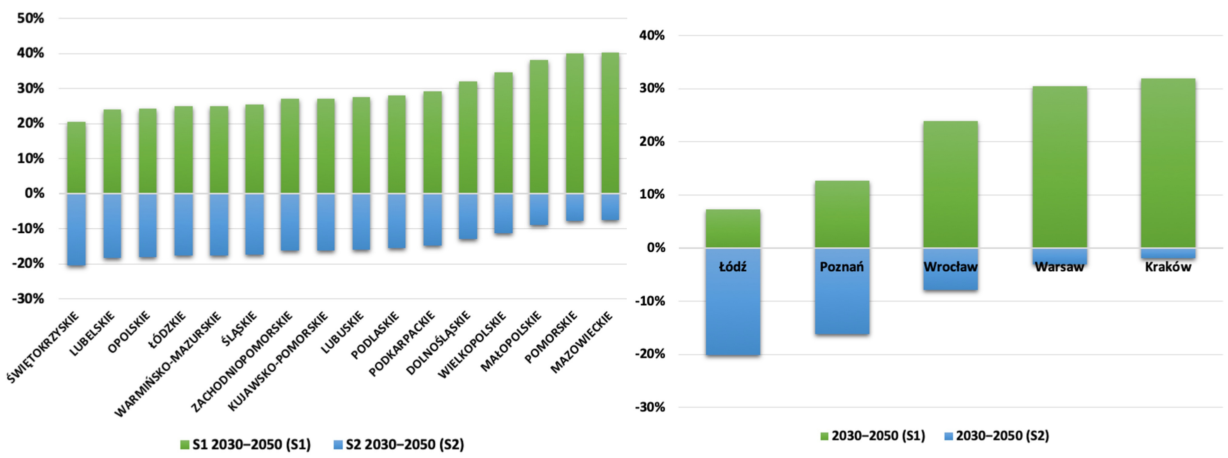
(**c**) (**d**)

Figure 5. FW in thousands of Mg generated in individual voivodeships in the base year 2023 (**a**), in 2030 for the S1 (**b**), in 2050 for the S1 (2050) scenario (**c**), and in 2050 for the S2 scenario (**d**). Differences in color intensity reflect variations in the FW generation rates.



(**a**) (**b**)

Figure 6. FW in thousands of Mg generated in big cities in scenarios S1 (**a**) and S2 (**b**).



(**a**) (**b**)

Figure 7. The projected changes in food waste generation between 2030 and 2050 for scenarios S1 and S2 in voivodeships (**a**) and major cities (**b**).

Based on the S1 scenario, the FW generated will reach its highest growth rate in 2050 (an increase of 47.8% compared to 2023). In major cities, the growth rate will average 34% between 2023 and 2050, reaching its peak in 2050.

It should be noted, however, that the demographic trend, and consequently the increase in the food waste stream, is not equally distributed across the regions (Figures 5 and 6).

By 2050, the Mazowieckie and Pomorskie voivodeships will see more than a 10% increase in FW generated compared to the baseline year 2023. The situation will be similar in some cities, particularly Kraków, Wrocław, and Warsaw.

In the case of scenario S2, the year of the largest increase will be 2030, when the activities related to the reduction of food waste will start to show results. In this scenario, a 5% increase in the FW generated is expected for the whole country in 2030, with the highest values for the Pomorskie and Mazowieckie voivodeships, where the increase will reach 8%. In major cities, the average increase until 2030 will be lower (2.7%), with the highest values for Warsaw and Krakow (an increase of 6%).

In the long term, the mass of food waste generated in Poland will decrease by 9%, remaining constant in the Mazowieckie and Pomorskie voivodeships. Regarding the change in the situation in major cities, the mass of food waste generated will decrease on average by 5%. In comparison, the increase in Kraków and Warsaw will be maintained (6% and 5%, respectively).

By 2030, there is little difference in the amount of waste generated in the S1 and S2 scenarios. Accordingly, for the S1 scenario, an average 12.5% increase in FW generated is observed for Poland, and for the S2 scenario, 5.3%. After 2030, the differences in changes in the FW generated by the region become more apparent. The S1 scenario continues to see intensive growth in the FW generated, at an average of 31.3% (difference for 2030–2050). In the S2 scenario, on the other hand, a decreasing trend emerges, with an average value of 13.4%. Changes in the FW generated between 2030 and 2050 by voivodeship and city are shown in Figure 7.

3.4. Spatial FW Generation Rate

The spatial FW generation rate (SFWGR), as the FW generation per 1 km^2 (Figure 8), was estimated as an indicative measure for planning the density of food waste management infrastructure and evaluating local waste management system efficiency; a similar measure was used in [144].

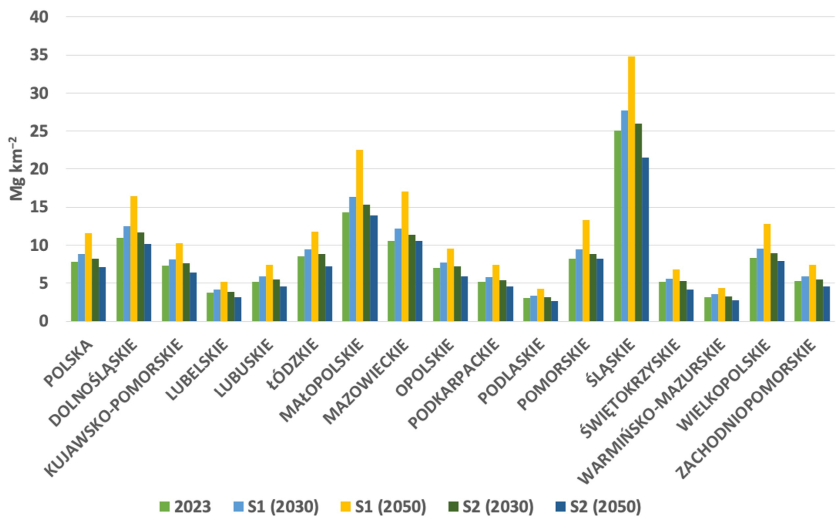


Figure 8. SFWGR for Poland and voivodships, 2030 and 2050 perspective in S1 and S2 scenarios.

The highest SFWGR for the analyzed scenarios was observed in the Śląskie, Małopolskie, Mazowieckie, and Dolnośląskie voivodeships. These regions have a high population density and strong urbanization, with a significant share of CAT 1 and CAT 2 regions. For the scenario with the SFWGR in 2050 (S1), the indicator's value in these voivodeships reaches 34.79, 22.58, 17.08, and 12.45 Mg km^{-2}, respectively. The lowest values can be observed in the Warmińsko-Mazurskie (4.41 Mg km^{-2}) and Podlaskie (4.31 Mg km^{-2})

voivodeships; these are regions with a low level of urbanization—with a dominant share of CAT3 areas. The difference in distribution of SFWGR in voivodeships and major cities is presented in Figure 9.

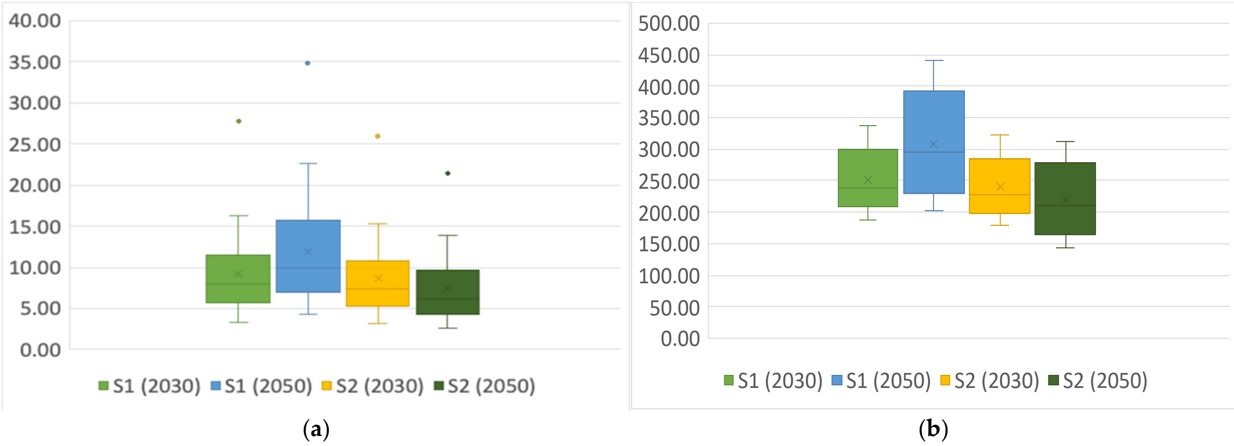


Figure 9. Box and whisker chart showing an average distribution of SFWGR for voivodeships (**a**) and major cities (**b**) for 2030 and 2050 in scenarios S1 and S2.

The value of the SFWGR in individual voivodships is similar, as indicated by the low median. There are outliers in voivodeships with large urban centers, especially in Śląskie and Małopolskie. In major cities, the SFWGR is more than 25 times higher than the average for voivodeships in each scenario. In the case of scenario S1, there is a significant difference in the value of the indicator for the short and long term. In 2050, the values are 22% higher for cities and 30% higher for voivodeships. In the case of the S2 scenario, the values in 2050 are 14% lower than in 2030 for voivodeships and 8% lower for major cities.

3.5. Energy Potential of FW in Poland

Analyses of the energy potential of FW in Poland were carried out, depending on the processing technology for three voivodeships and five major cities for the short-term perspective (2030) for scenario S1 and long-term perspective (2050) for scenarios S1 and S2. In this case, the short-term scenario S2 was not considered due to the similar results of the amount of FW generated in 2030 in scenarios S1 and S2. The Mazowieckie and Świętokrzyskie voivodeships were selected as the voivodeships with the largest and smallest amount of FW, respectively (Figure 5), and the Śląskie voivodeship was the voivodeship with the highest SFWGR at the level of 27.73–34.79 Mg km^{-2} in 2030 and 2050 according to S1 and 21.47–25.95 Mg km^{-2} for 2050 and 2030 according to S2 (Figure 8). At the same time, Mazowieckie is characterized by the highest growth rate of FW generation at 40.1% (according to S1) and the lowest decrease of FW generation at 8% (according to S2). The Świętokrzyskie voivodeship, on the other hand, is characterized by the lowest growth rate of FW generation at the level of 20.5% (according to S1) and the highest decline rate of FW generation at the level of 21% (according to S2). Świetokrzyskie is also one of the four regions with the lowest SFWGR (Figure 8). The energy potential of FW was estimated based on the analysis of products derived from individual processing methods and the amount of gross energy produced. The results are presented in Table 4. The unit yield of products and gross energy were calculated following the methodology presented in Section 2.4. In Section 4.3., the net energy potential is presented and discussed, considering the energy consumption for waste treatment.

Table 4. Unit yield of products and gross energy for individual processes per 1 Mg of FW.

Unit Yield of Products		Unit Yield of Gross Energy (GJ Mg^{-1} FW)
	Dry static methane fermentation	
Methane (m^3 Mg^{-1} FW)	55.8	2.0
	Dry dynamic methane fermentation	
Methane (m^3 Mg^{-1} FW)	34.1	1.2
	Wet methane fermentation	
Methane (m^3 Mg^{-1} FW)	42.7	1.5
	Alcoholic fermentation	
Ethanol (kg Mg^{-1} FW)	23.4	0.5
	Fast pyrolysis	
Bio-oil (kg Mg^{-1} FW)	149.2	5.5
Biochar (kg Mg^{-1} FW)	45.9	1.1
Syngas (kg Mg^{-1} FW)	34.4	0.6
	Moderate pyrolysis	
Bio-oil (kg Mg^{-1} FW)	97.6	3.6
Biochar (kg Mg^{-1} FW)	74.6	1.8
Syngas (kg Mg^{-1} FW)	57.4	1.0
	Biocarbonization	
Bio-oil (kg Mg^{-1} FW)	68.9	2.5
Biochar (kg Mg^{-1} FW)	80.3	1.9
Syngas (kg Mg^{-1} FW)	80.3	1.4
	Gasification	
Syngas (m^3 Mg^{-1} FW)	275.5	4.7
	Incineration	
Energy recovered from flue gases (GJ Mg^{-1} FW)	4.0	

4. Discussion

The prediction of energy-efficient technologies for processing FW from households in Poland was based on the current state of these technologies, demographic trends, regional characteristics, FW generation prospects, SFWGR, and FW energy potential.

4.1. Technology Selection Analysis

The nature/character of the regions, especially population density, should significantly impact the choice of FW treatment technologies, especially for biodegradable waste. Highly populated areas (CAT1) require clear and focused technological options. In such areas, anaerobic digestion (T1) can be used. A high population density also enables efficient incineration technology (T5), a mature and flexible process that does not require feedstock pre-treatment [145]. Incineration is possible for waste with suitable combustible properties, including calorific value, expressed by the Lower Heating Value (LHV) exceeding 8–10 MJ kg^{-1}. Nevertheless, despite its effectiveness in reducing waste volume, incineration is a widely discussed practice in the context of the circular economy and the principles of cascading use of biomass, which prioritizes recycling [146,147]. Moreover, the location of incinerators in densely populated urban areas necessitates a detailed consideration of environmental and social factors, given the health risks posed to the local population by pollutants from incinerators, particularly those employing older combustion technologies. Newer technologies are likely to pose a reduced risk, especially if subject to rigorous monitoring [148].

Composting (T3) is intended for areas with a medium population density (CAT2) and typical rural areas (CAT1) [149,150]. The feasibility of the process is determined by minimal requirements for the preparation of the feedstock and the possibility of local use of the compost. If these conditions are met, composting is a good solution for regions with dispersed food waste streams [151]. Among the available technological options, pyrolysis (T4) represents a significant potential for energy production. It is highly effective in the processing of bio-waste with a high lignin content (>10%) and cellulose (>30%) [152]. This technology is justified in areas with a high population density and concentrated waste streams (CAT1). An important aspect of this technology is maintaining stable feedstock parameters, which can be a challenge in the case of household food waste. Otherwise, the efficiency of the mentioned process decreases and translates into profitability [99,153]. In the case of alcoholic fermentation (T2), the raw material must meet certain quality criteria: sugar content exceeding 30% and starch content exceeding 20%. As a result, the technology requires pre-preparation processes for the feedstock. The above conditions make it less competitive than other discussed technologies for using energy from food waste [132].

The analysis presented in [154] indicates that bio-waste management is limited by logistical challenges related to the population density of the area served. In urban areas with a high population density (CAT1), concentrated bio-waste generation allows a smaller radius of the waste stream to the treatment facility, usually not exceeding 15 km. This proximity allows for the efficient collection and transport of organic materials to central facilities [155]. The literature analysis indicates a proportional relationship between the increase in processing capacity of the installation and the consequent decrease in the unit cost of processing FW. In urbanized areas with a higher SFWGR, the implementation of food waste processing plants with higher efficiency is a possibility. This can result in a reduction in the unit costs of FW processing; in the context of AD (CAT1), a fivefold increase in efficiency can result in a 50% reduction in the unit cost of processing food waste [156]. Furthermore, population density is an important factor that can significantly affect the quality of source separation. In areas of high population density, for example, due to the lack of space to store several waste streams in the home and the predominance of multi-family housing, sorting may be ineffective, which results in a lower quantity and purity of the target selective stream and difficulties in its efficient processing. In such conditions, it is advisable to implement technologies that do not demand high standards of input material quality [14,157].

In semi-urban or rural areas (CAT2 and CAT3), where bio-waste generation is more dispersed, the distances of waste to the facility reach about 50–60 km [158,159]. This is due to the need to collect adequate input waste streams for processing and maintain economic viability. The cost of waste collection is closely associated with the geographical distance from the final treatment site [130]. A modest, linear increase in collection costs is observed with increasing distance, with the cost ranging from 26 EUR per Mg^{-1} for a 15 km distance to 46 EUR per Mg^{-1} for a 40 km distance. It is also noted that the cost per ton of waste collected is generally higher in rural areas than in urban areas, with a cost difference of up to 40% per Mg. This increases the logistical challenges, including higher transport costs and associated emissions [159,160]. Logistical aspects significantly impact the selection and deployment of biological waste treatment facilities, emphasizing the importance of adapting collection systems to the geographical and demographic characteristics of the area served [161].

Analyzing trends in the change of food waste generation, it is predicted that by 2030, the development of organic waste treatment technologies will focus on integrating new solutions with local collection systems and increasing their overall efficiency [162]. The development of dry dynamic fermentation will contribute to the growing importance of methane fermentation (T1) in various bio-waste streams [24]. A major opportunity is the development of modular installations, which facilitates the implementation of fermentation systems in locations with limited infrastructure, thus supporting the circular economy strategy. At the same time, an interesting variant is pyrolysis (T4), with its high energy potential and possibilities of obtaining valuable products (e.g., bio-oil, biochar), and it is predicted that in the coming years, it will become an increasingly important element of municipal energy recovery systems, especially in connection with power grids.

In the long-term perspective, by 2050, waste treatment technologies, in line with technological trends on the market [163–166], will evolve towards greater automation and digitalization. Despite its status as a mature technology, composting (T3) will also undergo a transformation driven by technological advances. Composting technology will be directed towards the development of more efficient systems, integrating artificial intelligence, mathematical modelling, and novel reactor designs to optimize process efficiency, reduce greenhouse gas emissions, and increase nutrient recovery. This will continue to make it an attractive technology for FW processing, especially in less urbanized areas [163,167]. Implementing intelligent management systems supported by predictive algorithms and sensors can facilitate the efficiency of selective waste collection [144].

Combining methane fermentation with pyrolysis processes is a future solution in complex waste management systems [168,169]. Implementing system solutions will reduce dependence on large, centralized installations, thus promoting sustainable waste management at the place of their generation [170].

4.2. A Vision for Food Waste Processing Technologies in Poland by 2030 and 2050

Three basic criteria were adopted for selecting energy-efficient FW processing technologies for the country: (1) trend in the amount of FW generation, (2) SFWGR, and (3) energy potential of the technology. The Table 5 summarizes the parameters of the first two criteria for both short-term and long-term scenarios.

Table 5. Scenario characteristics—technology selection criteria.

	The Trend in FW Generation			
	S1 (2023–2050)	S1 (2030–2050)	S2 (2023–2050)	S2 (2030–2050)
country	+47.8%	+31.3%	−8.8%	−13.4%
voivodeships	+44.7%	+29.3%	−10.7%	−14.8%
major cities	+33.9%	+21.2%	−4.9%	−9.8%
	SFWGR (Mg km^{-2})			
	S1 (2030)	S1 (2050)	S2 (2030)	S2 (2050)
country	8.8	11.6	8.3	7.2
voivodeships	9.2	12.0	8.6	7.4
major cities	251.1	308.3	239.6	218.8

4.2.1. Short-Term Perspective

In the S1 scenario, it is assumed that the historical trend of an increasing food waste generation rate will continue, which, together with the demographic trend, will lead to an increase in food waste in all areas. By 2030, cities such as Warsaw, Kraków, and Poznań could see an average increase of 10.2% compared to 2023 and voivodeships could see an average increase of 11.9%. Moreover, in regions with a high population density (CAT1 areas), e.g., Warsaw and Kraków, the estimated mass of FW per 1 km^2 can exceed 300 tons per year (in the case of S1 and S2 for 2030 and 2050 for Warsaw and S1 2050 for Kraków), which indicates a high demand on the efficiency of FW collection and processing capacity. All this points to the need to invest in new, highly efficient facilities, especially in regions with forecasted increases in food waste generation rates. Under these conditions, technologies such as methane fermentation (T1) and thermochemical methods (T4) should be developed, which enable the effective treatment of increasing food waste streams in densely populated areas. In the long term, they will replace thermal methods, especially in areas with high waste generation potential, due to the smaller quantity of residues left after the process, thanks to the possibility of more complete waste management by producing both fuels and chemical raw materials. This is consistent with other studies and recommendations for urbanized areas [171,172]. Medium and large-scale pyrolysis plants (T1.1–T1.3) can be in urban areas with a high FW concentration and modern AD methods (rather dry—T1.1 or T1.2). This allows FW mass reduction and the local use of the generated syngas as an energy source. However, there is some risk in investing in centralized, large, and expensive facilities in uncertain food waste generation trends beyond 2030.

In the S2 scenario, the effects of food waste reduction policies will already be visible in 2030. There is still an increase in the mass of food waste generated, but it is much lower than in the S1 scenario and remains at 5% in all regions. In the S2 scenario, technologies like those in scenario S1 will be recommended for urbanized areas. However, the difference will concern their scale, as they should be medium- and small-scale facilities, allowing adaptation to the decreasing FW stream. In this scenario, a decrease in food waste generated will be visible after 2030 in most areas (from CAT1 to CAT3)—the years 2030–2035 will be the peak years. In this context, it is also necessary to consider the strategy of combining substrates, which will allow the co-processing of food waste with green waste (GW) and, in the next phase (with favorable formal and legal conditions), also with other bio-waste, e.g., of agricultural origin or with sewage sludge.

In voivodeships with the domination of rural regions (CAT3 areas), such as Podlaskie or Warmińsko-Mazurskie voivodeships, the increase in food waste generation per 1 km^2 will be less dynamic. It will not exceed an average of 5 Mg km^{-2}. This indicates investments in more dispersed FW management systems. In such regions, challenges will occur from population dispersion and logistical difficulties. Decentralized solutions, such as small and medium-scale methane fermentation units (can be wet—T1.3) or composting plants (T2), will be more suitable. Biocarbonization systems (T4.3) can be integrated with composting (T2) in rural regions or replaced with slightly less energy-efficient but technologically simpler incineration (T5).

In areas with a low and medium population density (CAT1 and CAT2) and moderate SFWGR (below 20 Mg km^{-2}), the difference between scenarios S1 and S2 is insignificant. This difference becomes more evident in the 2050 perspective.

4.2.2. Long-Term Perspective

In the S1 scenario, by 2050, the mass of food waste will increase by 47.8% in all of Poland and cities by an average of 34%, which will require the further development of centralized installations in densely populated voivodeships, such as Mazowieckie, Śląskie, and Małopolskie, as well as in the regions of major cities. These increases highlight the need to extend traditional solutions to modular methane digestion (T1) plants and hybrid energy systems such as fermentation and pyrolysis (T4.1). Cities with a SFWGR over 25 times higher than in voivodeships will require more advanced technological solutions.

In the S2 scenario, long-term actions bring a 9% reduction in FW mass by 2050, except for cities such as Kraków and Warsaw, where the mass increase will be 6% and 5%, respectively. This decline allows for a gradual shift from central technologies to decentralized solutions, especially in rural regions. Over the next 25 years, in line with technological trends, significant technological progress will occur in the market, influencing the evolution of traditional FW processing solutions. Highly automated composting systems (T2) supported by predictive algorithms and sensors should be developed in regions with a low population density, such as Warmińsko-Mazurskie and Podlaskie. By 2050, pyrolysis plants (T4.1) may also become more advanced and scalable, allowing them to be adapted to different types of waste generated in the region.

The analysis of FW processing technologies for Poland (based on the technological calculations of energy potential) is presented in Table 6.

Table 6. Analysis of technologies for FW processing in Poland—based on the technological calculations (for FW characteristics according to Section 2.4).

Technology	Pre-Treatment	Post-Treatment	Energy Potential Index (Net) (kWh kg^{-1} FW$_{DM}$)	Others
T1 Anerobic Digestion T1.1 Dry static	Simplified pre-treatment Sorting out impurities in the amount of approx. 3% of feedstock Need to correct humidity	Oxygen stabilization of digestate Digestate purification	2.2 *	Limited amount of wastewater Possibility of co-fermentation with GW (as part of humidity correction)—in the amount of approx. 20% of FW input Endothermic process
T1 Anerobic Digestion T1.2 Semi-dry dynamic	Simplified pre-treatment Sorting out impurities in the amount of approx. 3% of the feedstock No need for humidity correction	The need to dewater the digestate Oxygen stabilization of digestate Digestate purification	1.3	Larger amount of wastewater (approx. 45% of the feedstock) Endothermic process
T1 Anerobic Digestion T1.3 Wet	Advanced pre-treatment—grinding, fiberizing, slurring Sorting out impurities in the amount of approx. 5% of feedstock Need to increase humidity (water supply in the amount of approx. 90% of the feedstock)		1.7	A large amount of wastewater produced (approx. 120% of the feedstock) Endothermic process
T2 Ethanol fermentation	Advanced, specialized pre-treatment Sorting out impurities in the amount of approx. 3% of the feedstock	-	0.4	Endothermic process
T3 Composting	Simplified pre-treatment The need to correct (to lower) humidity	Compost gentrifying	No energy recovery Fertilizing use	Possibility of co-composting with GW (as part of humidity correction)—approx. 70% of the input Exothermic process
T4 Thermochemical conversion T4.1 Pyrolysis (fast and moderate)	No need to sort out impurities Drying, significant fragmentation required (up to 1–2 mm for flash pyrolysis) The degree of advancement depends on the type of pyrolysis	-	6.0—moderate pyrolysis 6.8—fast pyrolysis	Endothermic process
T4 Thermochemical conversion T4.2 Biocarbonization (slow pyrolysis)			5.9	
T4 Thermochemical conversion T4.3 Gasification			3.7	
T5 Thermal conversion Incineration	Simplified pre-treatment No need to sort out impurities Drying	Ash and slag valorization Fly ash solidification Flue gas purification	4.8	Exothermic process Autothermal combustion is possible after drying

* In co-fermentation with GW (in the amount of 20% FW) for humidity correction

4.3. Energy Potential

The energy potential of the individual FW treatment technologies was defined as the net energy that can be obtained from FW based on the gross potential energy (Table 2) and energy consumption in the process (according to the methodology presented in Section 2.4).

The analysis of the energy potential of the individual FW treatment technologies in Poland shows that, among the AD methods, dry static AD (T1.1) and wet AD (T1.3) offer the highest energy benefits. In the first case, this is associated with more feedstocks being directed to processing (FW co-fermentation with GW as part of the feedstock moisture control). In the second case, it is associated with a higher efficiency of biogas production (effective mixing due to high moisture content), but also with a higher environmental impact due to high water consumption and a large amount of wastewater produced (Table 6). Wet AD (T1.3) is a technology for areas with a lower population density, including rural areas. Among the thermochemical processes, fast pyrolysis (T4.1) will provide the greatest energy benefits, followed by moderate pyrolysis (T4.1) and biocarbonization (T4.2)—at similar levels. Fast pyrolysis is particularly interesting, as liquids can be stored and transported more efficiently and at a lower cost than solid or gaseous biomass. In turn, regarding the use of biochar as a soil amendment, biochar is considered the most stable of the pyrolysis end products. The use of pyrolysis methods also allows for changing the conditions of the process and, thus, the proportions between the products, depending on their demand. Such flexibility in pyrolysis methods is their essential advantage [73]. Traditional thermal conversion (incineration T5) falls between biocarbonization (T4.2) and gasification (T4.3) in terms of net energy potential. Ethanol fermentation (T2) should be used for waste with a higher ethanol yield (especially from fruit and vegetable processing, food, and distillery industries). According to [173], there are still many challenges in this range, and it is crucial to ensure the market maturity of the innovation.

Thermochemical methods (T4) with an energy potential index of 5.9–6.8 kWh kg^{-1} FW DM are recommended for the voivodeship with the highest SFWGR (Śląskie and Małopolskie) and the largest increase (according to S1) or the smallest decrease (according to S2) in the amount of FW generated (Mazowieckie, Pomorskie and Małopolskie). The clear advantage of these methods, apart from the high energy potential, is the possibility of complete waste management and a low amount of residues, which is particularly important in the case of regions with a high population density, large amounts of waste generated, and a high SFWGR.

On the other hand, for voivodeships with the lowest SFWGR and the lowest increase (according to S1) or the highest decrease (according to S2) in the SFWGR, methods based on biological conversion are recommended (with an energy potential index of 1.7–2.2 kWh kg^{-1} FW DM), which allow for the generation of energy (in the case of AD) but leave significant amounts of digestate or compost for management, in the case of AD (T1) and composting (T3), respectively. Moreover, composting methods require long processing times, while AD methods (T1) are generally accessible and can be implemented quickly. Incineration (T5) and gasification (T4.2), as technologically more straightforward among energy-efficient methods (with an energy potential index of 3.7–4.8 kWh kg^{-1} FW DM), can also be considered, but incineration is not feasible for small plants in contrast to gasification, the application of which is indicated for small and medium scales. Moreover, ashes and slags from incineration processes are more challenging to manage than pyrolysis products [68]. Biocarbonization (T4.3) can be regarded in later years—among the thermochemical processes.

Figure 10 presents the energy potential of individual FW processing methods in two scenarios, S1 and S2 (short-term and long-term), for three voivodeships. The selection of provinces was justified in Section 3.3. The energy potential was converted into GWh for comparisons, including analyzing the possibilities of using the obtained energy by households in Poland.

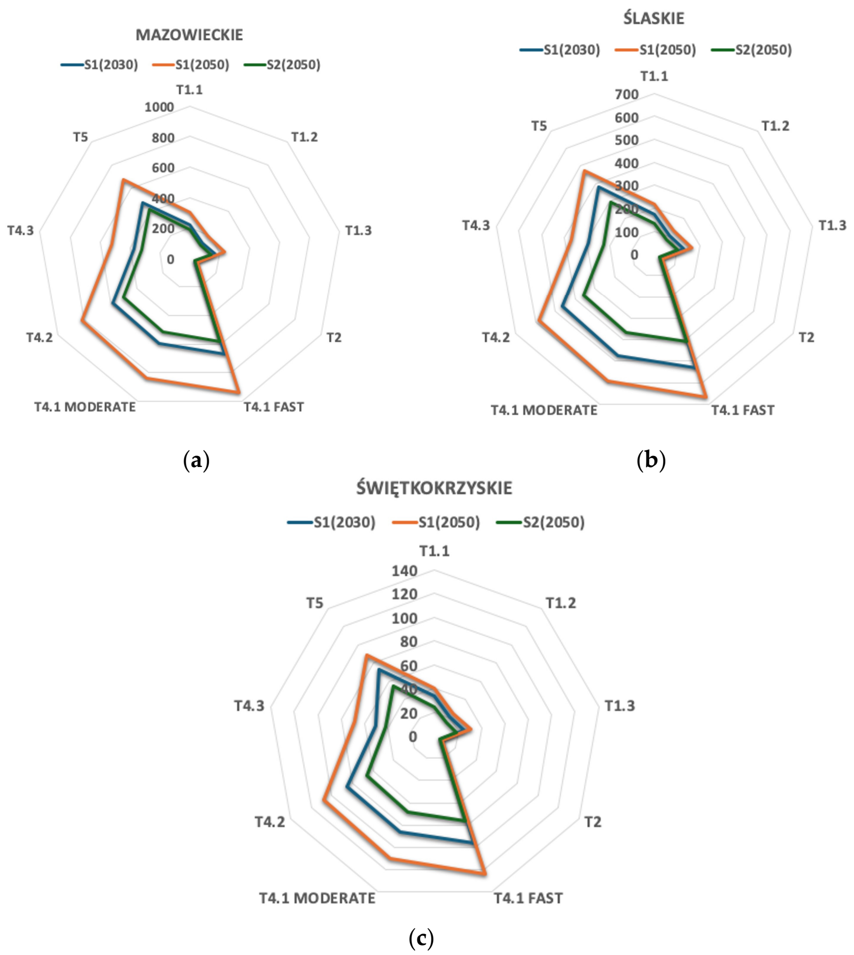


Figure 10. The energy potential (in GWh) of individual FW processing methods for S1(2050) and S2 (2030 and 2050), for Mazowieckie (**a**), Śląskie (**b**), and Świetokrzyskie (**c**) voivodeships.

In the Mazowieckie voivodeship, the use of the analyzed processing technologies allows for obtaining net energy in the range from 218 GWh (for biological conversion T1) through 481 GWh (for thermal conversion—T5) to 585–671 GWh (for thermochemical conversion—T4) in 2030, and from 188–305 GWh (for biological conversion—T1), through 416–674 GWh (for thermal conversion—T5), to 506–941 GWh (for thermochemical conversion—T4) in 2050.

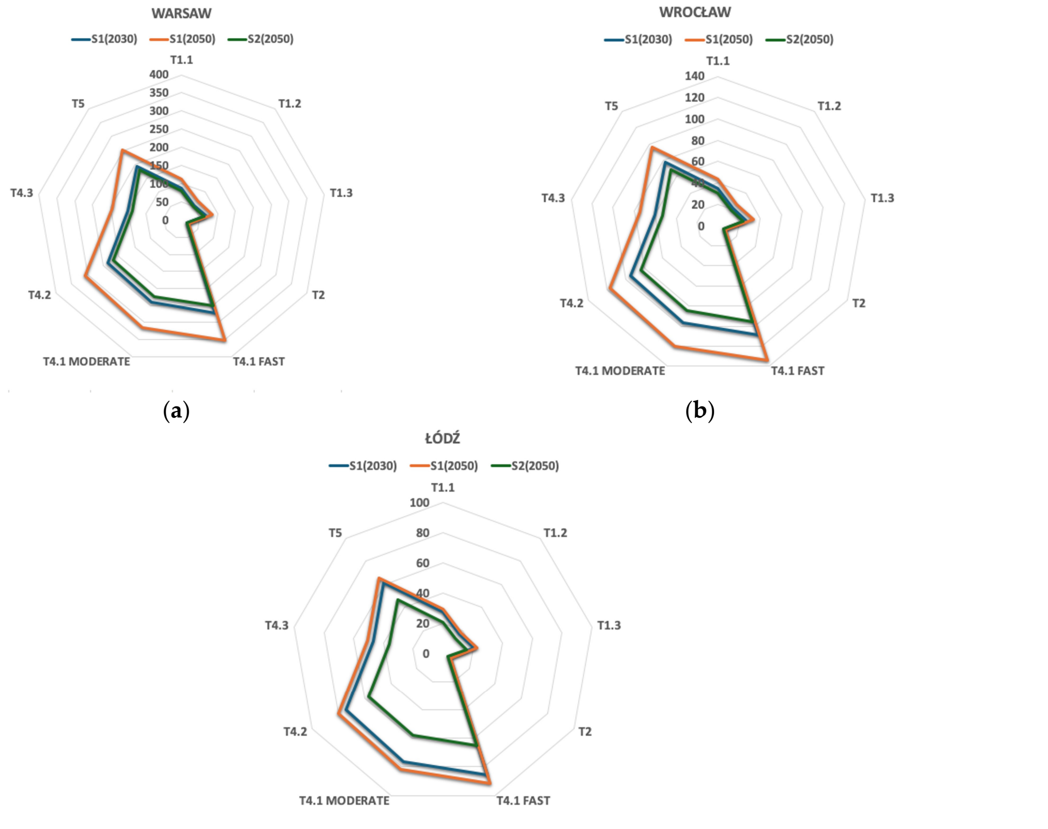
In 2050, significant differences will be visible depending on the scenario, making it difficult to plan a FW management strategy. In Warsaw, the energy generated using the above methods would allow for servicing from about 14.6 thousand to 45 thousand households, depending on the scenario.

The FW planned to be produced in the Śląskie voivodeship provides the possibility of obtaining energy at a level from 172 GWh (for biological conversion—T1) through 380 GWh (for thermal conversion—T5) to 462–530 GWh (for thermochemical conversion—T4) in 2030, and from 133–216 GWh (for biological conversion—T1), through 294–477 GWh (for thermal conversion—T5), to 358–665 GWh (for thermochemical conversion—T4) in 2050.

In turn, in the Świętokrzyskie voivodeship, the use of the analyzed conversion technologies provides the possibility of obtaining net energy in the range from 25 GWh (for biological conversion—T1) to 51–85 GWh (for thermochemical conversion—T4) in 2030. In this case, it is also possible to consider incineration (T5) with a net energy potential of 73 GWh. In 2050, net energy from biological methods (T1) is expected to be obtained at 19–31 GWh and from for thermochemical conversion (T4)—to 42–108 GWh.

The high SFWGR corresponds to the high energy production rate from FW per unit area of the voivodeship. This indicator will reach the highest value in the Silesian region, at 10.8–53.9 MWh km^{-2}, depending on the technology and scenario used. In the case of the Świętokrzyskie voivodeship, this indicator will be much lower—at 1.6–10.5 MWh km^{-2}.

Figure 11 illustrates the discrepancy in energy potential between selected cities for the analyzed technologies in scenarios S1 and S2. The fluctuations in energy potential across different scenarios are attributable to the varying local trends in FW generation.



(c)

Figure 11. The energy potential (in GWh) of individual FW processing methods for S1(2050) and S2 (2030 and 2050), for Warsaw (**a**), Wrocław (**b**), and Łodź (**c**).

In Kraków, Warsaw, and Wrocław, thermochemical methods (T4) will be recommended due to the significant predicted increase in the amount of FW produced in 2030–2050 according to S1 at the level of 24–32% and a slight decrease at the level of 2–8% according to S2.

5. Conclusions

In accordance with the waste management hierarchy, it is important to recognize the priority of prevention, reuse, and recycling throughout the food supply chain. In this context, the significance of energy recovery as a sustainable solution for extracting value, particularly from unavoidable FW, is critical to consider. Efficient energy recovery strategies for FW can significantly improve the sustainability of urban and rural communities by providing efficient waste management solutions and sustainable energy access.

The selection path for technology for energy-efficient FW processing should be based on the current state of knowledge about technologies, population density, and demographic changes in the region, the nature/character of areas, and the perspective of FW generation with the SFWGR and its energy potential. The most important criteria used for selecting energy-efficient FW processing technologies in the region include (1) a trend in the amount of FW generation, (2) SFWGR, and (3) the energy potential of the technology.

The analysis indicated that population density and SFWGR significantly influence the radius of FW transport. In areas with a high population density (over 1500 Inh km^{-2}) and high SFWGR (>200 Mg km^{-2}), the distance is typically shorter, with distances up to 15 km observed as a consequence of the concentrated FW generation. Lower-density semi-urban and rural areas with a lower value of the SFWGR require a larger transport radius, within the 50–60 km range, due to the influence of dispersed FW generation. In addition, in less populated areas with a lower SFWGR (<20 Mg km^{-2}), the strategy of combining substrates, which will allow for the co-processing of food waste with green waste and, in the next phase (with favorable formal and legal conditions), also with other bio-waste, e.g., of agricultural origin or with sewage sludge, should be considered. Decentralized solutions such as small- and medium-scale methane fermentation units (wet AD) or composting plants will be more suitable. Biocarbonization systems can be integrated with composting in rural regions.

Fast pyrolysis will provide the most significant energy benefits among thermochemical processes, followed by moderate pyrolysis and biocarbonization—at similar levels. Analyses indicate that incineration also enables effective energy recovery from FW, in this respect, placing itself between carbonization and gasification. However, this technology is associated with high emissions and resource wastage. In the long term, it should be replaced by modernized thermochemical methods, which should become increasingly efficient as advanced feedstock pre-treatment methods are developed.

Waste prevention activities will have a key impact on the selection path for energy-efficient food waste management, as evidenced by the significant differences in the amount of waste generated between scenarios S1 and S2 included in the analysis, especially in the long term.

Great hopes are placed on hydrothermal carbonization, a synergistic combination of thermochemical and biological processes, making it possible to process wet biomass without pre-drying. There are many unknowns in the situation for the year 2050, which makes long-term strategic planning difficult today. It is certainly important that future solutions, especially in the field of energy from food waste, are adapted to projected changes in local conditions. A promising direction in this context is the development of hybrid technologies, which allow for the modular development of the processing capacity and implementation of new technologies, increasing the efficiency and flexibility of traditional solutions.

Author Contributions: Conceptualization, A.R.-K. and K.L.-S.; methodology, A.R.-K.; validation, K.L.-S. and P.M.; formal analysis, P.M.; investigation, A.R.-K. and K.L.-S.; resources, A.R.-K. and K.L.-S.; data curation, K.L.-S. and A.R.-K.; writing—original draft preparation, A.R.-K.; writing—review and editing, K.L.-S. and P.M.; visualization, A.R.-K.; supervision, P.M.; funding acquisition, P.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Warsaw University of Technology Excellence Initiative Program Research University (IDUB), grant number POB 1820/56/Z01/2021.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Flanagan, K.; Robertson, K.; Hanson, C. *Reducing Food Loss and Waste: Setting a Global Action Agenda*; WRI Publications: Washington, DC, USA, 2019. [CrossRef]
2. Martin-Rios, C.; Arboleya, J.; Bolton, J.; Erhardt, N. Editorial: Sustainable Food Waste Management. *Front. Sustain. Food Syst.* **2022**, *6*, 885250. [CrossRef]
3. Amato, C.; Jerie, S.; Mutekwa, T.V. Impacts of Solid Waste Management Strategies in Urban High-Density Suburbs: A Case of Amaveni Suburb, Kwekwe, Zimbabwe. *Discov. Environ.* **2024**, *2*, 97. [CrossRef]
4. Tamasiga, P.; Miri, T.; Onyeaka, H.; Hart, A. Food Waste and Circular Economy: Challenges and Opportunities. *Sustainability* **2022**, *14*, 9896. [CrossRef]
5. Garcia-Garcia, G.; Woolley, E.; Rahimifard, S. A Framework for a More Efficient Approach to Food Waste Management. *Int. J. Food Eng.* **2015**, *1*, 65–72. [CrossRef]
6. Papargyropoulou, E.; Lozano, R.; Steinberger, J.K.; Wright, N.; bin Ujang, Z. The food waste hierarchy as a framework for the management of food surplus and food waste. *J. Clean. Prod.* **2014**, *76*, 106–115. [CrossRef]
7. Jiang, S.; Chen, H.; Vittuari, M.; Wu, J.A.; Wang, Y. Mapping quantity, composition, and embedded environmental impacts of post-consumer waste in the food service industry in China. *Waste Manag.* **2024**, *187*, 167–178. [CrossRef] [PubMed]
8. Parfitt, J.; Barthel, M.; Macnaughton, S. Food waste within food supply chains: Quantification and potential for change to 2050. *Philos. Trans. R. Soc. B Biol. Sci.* **2010**, *365*, 3065–3081. [CrossRef]
9. Ferdeș, M.; Zăbavă, B.Ș.; Paraschiv, G.; Ionescu, M.; Dincă, M.N.; Moiceanu, G. Food Waste Management for Biogas Production in the Context of Sustainable Development. *Energies* **2022**, *15*, 6268. [CrossRef]
10. Tursun, Y.; Xu, S.; Abulikemu, A.; Dilinuer, T. Biomass gasification for hydrogen rich gas in a decoupled triple bed gasifier with olivine and NiO/olivine. *Bioresour. Technol.* **2019**, *272*, 241–248. [CrossRef]
11. Zhou, J.; Li, D.; Zhang, X.; Liu, C.; Chen, Y. Valorization of protein-rich waste and its application. *Sci. Total Environ.* **2023**, *901*, 166141. [CrossRef]
12. Bujak, J.; Sitarz, P. Incineration of animal by-products–The impact of selected parameters on the flux of flue gas enthalpy. *Waste Manag.* **2016**, *50*, 309–323. [CrossRef]
13. Diaz-Ruiz, R.; Costa-Font, M.; López-i-Gelats, F.; Gil, J.M. Food waste prevention along the food supply chain: A multi-actor approach to identify effective solutions. *Resour. Conserv. Recycl.* **2019**, *149*, 249–260. [CrossRef]
14. Lelicińska-Serafin, K.; Manczarski, P.; Rolewicz-Kalińska, A. An Insight into Post-Consumer Food Waste Characteristics as the Key to an Organic Recycling Method Selection in a Circular Economy. *Energies* **2023**, *16*, 1735. [CrossRef]
15. Bojanowicz-Bablok, A.; Bidłasik, M.; Horak, N.; Kuśmierz, A.; Potapowicz, I. *The Institute of Environmental Protection*; National Research Institute: Warsaw, Poland, 2024; ISBN 978-83-972509-2-5. Available online: https://open.icm.edu.pl/handle/123456789/24728 (accessed on 20 November 2024).
16. Eurostat. Food Waste and Food Waste Prevention—Estimates. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Food_waste_and_food_waste_prevention_-_estimates (accessed on 30 November 2024).
17. Institute of Environmental Protection—Conference Material. Available online: https://ios.edu.pl/wp-content/uploads/2024/09/konferencja-mrirw.pdf (accessed on 6 December 2024).
18. Dou, Z.; Toth, J.D. Global primary data on consumer food waste: Rate and characteristics—A review. *Resour. Conserv. Recycl.* **2021**, *168*, 105332. [CrossRef]
19. European Parliament and Council. *Consolidated Text: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives (Text with EEA Relevance)*; European Union: Brussels, Belgium, 2024; Available online: http://data.europa.eu/eli/dir/2008/98/2024-02-18 (accessed on 20 December 2024).
20. Teigiserova, D.A.; Hamelin, L.; Thomsen, M. Towards transparent valorization of food surplus, waste and loss: Clarifying definitions, food waste hierarchy, and role in the circular economy. *Sci. Total Environ.* **2020**, *706*, 136033. [CrossRef] [PubMed]
21. Wang, K.; Tester, J.W. Sustainable management of unavoidable biomass wastes. *Green. Energy Res.* **2023**, *1*, 100005. [CrossRef]
22. Elgarahy, A.M.; Eloffy, M.G.; Alengebawy, A.; El-Sherif, D.M.; Gaballah, M.S.; Elwakeel, K.Z.; El-Qelish, M. Sustainable management of food waste; pre-treatment strategies, techno-economic assessment, bibliometric analysis, and potential utilizations: A systematic review. *Environ. Res.* **2023**, *225*, 115558. [CrossRef]
23. Awasthi, M.K.; Sarsaiya, S.; Wainaina, S.; Rajendran, K.; Awasthi, S.K.; Liu, T.; Duan, Y.; Jain, A.; Sindhu, R.; Binod, P.; et al. Techno-economics and life-cycle assessment of biological and thermochemical treatment of bio-waste. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110837. [CrossRef]
24. Wang, Z.; Hu, Y.; Wang, S.; Wu, G.; Zhan, X. A critical review on dry anaerobic digestion of organic waste: Characteristics, operational conditions, and improvement strategies. *Renew. Sustain. Energy Rev.* **2023**, *176*, 113208. [CrossRef]
25. Menzel, T.; Neubauer, P.; Junne, S. Role of microbial hydrolysis in anaerobic digestion. *Energies* **2020**, *13*, 5555. [CrossRef]
26. Hu, Y.; Shen, C. Thermophilic-mesophilic temperature phase anaerobic co-digestion compared with single phase co-digestion of sewage sludge and food waste. *Sci. Rep.* **2024**, *14*, 62998. [CrossRef] [PubMed]

27. Economou, F.; Voukkali, I.; Papamichael, I.; Phinikettou, V.; Loizia, P.; Naddeo, V.; Sospiro, P.; Liscio, M.C.; Zoumides, C.; Țîrcă, D.M.; et al. Turning Food Loss and Food Waste into Watts: A Review of Food Waste as an Energy Source. *Energies* **2024**, *17*, 3191. [CrossRef]
28. Wang, S.; Zou, C.; Lou, C.; Yang, H.; Mei, M.; Jing, H.; Cheng, S. Effects of hemicellulose, cellulose and lignin on the ignition behaviors of biomass in a drop tube furnace. *Bioresour. Technol.* **2020**, *310*, 123456. [CrossRef]
29. Gong, J.S.; Zhang, Q.; Gu, B.C.; Dong, T.T.; Li, H.; Li, H.; Lu, Z.M.; Shi, J.S.; Xu, Z.H. Efficient biocatalytic synthesis of nicotinic acid by recombinant nitrilase via high density culture. *Bioresour. Technol.* **2018**, *260*, 427–431. [CrossRef]
30. Ellacuriaga, M.; Cascallana, J.G.; González, R.; Gómez, X. High-Solid Anaerobic Digestion: Reviewing Strategies for Increasing Reactor Performance. *Environments* **2021**, *8*, 80. [CrossRef]
31. Faisal, S.; Thakur, N.; Jalalah, M.; Harraz, F.A.; Al-Assiri, M.S.; Saif, I.; Salama, E.S. Facilitated lignocellulosic biomass digestibility in anaerobic digestion for biomethane production: Microbial communities' structure and interactions. *J. Chem. Technol. Biotechnol.* **2021**, *96*, 1798–1817. [CrossRef]
32. Carraro, G.; Tonderski, K.; Enrich-Prast, A. Solid-liquid separation of digestate from biogas plants: A systematic review of the techniques' performance. *J. Environ. Manag.* **2024**, *356*, 120585. [CrossRef]
33. Tse, T.J.; Wiens, D.J.; Chicilo, F.; Purdy, S.K.; Reaney, M.J.T. Value-Added Products from Ethanol Fermentation—A Review. *Fermentation* **2021**, *7*, 267. [CrossRef]
34. Ladisch, M.R.; Svarczkopf, J.A. Ethanol production and the cost of fermentable sugars from biomass. *Bioresour. Technol.* **1991**, *36*, 83–95. [CrossRef]
35. Iwuozor, K.O.; Emmanuel, S.S.; Bello-Hassan, M.T.; Emenike, E.C.; Adeniyi, A.G. Advancements in high gravity fermentation strategies for optimizing ethanol production from sugarcane-based substrates. *Sugar Tech.* **2024**, *26*, 1016–1032. [CrossRef]
36. Beluhan, S.; Mihajlovski, K.; Šantek, B.; Ivančić Šantek, M. The production of bioethanol from lignocellulosic biomass: Pretreatment methods, fermentation, and downstream processing. *Energies* **2023**, *16*, 7003. [CrossRef]
37. Mankar, A.R.; Pandey, A.; Modak, A.; Pant, K.K. Pretreatment of lignocellulosic biomass: A review on recent advances. *Bioresour. Technol.* **2021**, *334*, 125235. [CrossRef]
38. Zhao, L.; Sun, Z.F.; Zhang, C.C.; Nan, J.; Ren, N.Q.; Lee, D.J.; Chen, C. Advances in pretreatment of lignocellulosic biomass for bioenergy production: Challenges and perspectives. *Bioresour. Technol.* **2022**, *343*, 126123. [CrossRef] [PubMed]
39. Li, J.; Zhao, R.; Xu, Y.; Wu, X.; Bean, S.R.; Wang, D. Fuel ethanol production from starchy grain and other crops: An overview on feedstocks, affecting factors, and technical advances. *Renew. Energy* **2022**, *188*, 223–239. [CrossRef]
40. Bibra, M.; Samanta, D.; Sharma, N.K.; Singh, G.; Johnson, G.R.; Sani, R.K. Food Waste to Bioethanol: Opportunities and Challenges. *Fermentation* **2023**, *9*, 8. [CrossRef]
41. Yin, J.; Xie, M.; Yu, X.; Feng, H.; Wang, M.; Zhang, Y.; Chen, T. A review of the definition, influencing factors, and mechanisms of rapid composting of organic waste. *Environ. Pollut.* **2024**, *342*, 123125. [CrossRef]
42. Ghinea, C.; Apostol, L.C.; Prisacaru, A.E.; Leahu, A. Development of a model for food waste composting. *Environ. Sci. Pollut. Res.* **2019**, *26*, 4056–4069. [CrossRef]
43. Microbiological activities in the composting process—A review. *COLUMELLA-J. Agric. Environ. Sci.* **2021**, *8*, 41–53. [CrossRef]
44. Lepesteur, M. Human and livestock pathogens and their control during composting. *Crit. Rev. Environ. Sci. Technol.* **2021**, *52*, 1639–1683. [CrossRef]
45. Zhou, J.Y.; Zhong, H.M.; An., Z.G.; Niu, K.F.; Zhang, X.X.; Yao, Z.Q.; Yuan, J.; Nie, P.; Yang, L.G. Dung treated by high-temperature composting is an optimal bedding material for suckling calves according to analyses of microbial composition, growth performance, health status, and behavior. *J. Dairy Sci.* **2023**, *106*, 4785–4798. [CrossRef]
46. Liu, Z.; Wang, X.; Wang, F.; Bai, Z.; Chadwick, D.R.; Misselbrook, T.H.; Ma, L. The progress of composting technologies from static heap to intelligent reactor: Benefits and limitations. *J. Clean. Prod.* **2020**, *270*, 122328. [CrossRef]
47. Fan, S.; Li, A.; Heijne, A.T.; Buisman, C.J.; Chen, W.S. Heat potential, generation, recovery and utilization from composting: A review. *Resour. Conserv. Recycl.* **2021**, *175*, 105850. [CrossRef]
48. Negri, C.; Ricci, M.; Zilio, M.; D'Imporzano, G.; Qiao, W.; Dong, R.; Adani, F. Anaerobic digestion of food waste for bio-energy production in China and Southeast Asia: A review. *Renew. Sustain. Energy Rev.* **2020**, *133*, 110138. [CrossRef]
49. De Boni, A.; Melucci, F.M.; Acciani, C.; Roma, R. Community composting: A multidisciplinary evaluation of an inclusive, participative, and eco-friendly approach to biowaste management. *Clean. Environ. Syst.* **2022**, *6*, 100092. [CrossRef]
50. Mao, I.F.; Tsai, C.J.; Shen, S.H.; Lin, T.F.; Chen, W.K.; Chen, M.L. Critical components of odors in evaluating the performance of food waste composting plants. *Sci. Total Environ.* **2006**, *370*, 323–329. [CrossRef] [PubMed]
51. Azim, K.; Soudi, B.; Boukhari, S.; Perissol, C.; Roussos, S.; Thami Alami, I. Composting parameters and compost quality: A literature review. *Org. Agric.* **2018**, *8*, 141–158. [CrossRef]
52. Manu, M.K.; Li, D.; Liwen, L.; Jun, Z.; Varjani, S.; Wong, J.W.C. A review on nitrogen dynamics and mitigation strategies of food waste digestate composting. *Bioresour. Technol.* **2021**, *334*, 125032. [CrossRef]

53. Igliński, B.; Kujawski, W.; Kiełkowska, U. Pyrolysis of Waste Biomass: Technical and Process Achievements, and Future Development—A Review. *Energies* **2023**, *16*, 1829. [CrossRef]
54. Aboelela, D.; Saleh, H.; Attia, A.M.; Elhenawy, Y.; Majozi, T.; Bassyouni, M. Recent Advances in Biomass Pyrolysis Processes for Bioenergy Production: Optimization of Operating Conditions. *Sustainability* **2023**, *15*, 11238. [CrossRef]
55. Vuppaladadiyam, A.K.; Vuppaladadiyam, S.S.V.; Sahoo, A.; Murugavelh, S.; Anthony, E.; Bhaskar, T.; Zheng, Y.; Zhao, M.; Duan, H.; Zhao, Y.; et al. Bio-oil and biochar from the pyrolytic conversion of biomass: A current and future perspective on the trade-off between economic, environmental, and technical indicators. *Sci. Total Environ.* **2023**, *857*, 159155. [CrossRef]
56. Frantzi, D.; Zabaniotou, A. Waste-based intermediate bioenergy carriers: Syngas production via coupling slow pyrolysis with gasification under a circular economy model. *Energies* **2021**, *14*, 7366. [CrossRef]
57. Kavan Kumar, V.; Panwar, N.L. Pyrolysis technologies for biochar production in waste management: A review. *Clean. Energy* **2024**, *8*, 61–78. [CrossRef]
58. Czajczyńska, D.; Anguilano, L.; Ghazal, H.; Krzyżyńska, R.; Reynolds, A.; Spencer, N.; Jouhara, H. Potential of pyrolysis processes in the waste management sector. *Therm. Sci. Eng. Prog.* **2017**, *3*, 171–197. [CrossRef]
59. Mong, G.R.; Chong, C.T.; Chong, W.W.F.; Ng, J.H.; Ong, H.C.; Ashokkumar, V.; Yasin, M.F.M. Progress and challenges in sustainable pyrolysis technology: Reactors, feedstocks and products. *Fuel* **2022**, *324*, 124777. [CrossRef]
60. El Bari, H.; Fanezoune, C.K.; Dorneanu, B.; Arellano-Garcia, H.; Majozi, T.; Elhenawy, Y.; Ashour, F. Catalytic fast pyrolysis of lignocellulosic biomass: Recent advances and comprehensive overview. *J. Anal. Appl. Pyrolysis* **2024**, *178*, 106390. [CrossRef]
61. Dada, T.K.; Sheehan, M.; Murugavelh, S.; Antunes, E. A review on catalytic pyrolysis for high-quality bio-oil production from biomass. *Biomass Convers. Biorefin.* **2023**, *13*, 2595–2614. [CrossRef]
62. Vershinina, K.; Nyashina, G.; Strizhak, P. Combustion, pyrolysis, and gasification of waste-derived fuel slurries, low-grade liquids, and high-moisture waste: Review. *Appl. Sci.* **2022**, *12*, 1039. [CrossRef]
63. Galavote, T.; Cerqueira, A.; Alves, R.; Ramalho, J.; Yamane, L.; Siman, R. Energy recovery technologies from municipal solid waste: Enhancing solid waste Brazilian policy. *Rev. Bras. Energia* **2022**, *28*, 1–15. [CrossRef]
64. Rezania, S.; Oryani, B.; Nasrollahi, V.R.; Darajeh, N.; Lotfi Ghahroud, M.; Mehranzamir, K. Review on waste-to-energy approaches toward a circular economy in developed and developing countries. *Processes* **2023**, *11*, 2566. [CrossRef]
65. Khan, M.S.; Mubeen, I.; Yu, C.; Zhu, G.; Khalid, A.; Yan, M. Waste-to-energy incineration technology: Recent development under climate change scenarios. *Waste Manag. Res.* **2022**, *40*, 1054–1068. [CrossRef]
66. 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]
67. Thabit, Q.; Nassour, A.; Nelles, M. Flue gas composition and treatment potential of a waste incineration plant. *Appl. Sci.* **2022**, *12*, 5236. [CrossRef]
68. Dadario, N.; Gabriel Filho, L.R.A.; Cremasco, C.P.; Santos, F.A.d.; Rizk, M.C.; Mollo Neto, M. Waste-to-energy recovery from municipal solid waste: Global scenario and prospects of mass burning technology in Brazil. *Sustainability* **2023**, *15*, 5397. [CrossRef]
69. Cheng, S.Y.; Tan, X.; Show, P.L.; Rambabu, K.; Banat, F.; Veeramuthu, A.; Lau, B.F.; Ng, E.P.; Ling, T.C. Incorporating biowaste into circular bioeconomy: A critical review of current trend and scaling up feasibility. *Environ. Technol. Innov.* **2020**, *19*, 101034. [CrossRef]
70. Sharma, K.; Sharma, M.; Kaul, K.; Singh, G.; Arya, S. Commercial waste to energy, technologies, economics, and challenges: Stores, hotels, restaurant. In *Advances in Sustainable Waste Management*; Elsevier: Amsterdam, The Netherlands, 2024; pp. 1–12. [CrossRef]
71. Hoang, A.; Varbanov, P.; Nižetić, S.; Sirohi, R.; Pandey, A.; Luque, R.; Ng, K.; Pham, V.V. Perspective review on municipal solid waste-to-energy route: Characteristics, management strategy, and role in circular economy. *J. Clean. Prod.* **2022**, *359*, 131897. [CrossRef]
72. Slorach, P.; Jeswani, H.; Cuéllar-Franca, R.; Azapagic, A. Environmental and economic implications of recovering resources from food waste in a circular economy. *Sci. Total Environ.* **2019**, *693*, 133897. [CrossRef]
73. Verheijen, F.; Jeffery, S.; Bastos, A.; Van Der Velde, M.; Diafas, I. *Biochar Application to Soils—A Critical Scientific Review of Effects on Soil Properties, Processes and Functions*; EUR 24099 EN; European Commission: Luxembourg, 2010; JRC55799.
74. Murugesan, P.; Raja, V.; Dutta, S.; Moses, J.A.; Anandharamakrishnan, C. Food waste valorisation via gasification—A review on emerging concepts, prospects and challenges. *Sci. Total Environ.* **2022**, *851*, 157955. [CrossRef]
75. Bhatia, S.K.; Joo, H.S.; Yang, Y.H. Biowaste-to-bioenergy using biological methods—A mini-review. *Energy Convers. Manag.* **2018**, *177*, 640–660. [CrossRef]
76. Lohri, C.R.; Diener, S.; Zabaleta, I.; Mertenat, A.; Zurbrügg, C. Treatment technologies for urban solid biowaste to create value products: A review with focus on low- and middle-income settings. *Rev. Environ. Sci. Biotechnol.* **2017**, *16*, 81–130. [CrossRef]
77. Alengebawy, A.; Ran, Y.; Osman, A.; Jin, K.; Samer, M.; Ai, P. Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: A review. *Environ. Chem. Lett.* **2024**, *22*, 2641–2668. [CrossRef]

78. Tabasso, S.; Ginepro, M.; Tomasso, L.; Montoneri, E.; Nisticò, R.; Francavilla, M. Integrated biochemical and chemical processing of municipal bio-waste to obtain bio-based products for multiple uses: The case of soil remediation. *J. Clean. Prod.* **2020**, *245*, 119191. [CrossRef]
79. Jain, A.; Sarsaiya, S.; Awasthi, M.K.; Singh, R.; Rajput, R.; Mishra, U.C.; Shi, J. Bioenergy and bio-products from bio-waste and its associated modern circular economy: Current research trends, challenges, and future outlooks. *Fuel* **2022**, *307*, 121859. [CrossRef]
80. Manczarski, P.; Rolewicz-Kalińska, A.; Lelicińska-Serafin, K. Quantitative Analysis of Household Food Waste Collection in Warsaw: Assessing Efficiency and Waste Minimization. *Sustainability* **2023**, *15*, 16827. [CrossRef]
81. Di Stefano, V.; Durazzo, A.; Lucarini, M. Food Waste: Treatments, Environmental Impacts, Current and Potential Uses. *Sustainability* **2022**, *14*, 234. [CrossRef]
82. Becker, S.; Fanzo, J. Population and food systems: What does the future hold? *Popul. Environ.* **2023**, *45*, 20. [CrossRef]
83. Central Statistical Office of Poland (GUS). Administrative Division of Poland. Available online: https://stat.gov.pl/en/regional-statistics/classification-of-territorial-units/administrative-division-of-poland/ (accessed on 10 November 2024).
84. Wikimedia Commons. Map of Polish Voivodeships. Available online: https://commons.wikimedia.org/wiki/File:POL_voivodships_map.svg (accessed on 30 December 2024).
85. Central Statistical Office of Poland (GUS). Available online: https://stat.gov.pl/en/regional-statistics/classification-of-territorial-units/delimitation-of-rural-areas/ (accessed on 20 October 2024).
86. Central Statistical Office of Poland (GUS). Urbanization Levels—DEGURBA. Available online: https://stat.gov.pl/en/regional-statistics/classification-of-territorial-units/union-territorial-typologies-tercet/degree-of-urbanisation-degurba/ (accessed on 11 October 2024).
87. Central Statistical Office of Poland (GUS). Demographic Forecast. Available online: https://stat.gov.pl/en/topics/population/population-projection/population-projection-20232060,4,1.html (accessed on 20 October 2024).
88. Central Statistical Office of Poland (GUS). Data on Waste Generation for years 2003-2023. Bank Danych Lokalnych—Statistical Data. Available online: https://bdl.stat.gov.pl/bdl/metadane/podgrupy/223 (accessed on 11 October 2024).
89. European Commission. Proposal for a Directive of the European Parliament and of the Council amending Directive 2008/98/EC on Waste. COM/2023/420 final. Official Journal of the European Union. 2023. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52023PC0420 (accessed on 30 December 2024).
90. Kolanowska, J.; Skwara, A. Households Biological Waste from Different Urban Environments—Technological and Survey Research and Proposed Solutions Regarding Their Selective Collection in the Capital City of Warsaw. Master's Thesis, Warsaw University of Technology, Warsaw, Poland, 2021. Supervisors: Lelicińska-Serafin, K.; Rolewicz-Kalińska, A. (Unpublished Work). Available online: https://apd.usos.pw.edu.pl/diplomas/41174/ (accessed on 7 November 2024).
91. Matsakas, L.; Kekos, D.; Loizidou, M.; Christakopoulos, P. Utilization of household food waste for the production of ethanol at high dry material content. *Biotechnol. Biofuels* **2014**, *7*, 4. [CrossRef]
92. IEA. *Outlook for Biogas and Biomethane: Prospects for Organic Growth*; IEA: Paris, France, 2020; Available online: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth (accessed on 20 April 2024).
93. Ouadi, M.; Bashir, M.A.; Speranza, L.G.; Jahangiri, H.; Hornung, A. Food and market waste—A pathway to sustainable fuels and waste valorization. *Energy Fuels* **2019**, *33*, 9843–9850. [CrossRef]
94. Meyer-Kohlstock, D.; Haupt, T.; Heldt, E.; Heldt, N.; Kraft, E. Biochar as Additive in Biogas-Production from Bio-Waste. *Energies* **2016**, *9*, 247. [CrossRef]
95. Bong, C.P.C.; Lim, L.Y.; Lee, C.T.; Klemeš, J.J.; Ho, C.S.; Ho, W.S. The characterisation and treatment of food waste for improvement of biogas production during anaerobic digestion—A review. *J. Clean. Prod.* **2018**, *172*, 1545–1558. [CrossRef]
96. Al-Wahaibi, A.; Osman, A.I.; Al-Muhtaseb, A.H.; Alqaisi, O.; Baawain, M.; Fawzy, S.; Rooney, D.W. Techno-economic evaluation of biogas production from food waste via anaerobic digestion. *Sci. Rep.* **2020**, *10*, 15719. [CrossRef] [PubMed]
97. Lorenz, D.; Morris, D. *Ethanol Net Energy Balance*; Institute for Local Self Reliance: Washington, DC, USA, 1995; Available online: https://ilsr.org/wp-content/uploads/files/ethanolnetenergy.pdf (accessed on 12 November 2024).
98. Fambri, G.; Lombardi, G.; Badami, M.; Chiaramonti, D. Energy assessment of a slow pyrolysis plant for biochar and heat cogeneration. *Chem. Eng. Trans.* **2024**, *109*, 571–576. [CrossRef]
99. Jerzak, W.; Reinmöller, M.; Magdziarz, A. Estimation of the heat required for intermediate pyrolysis of biomass. *Clean. Technol. Environ. Policy* **2022**, *24*, 3061–3075. [CrossRef]
100. Wu, D.; Zhang, Z.; Yu, Z.; Zhu, L. Optimization of F/M ratio for stability of aerobic granular process via quantitative sludge discharge. *Bioresour. Technol.* **2018**, *252*, 150–156. [CrossRef]
101. Jędrczak, A. Composting and Fermentation of Biowaste—Advantages and Disadvantages of Processes. *Civ. Environ. Eng. Rep.* **2018**, *28*, 71–87. [CrossRef]
102. Ma, X.; Yu, M.; Song, N.; Xu, B.; Gao, M.; Wu, C.; Wang, Q. Effect of ethanol pre-fermentation on organic load rate and stability of semi-continuous anaerobic digestion of food waste. *Bioresour. Technol.* **2020**, *299*, 122587. [CrossRef]

103. Angelonidi, E.; Smith, S. A comparison of wet and dry anaerobic digestion processes for the treatment of municipal solid waste and food waste. *Water Environ. J.* **2015**, *29*, 549–557. [CrossRef]
104. Chatterjee, S.; Mohan, S.V. Refining of vegetable waste to renewable sugars for ethanol production: Depolymerization and fermentation optimization. *Bioresour. Technol.* **2021**, *340*, 125650. [CrossRef] [PubMed]
105. Robak, K.; Balcerek, M. Current state-of-the-art in ethanol production from lignocellulosic feedstocks. *Microbiol. Res.* **2020**, *240*, 126534. [CrossRef]
106. Yeh, C.K.; Lin, C.; Shen, H.C.; Cheruiyot, N.K.; Camarillo, M.E.; Wang, C.L. Optimizing food waste composting parameters and evaluating heat generation. *Appl. Sci.* **2020**, *10*, 2284. [CrossRef]
107. Palaniveloo, K.; Amran, M.A.; Norhashim, N.A.; Mohamad-Fauzi, N.; Peng-Hui, F.; Hui-Wen, L.; Kai-Lin, Y.; Jiale, L.; Chian-Yee, M.G.; Jing-Yi, L.; et al. Food waste composting and microbial community structure profiling. *Processes* **2020**, *8*, 723. [CrossRef]
108. Voběrková, S.; Maxianová, A.; Schlosserová, N.; Adamcová, D.; Vršanská, M.; Richtera, L.; Vaverková, M.D. Food waste composting—Is it really so simple as stated in scientific literature?–A case study. *Sci. Total Environ.* **2020**, *723*, 138202. [CrossRef]
109. Lelicińska-Serafin, K.; Rolewicz-Kalińska, A.; Manczarski, P. Challenges in the Valorization of Green Waste in the Central European Region: Case Study of Warsaw. *Energies* **2024**, *17*, 5056. [CrossRef]
110. Su, G.; Ong, H.C.; Fattah, I.R.; Ok, Y.S.; Jang, J.H.; Wang, C.T. State-of-the-art of the pyrolysis and co-pyrolysis of food waste: Progress and challenges. *Sci. Total Environ.* **2022**, *809*, 151170. [CrossRef] [PubMed]
111. Kim, S.; Lee, Y.; Lin, K.Y.A.; Hong, E.; Kwon, E.E.; Lee, J. The valorization of food waste via pyrolysis. *J. Clean. Prod.* **2020**, *259*, 120816. [CrossRef]
112. Zhao, J.; Wang, Z.; Li, J.; Yan, B.; Chen, G. Pyrolysis of food waste and food waste solid digestate: A comparative investigation. *Bioresour. Technol.* **2022**, *354*, 127191. [CrossRef] [PubMed]
113. Xu, F.; Ming, X.; Jia, R.; Zhao, M.; Wang, B.; Qiao, Y.; Tian, Y. Effects of operating parameters on products yield and volatiles composition during fast pyrolysis of food waste in the presence of hydrogen. *Fuel Process. Technol.* **2020**, *210*, 106558. [CrossRef]
114. Hasan, M.R.; Anzar, N.; Sharma, P.; Malode, S.J.; Shetti, N.P.; Narang, J.; Kakarla, R.R. Converting biowaste into sustainable bioenergy through various processes. *Bioresour. Technol. Rep.* **2023**, *23*, 101542. [CrossRef]
115. Kougioumtzis, M.A.; Kanaveli, I.P.; Karampinis, E.; Grammelis, P.; Kakaras, E. Combustion of olive tree pruning pellets versus sunflower husk pellets at industrial boiler: Monitoring of emissions and combustion efficiency. *Renew. Energy* **2021**, *171*, 516–525. [CrossRef]
116. Mayer, F.; Bhandari, R.; Gäth, S.A. Life cycle assessment on the treatment of organic waste streams by anaerobic digestion, hydrothermal carbonization and incineration. *Waste Manag.* **2021**, *130*, 93–106. [CrossRef]
117. Istrate, I.R.; Galvez-Martos, J.L.; Vázquez, D.; Guillén-Gosálbez, G.; Dufour, J. Prospective analysis of the optimal capacity, economics and carbon footprint of energy recovery from municipal solid waste incineration. *Resour. Conserv. Recycl.* **2023**, *193*, 106943. [CrossRef]
118. International Solid Waste Association (ISWA). Whitebook on Energy-from-Waste Technologies. 2023. Available online: https://www.iswa.org/wp-content/uploads/2023/07/ISWA-Whitebook-on-Energy-from-Waste-Technologies.pdf (accessed on 20 April 2024).
119. Miguez, M.G.; Veról, A.P.; Battemarco, B.P.; Yamamoto, L.M.T.; de Brito, F.A.; Fernandez, F.F.; Rego, A.Q. A framework to support the urbanization process on lowland coastal areas: Exploring the case of Vargem Grande–Rio de Janeiro, Brazil. *J. Clean. Prod.* **2019**, *231*, 1281–1293. [CrossRef]
120. Holden, E.; Linnerud, K.; Rygg, B.J. A review of dominant sustainable energy narratives. *Renew. Sustain. Energy Rev.* **2021**, *144*, 110955. [CrossRef]
121. Bilska, B.; Tomaszewska, M.; Kołożyn-Krajewska, D. Food waste in Polish households—Characteristics and sociodemographic determinants on the phenomenon. Nationwide research. *Waste Manag.* **2024**, *176*, 30–40. [CrossRef] [PubMed]
122. Grant, B. *Organics Processing Technology Assessment*; NSW EPA, Blue Environment: Sydney, Australia, 2023. Available online: https://www.epa.nsw.gov.au/-/media/epa/corporate-site/resources/wasteregulation/organics-processing-technology-emissions-2023.pdf (accessed on 27 December 2024).
123. Pavlas, M.; Dvořáček, J.; Pitschke, T.; Peche, R. Biowaste Treatment and Waste-To-Energy—Environmental Benefits. *Energies* **2020**, *13*, 1994. [CrossRef]
124. Kemppainen, A.J.; Shonnard, D.R. Comparative Life-Cycle Assessments for Biomass-to-Ethanol Production from Different Regional Feedstocks. *Biotechnol. Prog.* **2005**, *21*, 1075–1084. [CrossRef]
125. Sayara, T.; Sánchez, A. Gaseous Emissions from the Composting Process: Controlling Parameters and Strategies of Mitigation. *Processes* **2021**, *9*, 1844. [CrossRef]
126. Garrido, M.A.; Font, R.; Conesa, J.A. Pollutant Emissions during the Pyrolysis and Combustion of Flexible Polyurethane Foam. *Waste Manag.* **2016**, *52*, 138–146. [CrossRef]
127. Li, S. Reviewing Air Pollutants Generated during the Pyrolysis of Solid Waste for Biofuel and Biochar Production: Toward Cleaner Production Practices. *Sustainability* **2024**, *16*, 1169. [CrossRef]

128. Hutchings, N.; Mikkelsen, M.; Dore, C.; German, R.; Mitchell, J.; Thornton, A.; Sanchez, B.; Amon, B.; Mellios, G.; Juhrich, K.; et al. *EMEP/EEA Air Pollutant Emission Inventory Guidebook 2023: Technical Guidance to Prepare National Emission Inventories*; European Environment Agency: Copenhagen, Denmark, 2023; ISBN 978-92-9480-598-0. ISSN 1977-8449. [CrossRef]
129. Bilitewski, B.; Wagner, J.; Reichenbach, J. *Best Practice Municipal Waste Management: Information Pool on Approaches Towards a Sustainable Design of Municipal Waste Management and Supporting Technologies and Equipment*; TEXTE 40/2018; Umweltbundesamt (UBA): Dessau-Roßlau, Germany, 2018; Available online: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2018-05-30_texte_40-2018-municipal-waste-management_en.pdf (accessed on 25 December 2024).
130. International Bank for Reconstruction and Development/The World Bank. *Municipal Solid Waste Cost Calculation Technical Guidelines for Low- and Middle-Income Countries*; The World Bank: Washington, DC, USA, 2024; Available online: https://documents1.worldbank.org/curated/en/099032224175084042/pdf/P17734410d06ad0e91af6019fc9a2cd9659.pdf (accessed on 27 December 2024).
131. Kalligeros, S.; Maniatis, K.; Landälv, I.; van den Heuvel, E.; Waldheim, L. *Building Up the Future—Cost of Biofuel*; Publications Office of the European Union: Luxembourg, 2018. [CrossRef]
132. Susmozas, A.; Matschegg, D.; Davidis, B.; Spekreijse, J.; Tzelepi, V.; Kourkoumpas, D.-S.; Alonso, J.M.G.; Coto, B.; Iglesias, R. Economic and Environmental Assessment of the Retrofitting of a First-Generation Ethanol Plant. *Biomass Convers. Biorefin.* **2024**. [CrossRef]
133. Sakarika, M.; Spiller, M.; Baetens, R.; Donies, G.; Vanderstuyf, J.; Vinck, K.; Vrancken, K.C.; Van Barel, G.; Du Bois, E.; Vlaeminck, S.E. Proof of Concept of High-Rate Decentralized Pre-Composting of Kitchen Waste: Optimizing Design and Operation of a Novel Drum Reactor. *Waste Manag.* **2019**, *95*, 241–251. [CrossRef] [PubMed]
134. Salimbeni, A.; Lombardi, G.; Rizzo, A.M.; Chiaramonti, D. Techno-Economic Feasibility of Integrating Biomass Slow Pyrolysis in an EAF Steelmaking Site: A Case Study. *Appl. Energy* **2023**, *345*, 120991. [CrossRef]
135. Watson, J.; Zhang, Y.; Si, B.; Chen, W.-T.; de Souza, R. Gasification of Biowaste: A Critical Review and Outlooks. *Renew. Sustain. Energy Rev.* **2018**, *83*, 1–17. [CrossRef]
136. Arfan, M.; Eriksson, O.; Wang, Z.; Soam, S. Life Cycle Assessment and Life Cycle Costing of Hydrogen Production from Biowaste and Biomass in Sweden. *Energies Convers. Manag.* **2023**, *291*, 117262. [CrossRef]
137. Haeldermans, T.; Campion, L.; Kuppens, T.; Vanreppelen, K.; Cuypers, A.; Schreurs, S. A Comparative Techno-Economic Assessment of Biochar Production from Different Residue Streams Using Conventional and Microwave Pyrolysis. *Bioresour. Technol.* **2020**, *318*, 124083. [CrossRef] [PubMed]
138. KindleTech. How Much Does a Pyrolysis Unit Cost? KindleTech FAQs. Available online: https://kindle-tech.com/faqs/how-much-does-a-pyrolysis-unit-cost (accessed on 29 December 2024).
139. WTE International. Cost of Incineration Plant. Available online: https://wteinternational.com/news/cost-of-incineration-plant/ (accessed on 26 December 2024).
140. Hogg, D.; Eunomia Research & Consulting. *Costs for Municipal Waste Management in the EU: Final Report to Directorate General Environment, European Commission*; European Commission: Brussels, Belgium, 2001; Available online: http://projects.mcrit.com/ceara/attachments/article/154/cost%20for%20municipal%20waste%20management%20UE.pdf (accessed on 23 December 2024).
141. Tong, H.; Shen, Y.; Zhang, J.; Wang, C.-H.; Ge, T.S.; Tong, Y.W. A Comparative Life Cycle Assessment on Four Waste-to-Energy Scenarios for Food Waste Generated in Eateries. *Appl. Energy* **2018**, *225*, 1143–1157. [CrossRef]
142. den Boer, J.; Kobel, P.; den Boer, E.; Obersteiner, G. Food waste quantities and composition in Polish households. *Waste Manag. Res.* **2023**, *41*, 1318–1330. [CrossRef]
143. Household food waste generation in high-income countries: A scoping review and pooled analysis between 2010 and 2022. *J. Clean. Prod.* **2024**, *143375*. [CrossRef]
144. Vambol, V.; Kowalczyk-Juśko, A.; Vambol, S.; Khan, N.A.; Mazur, A.; Goroneskul, M.; Kruzhilko, O. Multi criteria analysis of municipal solid waste management and resource recovery in Poland compared to other EU countries. *Sci. Rep.* **2023**, *13*, 22053. [CrossRef]
145. Mazalan, M.; Bong, C.P.C.; Ho, W.S.; Lim, J.S.; Muis, Z.A.; Hashim, H.; Elagroudy, S.; Teck, G.L.H.; Ho, C.S. Review on the suitability of waste for appropriate waste-to-energy technology. *Chem. Eng. Trans.* **2018**, *63*, 187–192. [CrossRef]
146. Awino, F.B.; Apitz, S.E. Solid waste management in the context of the waste hierarchy and circular economy frameworks: An international critical review. *Integr. Environ. Assess. Manag.* **2024**, *20*, 9–35. [CrossRef]
147. Deviatkin, I.; Horttanainen, M.; Havukainen, J. Sustainability of Waste Management Systems: Energy Recovery. In *Encyclopedia of Sustainable Management*; Idowu, S.O., Schmidpeter, R., Capaldi, N., Zu, L., Del Baldo, M., Abreu, R., Eds.; Springer: Cham, Switzerland, 2023; pp. 1–5. [CrossRef]
148. Tait, P.W.; Brew, J.; Che, A.; Costanzo, A.; Danyluk, A.; Davis, M.; Khalaf, A.; McMahon, K.; Watson, A.; Rowcliff, K.; et al. The health impacts of waste incineration: A systematic review. *Aust. N. Z. J. Public Health* **2020**, *44*, 40–48. [CrossRef] [PubMed]

149. Salleh, N.A.; Mohd Shafiei, M.W.; Anwar, A.; Zulhumadi, F.; Hubadillah, S.K. Sustaining the environment: Critical success factors and barriers of solid waste management through composting practices by rural communities in Malaysia. *Sustainability* **2022**, *14*, 13541. [CrossRef]
150. Manea, E.E.; Bumbac, C.; Dinu, L.R.; Bumbac, M.; Nicolescu, C.M. Composting as a sustainable solution for organic solid waste management: Current practices and potential improvements. *Sustainability* **2024**, *16*, 6329. [CrossRef]
151. Ayilara, M.S.; Olanrewaju, O.S.; Babalola, O.O.; Odeyemi, O. Waste management through composting: Challenges and potentials. *Sustainability* **2020**, *12*, 4456. [CrossRef]
152. Ighalo, J.O.; Iwuchukwu, F.U.; Eyankware, O.E.; Iwuozor, K.O.; Olotu, K.; Bright, O.C.; Igwegbe, C.A. Flash pyrolysis of biomass: A review of recent advances. *Clean. Technol. Environ. Policy* **2022**, *24*, 2349–2363. [CrossRef]
153. Li, Y.; Chen, W.; Fang, S.; Xu, Z.; Weng, H.; Zhang, X. The influence of pyrolysis temperature and feedstocks on the characteristics of biochar-derived dissolved organic matter: A systematic assessment. *Clean. Technol.* **2024**, *6*, 1314–1325. [CrossRef]
154. Rolewicz-Kalińska, A.; Oniszk-Popławska, A.; Wesołowska, J.; Ryńska, E.D. Conditions for the development of anaerobic digestion technologies using the organic fraction of municipal solid waste: Perspectives for Poland. *Environ. Dev. Sustain.* **2016**, *18*, 1279–1296. [CrossRef]
155. Zhang, L.; Li, H.; Yang, L.; Du, X.; Zhou, Y.; Sun, G.; Liu, J. Carbon footprints of centralized and decentralized food waste utilization pathways. *Renew. Sustain. Energy Rev.* **2025**, *208*, 115040. [CrossRef]
156. Bilitewski, B.; Wagner, J.; Reichenbach, J. Sprawdzone Metody Gospodarowania Odpadami Komunalnymi. Zbiór Informacji i Założenia dla Zrównoważonej Gospodarki Odpadami Komunalnymi Wraz z Odpowiednimi Instalacjami i Technologiami Umweltbundesamt. Podręcznik Ochrony Środowiska. 2010. (In Polish). Available online: https://www.umweltbundesamt.de/sites/default/files/podrecznik.pdf (accessed on 2 January 2025).
157. Manfredi, S.; Pant, R. *Supporting Environmentally Sound Decisions for Bio-waste Management: A Practical Guide to Life Cycle Thinking (LCT) and Life Cycle Assessment (LCA)*; Publications Office of the European Union: Luxembourg, 2011; EUR 24917 EN; ISBN 978-92-79-21019-8. [CrossRef]
158. Lubańska, A.; Kazak, J.K. The role of biogas production in circular economy approach from the perspective of locality. *Energies* **2023**, *16*, 3801. [CrossRef]
159. Hannan, M.A.; Begum, R.; Al-Shetwi, A.; Ker, P.J.; Mamun, M.A.; Hussain, A.; Basri, H.; Mahlia, T.M.I. Waste collection route optimisation model for linking cost saving and emission reduction to achieve sustainable development goals. *Sustain. Cities Soc.* **2020**, *62*, 102393. [CrossRef]
160. Weber, L.; Bartek, L.; Brancoli, P.; Sjölund, A.; Eriksson, M. Climate change impact of food distribution: The case of reverse logistics for bread in Sweden. *Sustain. Prod. Consum.* **2023**, *36*, 386–396. [CrossRef]
161. Xu, Y.; Sahnoun, M.; Ben Abdelaziz, F.; Louis, A. Multimodal transportation network for bio-waste collection: The case of Normandy. *Ann. Oper. Res.* **2024**. [CrossRef]
162. Sharma, P.; Bano, A.; Singh, S.P.; Varjani, S.; Tong, Y.W. Sustainable organic waste management and future directions for environmental protection and techno-economic perspectives. *Curr. Pollut. Rep.* **2024**, *10*, 459–477. [CrossRef]
163. Zhou, Y.; Xiao, R.; Klammsteiner, T.; Kong, X.; Yan, B.; Mihai, F.C.; Awasthi, M.K. Recent trends and advances in composting and vermicomposting technologies: A review. *Bioresour. Technol.* **2022**, *360*, 127591. [CrossRef] [PubMed]
164. Applications of machine learning tools for biological treatment of organic wastes: Perspectives and challenges. *Curr. Environ. Chang.* **2024**, *3*, 100088. [CrossRef]
165. Joshi, L.; Bharti, R.; Singh, R. Internet of things and machine learning-based approaches in the urban solid waste management: Trends, challenges, and future directions. *Expert Syst.* **2021**, *39*, e12865. [CrossRef]
166. Singh, D.; Dikshit, A.K.; Kumar, S. Smart technological options in collection and transportation of municipal solid waste in urban areas: A mini review. *Waste Manag. Res.* **2024**, *42*, 3–15. [CrossRef]
167. Olívierı, L.M.; Arfò, S.; Matarazzo, A.; D'Urso, D.; Chıacchıo, F. Improving the composting process of a treatment facility via an Industry 4.0 monitoring and control solution: Performance and economic feasibility assessment. *J. Environ. Manag.* **2023**, *345*, 118776. [CrossRef]
168. Tayibi, S.; Monlau, F.; Bargaz, A.; Jimenez, R.; Barakat, A. Synergy of anaerobic digestion and pyrolysis processes for sustainable waste management: A critical review and future perspectives. *Renew. Sustain. Energy Rev.* **2021**, *152*, 111603. [CrossRef]
169. Singh, R.; Paritosh, K.; Pareek, N.; Vivekanand, V. Integrated system of anaerobic digestion and pyrolysis for valorization of agricultural and food waste towards circular bioeconomy: Review. *Bioresour. Technol.* **2022**, *360*, 127596. [CrossRef] [PubMed]
170. Rathore, P.; Chakraborty, S.; Gupta, M.; Sarmah, S.P. Towards a sustainable organic waste supply chain: A comparison of centralized and decentralized systems. *J. Environ. Manag.* **2022**, *315*, 115141. [CrossRef]
171. Tonini, D.; Wandl, A.; Meister, K.; Unceta, P.M.; Taelman, S.E.; Sanjuan-Delmás, D.; Dewulf, J.; Huygens, D. Quantitative sustainability assessment of household food waste management in the Amsterdam Metropolitan Area. *Resour. Conserv. Recycl.* **2020**, *160*, 104854. [CrossRef] [PubMed]

172. Dalke, R.; Demro, D.; Khalid, Y.; Wu, H.; Urgun-Demirtas, M. Current status of anaerobic digestion of food waste in the United States. *Renew. Sustain. Energy Rev.* **2021**, *151*, 111554. [CrossRef]
173. Tsafara, P.; Passadis, K.; Christianides, D.; Chatziangelakis, E.; Bousoulas, I.; Malamis, D.; Mai, S.; Barampouti, E.M.; Moustakas, K. Advanced bioethanol production from source-separated bio-waste in pilot scale. *Sustainability* **2022**, *14*, 12127. [CrossRef]