sustainability

MDPI

Article

Quantitative Analysis of Household Food Waste Collection in Warsaw: Assessing Efficiency and Waste Minimization

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

Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, 00-653 Warsaw, Poland; piotr.manczarski@pw.edu.pl (P.M.); anna.kalinska@pw.edu.pl (A.R.-K.)
* Correspondence: krystyna.lelicinska@pw.edu.pl

Abstract: Food waste management is one of the key challenges of the circular economy and climate transition policies. The proper collection of food waste is the starting point for its further value recovery. Most of the quantitative and qualitative data used to measure the scale of food waste in households and its collection are based on statistical data, diaries, and questionnaires. There is a visible gap in research in terms of the use of direct research methods. This paper presents the results of a quantitative research study on household food waste accumulation and collection in Warsaw from two sources: single-family and multi-family households. The results of the study indicate that in Warsaw households, one can expect generation at the level of 33.4 kg·capita^{-1}·year^{-1} of avoidable food waste and 38.2 kg·capita^{-1}·year^{-1} of unavoidable food waste. The average food waste collection rate from households in Warsaw was determined to be at a level of 19.6 kg·capita^{-1}·year^{-1}. In multi-family buildings, which are dominant in Warsaw, this rate is half as pronounced (17.3 kg·capita^{-1}·year^{-1}) compared to single-family buildings (36.2 kg·capita^{-1}·year^{-1}). The average food waste collection efficiency rate from Warsaw households was at a level of 32%. Avoidable food waste accounted for 47% of all food waste generated. The study indicates a growing need to develop policy tools to support the separate collection and prevention of food waste.

Keywords: food waste; unavoidable food waste; bio-waste; waste collection rate; food waste utilization

Citation: 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. https://doi.org/10.3390/su152416827

Academic Editors: Philip Soladoye and Dario Donno

Received: 24 September 2023
Revised: 5 December 2023
Accepted: 11 December 2023
Published: 14 December 2023

1. Introduction

Sustainable food waste management is considered one of the key social and environmental challenges, especially in the context of the circular economy and the transition to climate neutrality [1,2].

Food waste generated in households constitutes a significant share of the total amount of municipal solid waste [3–5]. Data for the European Union indicate that approximately 88 million tons of food are wasted in the EU each year, of which 53% is household waste, which is food waste [3,5]. Food waste ends up in the municipal solid waste stream [6,7], and by the guidelines for separate collection in the European Union developed by the European Commission, it should go to the separately collected bio-waste [8]. An important aspect of analyzing food waste generated, including using the waste accumulation rate, is the distinction between avoidable and unavoidable food waste. Avoidable food waste is that which is thrown away but could have been eaten by humans if treated properly throughout the food supply chain [9]. Unavoidable food waste is understood as the portion of food waste that is not edible under normal circumstances, for example, bones, eggshells, or fruit pits [6]. The problem of avoidable food waste occurs mainly at the household level [10]. Identification of the share of avoidable food waste indicates the need to implement strategies aimed at minimizing food waste [9,11].

Within the hierarchy of solutions that can be used concerning food waste management, a particular challenge is effective collection at the source, which is the starting point for

further value recovery [2]. Accurate bio-waste generation and collection data are essential to implement a sustainable and effective waste management strategy that is compliant with the circular economy [12]. The basic quantitative parameters of municipal solid waste are accumulation rates. However, collection and recycling rates also play a critical role [13,14].

An important aspect in determining the accumulation and collection rate for food waste is the adopted methodology for measuring this phenomenon. The methodology for food waste is defined in the Commission delegated decision (EU) 2019/1597 (Annex III), which indicates appropriate methods for measuring food waste depending on the level of the supply chain where the waste is created. For food waste generated in households, direct measurement, waste composition analysis, and food diaries are recommended [15]. Direct measurement and waste composition analysis (preferably on-site) are considered the best and most accurate methods. However, due to the costs and complexity, this method is used relatively rarely and on a micro-scale. Methods based on diaries and questionnaires are burdened with greater uncertainty, and often raise questions about the accuracy of the data; however, they enable large-scale research [16].

According to Eurostat data for 2020, the amount of food waste reported in accordance with the methodologies indicated in the Commission delegated decision (EU) 2019/1597 reached 131 kg·capita^{-1}·year^{-1} of food waste, of which 70 kg·capita^{-1}·year^{-1} (54%) was household waste (excluding food waste generated by the catering business). However, different measurement methods were used in individual countries, and no distinction was made between the share of avoidable and unavoidable food waste in this report. The food waste generated by households ranged from 26 kg·capita^{-1}·year^{-1} (Bulgaria) to 124 kg·capita^{-1}·year^{-1} (Portugal) [17]. Other data on food waste accumulation rates can be found in studies based on various types of direct research. In a study carried out in Denmark, based on the analysis of bio-waste from 1474 households, the estimated rate of food waste accumulation from households was 183 ± 10 kg·capita^{-1}·year^{-1}, of which 103 ± 9 kg was avoidable food waste [18]. In research carried out in Finland in 380 households, using the method of a 2-week food waste diary study accompanied by a background questionnaire, the annual amount of avoidable food waste generated was 23 kg·capita^{-1}·year^{-1} [19]. Similar values were indicated in a paper on food waste research conducted in Italy in 2016–2017, also using the food waste diary study and a background questionnaire method in 388 households, in which the amount of food waste was 26.5–33 kg·capita^{-1}·year^{-1} [20]. In the assessment of the amount of food waste in Hungary, where 100 households were surveyed using the diary study and background questionnaire method, the food waste accumulation rate was determined to be 68.04 kg·capita^{-1}·year^{-1} [21]; at the same time, it was indicated that this amount was much higher than the amount reported for 2011 (39 kg·capita^{-1}·year^{-1}). From the total amount of waste, 32.07 kg·capita^{-1}·year^{-1} was considered unavoidable [22,23]. In a study describing a survey of 101 households using the diary method, it was indicated that the food waste accumulation rate in Greece in 2013–2014 was 76.1 ± 68.3 kg·capita^{-1}·year^{-1}, of which 25.9 ± 34.9 kg·capita^{-1}·year^{-1} was avoidable food waste and 50.2 ± 47.1 kg·capita^{-1}·year^{-1} was unavoidable food waste [24]. In a study conducted in Greece that also used the diary method, the food waste accumulation rate was 98.9 kg·capita^{-1}·year^{-1}, of which avoidable waste amounted to 29.8 kg·capita^{-1}·year^{-1} [25]. A direct study that was conducted in Poland (Opole) by den Boer et al. in 2018–2019 in a region with approximately 500 inhabitants living in single-family houses and in few-family and multi-family buildings, the total amount of food waste generated by the households was 61.7 kg·capita^{-1}·year^{-1} [25]. The data included both avoidable and unavoidable food waste. The study included food waste contained in the stream of mixed municipal waste (42.8 kg·capita^{-1}·year^{-1}) and in the stream of separately collected bio-waste (19 kg·capita^{-1}·year^{-1}). Of this waste, the avoidable portion was 21.5 kg·capita^{-1}·year^{-1} in mixed waste, and 7.1 kg·capita^{-1}·year^{-1} in separately collected bio-waste. The data from the research carried out in 500 households using the diary study and background questionnaire method in Poland in 2019 indicates that the food waste accumulation rate in that year was 76.7 kg·capita^{-1}·year^{-1} [26].

Based on a review of the source literature, most of the quantitative and qualitative data that measured the scale of food waste in households are based on statistical data, diaries, and questionnaires. There is a visible gap in research in terms of the use of direct methods and combining data on food waste generation (with avoidable fractions distinction) with the collection rates.

This paper presents the results of quantitative research on household bio-waste accumulation and collection rates in Warsaw from two sources: single-family and multi-family households. This research aims to determine the collection rate and effectiveness of selective collection of food waste in Warsaw, and to indicate what part of the food waste generated is the fraction that could have been avoided. It is a continuation of the study on the technological and organizational parameters of selective collection of household bio-waste in Warsaw that determine the optimal waste management scenario [27,28]. The authors of the study aim to fill significant gaps in the quantitative data in the field of selective collection of municipal waste in urban areas for a developing system of segregation at the source of the waste. The Polish capital city was used as a case study, as the system of segregation at the source has been in operation here for up to 5 years. Such a study is relevant and important in the context of the selective collection of the organic fraction of municipal solid waste, compulsory in all EU member states from the beginning of 2024 [7]. The research aims to draw attention to the fact that a significant challenge in managing household bio-waste is the stage of its collection [29]. The proper and effective collection of food waste is the starting point for its further sustainable treatment (both its high-value and low-value utilization), including validation, recycling, biofuel production, and energy and heat generation.

2. Materials and Methods

Household bio-waste generated by multi-family housing (M) and single-family housing (S) in Warsaw was subjected to a direct quantitative study. According to the selective collection system in force in Warsaw, vegetable and fruit leftovers, eggshells, coffee grounds and tea leaves, wilted flowers and pot plants, and food leftovers (excluding meat, bones, and animal fats) can be placed in containers for household bio-waste. The Warsaw system is modeled on the Belgian and Netherlands systems [30]—the so-called VGF system (vegetable, garden, and fruit waste). In Poland, the selective collection system is uniform throughout the country [31]. In Warsaw, as in the whole country, animal residues should not be included in the bio-waste stream, as required by the system. The study did not cover green waste (from gardens and parks), which is collected separately in the Warsaw collection system.

The research was carried out in the cycle from June 2020 to August 2022. There was cooperation with one company that collects municipal waste. The waste came from the same designated collection routes. The waste was collected once a week from both the multi-family and single-family buildings according to [32], which specifies the schedule of MSW collection in Warsaw. In the research, a direct measurement (physical survey) method was used based on samples taken from ordinary waste-collection [16]. The amount of food waste was measured by weighing and recording it by a third party (the company that collects municipal solid waste). The amount of avoidable and unavoidable food waste was determined based on the analysis of literature data [18,19,22–25], considering especially national data as more representative [26]. Thanks to cooperation with the Environmental Protection Office of the City of Warsaw, the number of properties from which the waste was collected was determined, and then the number of inhabitants living along the collection routes in multi-family and single-family buildings. The waste subjected to quantitative tests was collected from 20,123 residents. Both permanent and temporarily registered residents were included. Waste collection routes from multi-family buildings were in the Bielany district, and single-family buildings were in the Bielany and Żoliborz districts. The selection of districts reflects the ratio of multi-family to single-family buildings in Warsaw, which is 88% to 12% [33]. Figure 1 shows the location of the Warsaw districts.

Figure 1. The Bielany and Żoliborz districts—location in the city of Warsaw (marked in gray).

Municipal bio-waste (food waste) was collected from multi-family buildings (6745 households) in the Bielany district of Warsaw (15 collection routes) with 17,537 residents. In single-family housing, municipal bio-waste was collected from 740 households in the Bielany and Żoliborz districts of Warsaw (57 collection routes), inhabited by 2586 people.

According to the literature, the bio-waste accumulation rate is determined as the ratio of the bio-waste generated per unit of time in each area to the number of residents living in that area [34]. By analogy, the collection rate of bio-waste from households was defined as the ratio between the bio-waste collected per unit of time in each area and the number of residents living in this area. The collection efficiency of the selective bio-waste collection system was determined as the ratio of the portion of bio-waste collected to the total amount of bio-waste generated [35].

The results were statistically analyzed using the Mann–Whitney U test. This is a non-parametric test that does not depend on assumptions on the distribution, and one can use it when the sample is small [36]. In addition, basic measures of diversity in terms of the standard deviation and coefficient of variation were used [37].

The research carried out in these Warsaw districts should be treated as a pilot study, which can be extended using the indicated methodology to other cities in Poland and similar European cities.

3. Results

3.1. Amount of Municipal Bio-Waste Collected

Figure 2 includes the amounts of bio-waste collected from single-family and multi-family buildings on the analyzed collection routes during the period covered by the analysis.

Quantitative food waste research was conducted for 27 months. In individual months, food waste was collected from households in multi-family buildings in amounts ranging from 16.5 thou. to over 38 thou. kg, and in single-family buildings from about 5 thou. to over 12 thou. kg. In total, over 887 thou. kg of food waste was collected during the research period (approximately 679.5 thou. kg from multi-family households and almost 208 thou. kg from single-family households). The largest amounts of food waste were collected in August (2020) and December (2020)—from multi-family and single-family households, respectively; the lowest amounts were collected in April (2023) and February (2020)—from multi-family and single-family households, respectively.

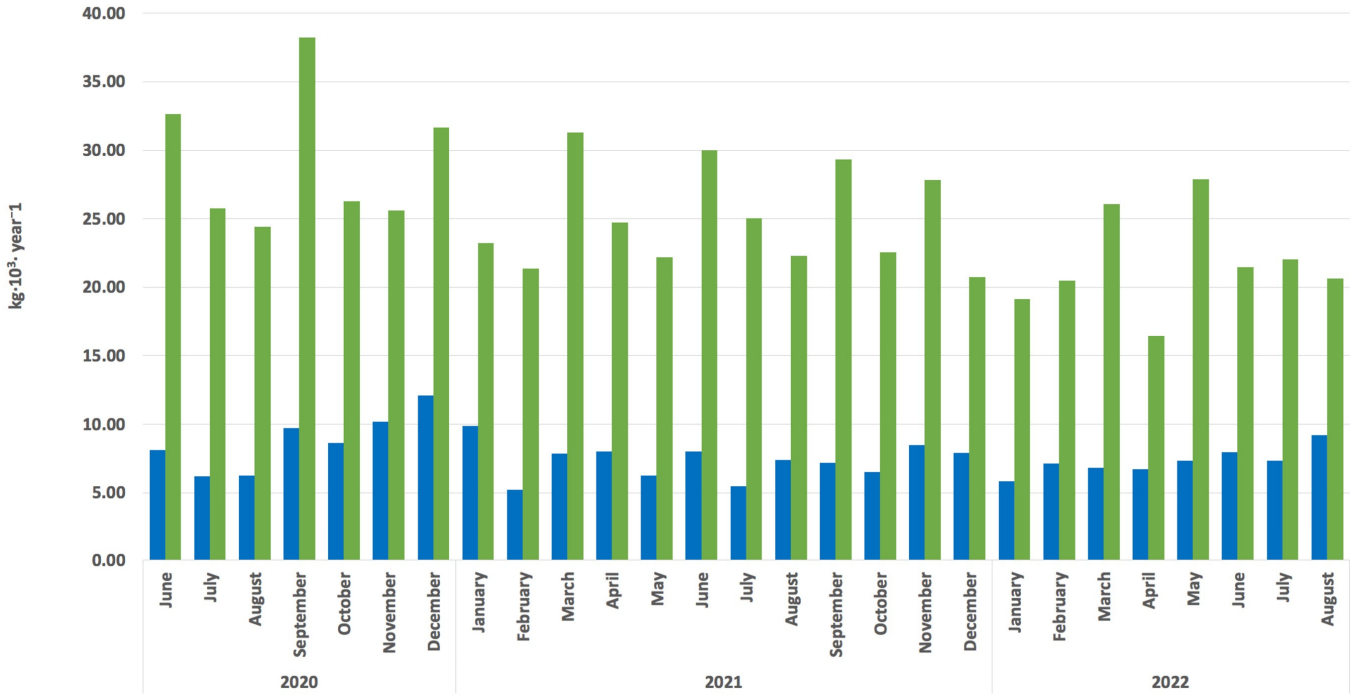

Figure 2. Amounts of bio-waste collected from single-family buildings (blue bars) and multi-family buildings (green bars).

Table 1 shows the average monthly amounts of bio-waste collected from multi-family and single-family buildings, along with basic measures of diversity in terms of the standard deviation and coefficient of variation.

Table 1. Amounts of bio-waste collected from multi-family and single-family buildings.

Year	Average Monthly Amounts of Bio-Waste Collected [kg]	Range [kg]	Coefficient of Variation [%]
Multi-family buildings (M)			
2020	29,223 ± 4717	24,420–38,240	16
2021	25,220 ± 3612	20,760–31,280	14
2022	21,778 ± 3427	16,440–27,860	15
Single-family buildings (S)			
2020	8746 ± 1967	6220–12,080	23
2021	7360 ± 1263	5240–9900	17
2022	7288 ± 921	5840–9200	13

Note: 2020—14 measurement series; 2021—24 measurement series; 2022—16 measurement series.

The highest average value of monthly bio-waste collection occurred in 2020, both in multi-family and single-family buildings. During this period, the greatest variability in bio-waste collection was also recorded.

3.2. Indicators of Selective Collection of Municipal Bio-Waste

Figure 3 presents the calculated indicators of selective collection of municipal bio-waste from multi-family and single-family buildings for each month in the analyzed years.

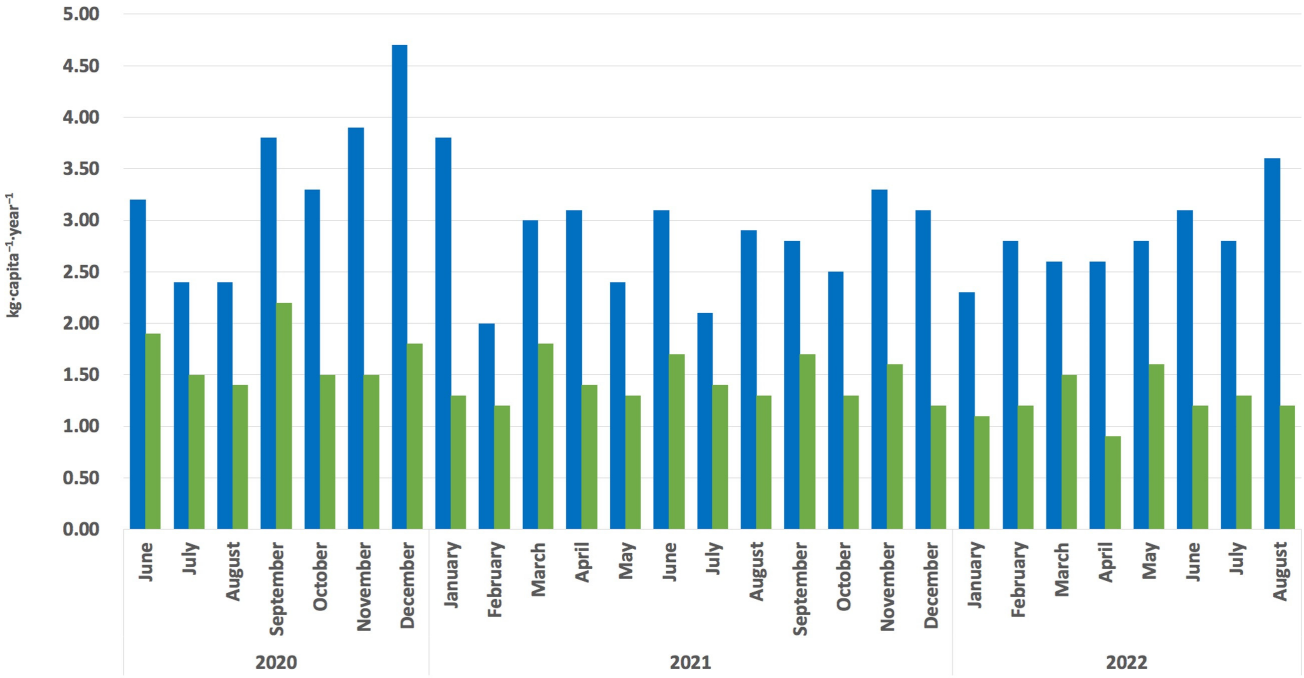

Figure 3. Bio-waste separate collection rates for single-family buildings (blue bars) and multi-family buildings (green bars).

Although the absolute amount of food waste collected in single-family buildings was approximately three times lower than in multi-family housing (Figure 2), the monthly collection rate (per inhabitant) turned out to be higher in single-family buildings. The highest collection rates correspond to the months in which the largest amounts of bio-waste were collected.

The analysis carried out with the Mann–Whitney U test allows the conclusion that for the adopted level of significance ($\alpha = 0.05$), the difference between the waste collection rate values from single-family and multi-family households is large enough to be statistically significant (U is 1092.5, p-value is 0.0251).

Table 2 presents the annual values, along with the basic measures of diversity, in the forms of standard deviation and coefficient of variation.

Table 2. Annual bio-waste collection rates along with the basic measures of diversity.

Average Year Collection Rate of Bio-Waste [kg·capita^{-1}·year^{-1}]	Range [kg·capita^{-1}·year^{-1}]	Coefficient of Variation [%]
Multi-family buildings (M)		
17.3 ± 2.1	14.9–20.0	12
Single-family buildings (S)		
36.2 ± 3.1	33.8–40.6	9

Note: Multi-family buildings (M): 15 collection routes in each year; number of properties in one collection route: 1–77; number of residents in one collection route: 30–7319. Single-family buildings (S): 57 collection routes in each year; number of properties in one collection route: 1–101; number of residents in one collection route: 4–341.

The monthly waste collection rates (Figure 3) were converted into annual rates for the subsequent years covered by the analysis, and then average annual collection rates were determined for the two types of buildings (Table 2).

3.3. The Efficiency of the Selective Bio-Waste Collection System

The efficiency of the selective food waste collection was determined as the share of the portion collected in relation to the portion generated. According to Environment 2022, in 2021 there was an increase in the generation of municipal waste in Poland by 4.2% compared to the previous year. This means there was an increase in the amount of municipal waste generated by one resident of Poland from 344 kg in 2020 to 360 kg in 2021 [38]. According to the research conducted by the Institute of Environmental Protection, the share of bio-waste in municipal waste generated in the municipal system in Poland was 28.68%. At the same time, the share of kitchen waste in the morphological composition of mixed municipal waste generated in large cities in Poland was 19.1% [38]. These data are similar to Eurostat data for 2021, according to which 62 kg·capita^{-1}·year^{-1} of bio-waste were generated in households [39]. In turn, according to unpublished research carried out by the authors of this study, the average share of the animal origin food waste generated in households in Warsaw was 11.2 ± 7.5% by multi-family buildings residents and 11.0 ± 1.5% by single-family buildings residents [40].

Considering the above data, the indicators of the accumulation of food waste with the predominance of plant origin fractions from households in particular years, collection rates, and the efficiency of this collection in Warsaw are shown in Table 3.

Table 3. Food waste accumulation rates (plant origin fractions), collection rates from households, and the efficiency of bio-waste collection in Warsaw.

Year	Accumulation Rate of Food Waste from Households [kg·capita^{-1}·year^{-1}]		Collection Rate of Food Waste from Households [kg·capita^{-1}·year^{-1}]		Food Waste Collection Efficiency [%]	
	M	**S**	**M**	**S**	**M**	**S**
2020	58.3	58.5	20.0	40.6	34	69
2021	61.1	61.2	17.1	34.2	28	56
2022	63.6	63.8	14.9	33.8	23	53

Note: Multi-family buildings (M): 15 collection routes in each year; number of properties in one collection route: 1–77; number of residents in one collection route: 30–7319. Single-family buildings (S): 57 collection routes in each year; number of properties in one collection route: 1–101; number of residents in one collection route: 4–341.

Table 3 compares the food waste accumulation rates with the collection rates to determine the collection efficiency (following the relationship presented in Section 2).

4. Discussion

A quantitative direct study on the selective collection of food waste from households was conducted from June 2020 to August 2022 for two Warsaw districts (20,123 residents), which allowed the authors to determine the parameters that play a critical role in planning waste management systems, with an emphasis on opportunities to improve food waste prevention and efficiency for the system of bio-waste selective collection.

The determined bio-waste collection rates in Warsaw were relatively low for multi-family buildings, on average 17.3 kg·capita^{-1}·year^{-1}, but twice as high, i.e., 36.2 kg·capita^{-1}·year^{-1}, for single-family buildings. Considering the proportions between the number of residents in these two types of buildings, the food waste collection rate in the collection area is 19.6 kg·capita^{-1}·year^{-1} (the area of collection was selected so that the type of development corresponds to the type of development in Warsaw). This value is like the results obtained in the study by den Boer [26], where the absolute amount of both the avoidable and unavoidable food waste in the bio-waste was estimated at a level of 19 kg·capita^{-1}·year^{-1} for a city in southwestern Poland.

The value of the food waste collection rate from households in Warsaw was assessed as very low, typical for immature and still developing selective collection systems. For

example, in accordance with the guidance for the selective collection of municipal waste in Germany, targets are set for the collection of 60 kg of kitchen waste per capita per year [7].

The values of the food waste collection rate by households in Warsaw are characterized by high variability, which is typical for municipal waste [13]. The coefficient of variation of monthly kitchen waste collection in Warsaw is in the range of CV = 14–16% for multi-family buildings and CV = 13–23% for single-family buildings. The average value of this coefficient, considering the ratio between these two types of buildings, is 16%. The coefficient of annual variability of food waste collection was estimated at CV = 11% (12% for multi-family buildings and 9% for single-family buildings). It is recommended to adopt these values to create and modernize systems for the selective collection of municipal bio-waste in Warsaw and other large cities.

The efficiency of the selective waste collection system can be determined in various ways. One of the methods is the quality in container rate (QCR), which determines the proportion of bio-waste and impurities contained therein. The study by Gallardo et al. reports that these values reach levels of 79.95–90.00% (Spain—various regions), 89% (Italy—Calabria), 70–90% (Czech Republic—Usti nad Labem), and 97% (Belgium—Antwerp) [28]. In previous research [41], the authors of this paper determined the efficiency of selective collection of bio-waste from households based on quality in container rate at the level of QCR = 92–97%. The quantitative study on the selective collection of food waste in Warsaw, conducted as part of this research, allowed us to determine the efficiency of this system, reflecting the share of the portion collected in relation to the total amount generated. The average efficiency of the single-family buildings' food waste collection is at a high level of 59 $\pm$ 7%, while the average efficiency of the multi-family buildings' food waste collection is approximately half of this, and amounts to 28% $\pm$ 4%. At the same time, single-family buildings' food waste collection is characterized by slightly lower variability (CV = 12%) compared to multi-family buildings (CV = 16%). Considering the ratio between multi-family and single-family buildings, the average efficiency of household municipal bio-waste collection in Warsaw is at a level of 32%. A very similar value of the efficiency of selective food waste collection was determined by den Boer for a city in southwestern Poland (31%) [26].

The difficulties in the selective collection of bio-waste, including its high and variable humidity, affect the logistical and technical requirements for its collection and further processing [6]. Food waste collected from households in Warsaw has a humidity level of 77 $\pm$ 3% (CV = 3%) for multi-family buildings and 78 $\pm$ 4% (CV = 5%) for single-family buildings [27]. The collection system used has a significant impact on the efficiency of the selective collection of bio-waste. In highly populated areas, door-to-door collection is optimal and cost-effective. However, living space, especially in high-rise buildings, may not allow for separating the waste into several waste streams, and inhibits separation [6] (hence, among other things, the efficiency of the food waste collection system in multi-family buildings in Warsaw is halved).

Effective selective waste collection is not only a matter of the quantity of collected fractions, but also their quality. According to [7], bio-waste with more than 10% of impurities makes valorization hardly feasible. According to previous research by the authors of this study [28], the inclusions and contaminants occurring in selectively collected food waste in Warsaw constitute 5.79 $\pm$ 3.58% of the total amount of waste for multi-family buildings and 6.60 $\pm$ 3.72% for single-family buildings; taking into account the type of building development in the city, this gives an average value of approximately 6%. In this respect, the collection system should be considered effective. Door-to-door collection of bio-waste is an expensive system in terms of operational costs, but also results in the highest capture rates while allowing for a minimization of impurities. Moreover, it turns out that people in European Union capitals tend to sort more plastic, metal, paper, and glass when door-to-door bio-waste collection is in place [41]. Also, the optical bag system can encourage society to implement food waste separation at the source [42]. In turn, on average, bio-waste collected via local collection points (e.g., underground containers for bio-waste) has a higher content of contaminants than bio-waste collected using door-to-

door systems. Underground containers may be an option in city centers, but these require an intensive follow-up to improve the quality of the collected fractions [7].

To increase the efficiency of biodegradable waste collection and increase the level of recycling, it could be considered to include in the collection system all biodegradable fractions, including animal-origin bio-waste and biodegradable plastics. In other European Union countries, e.g., Germany and Austria, all food waste (kitchen waste) is targeted. In Austria, the separate collection of, e.g., leftover raw meat scraps from kitchens has been implemented depending on the region and further treatment. Both systems have their advantages and disadvantages. VGF system tends to leave a large part of food scraps in residual waste, which is also demonstrated by the high percentages of organics in residual waste. In turn, the selective collection of animal-origin food waste increases the nuisance of this collection (odor nuisance), creates sanitary problems, and expands the risk of contamination of bio-waste [43]. According to [44], biodegradable plastics can be collected jointly with bio-waste. However, most bioplastics degrade slower than normal kitchen waste, which slows down the process or induces elements that are not fully degraded. Therefore, proper certification and clear instructions for handling bioplastics are important to incorporate such materials into the collection system. Nonetheless, in the current legal situation in Poland [31], these are only considerations of technological possibilities, because current bio-waste collection systems do not allow animal-origin scraps and biodegradable plastics to be combined with household food waste.

The amount of food waste collected depends on the amount of the waste generated. In lower-income countries of the EU, food waste constitutes around 30% of the total household waste, whereas in Member States with a higher average income, food waste constitutes only around 20% of the total household waste, which is primarily related to wasteful food habits [5]. An important issue from the standpoint of sustainability, including minimizing the bio-waste amount generated and preventing the wasting of food, is awareness of the content of avoidable food waste in the municipal waste that is generated and collected. The qualitative study on food waste generated in Warsaw households presented in study [28] indicates that the plant fractions in separately collected bio-waste constitute 93.53% of the bio-waste from multi-family buildings and 92.11% of the bio-waste from single-family buildings. Among the fractions, the presence of citrus peels (recognized as non-avoidable food waste) was recorded at the levels of 5.22% and 8.63%, respectively; garden fractions, which are not food waste (recognized as non-avoidable food waste), at the levels of 0.90% and 3.92%, respectively; and other impurities, including soil and teabags (non-avoidable food waste), at the levels of 0.14% and 0.10%, respectively. In turn, in the selectively collected bio-waste generated in Warsaw households, the share of animal fractions that are undesirable additives to the system (recognized as avoidable food waste) are at the levels of 0.68% and 1.29%, respectively. In den Boer's study [26], the content of avoidable food waste in three waste streams was estimated—in bio-waste collected separately (37%), in food waste included in residual waste (50%), and in food waste generated within the total amount of MSW (46%). The results of studies by other authors indicate slightly different shares of avoidable food waste in bio-waste contained in mixed municipal waste—in Denmark (56%), Hungary (53%), and Greece (34%) [26].

Assuming the quoted data obtained in Poland (according to den Boer) and taking into account the efficiency of selective collection of municipal bio-waste (plant fraction) in Warsaw at a level of 32%, this means that residual waste still contains food waste (plant and animal fractions) at a level of 53.2 kg·capita^{-1}·year^{-1}, including 26.6 kg·capita^{-1}·year^{-1} of avoidable and the same amount of unavoidable waste. In turn, in the selectively collected bio-waste generated in Warsaw households, one can expect avoidable fractions at a level of 6.8 kg·capita^{-1}·year^{-1}, which gives a total of 33.4 kg·capita^{-1}·year^{-1} of avoidable food waste and 38.2 kg·capita^{-1}·year^{-1} of unavoidable food waste (a total of 71.6 kg·capita^{-1}·year^{-1} food waste). Similar results were obtained based on research projects conducted in Hungary—68 kg·capita^{-1}·year^{-1} of food waste (36 kg·capita^{-1}·year^{-1} of avoidable fractions) [23], in Greece—76.1 (including 25.9 kg·capita^{-1}·year^{-1} of avoidable

fractions) [45], in Croatia—75 kg·capita^{-1}·year^{-1} (although only 9 kg·capita^{-1}·year^{-1} of avoidable fractions) [46], in Bosnia-Herzegovina—49.5 kg·capita^{-1}·year^{-1} of avoidable food waste [47], and in Norway—46.3 kg·capita^{-1}·year^{-1} of avoidable fractions [48]. Higher values were recorded in Denmark: 183 kg·capita^{-1}·year^{-1} of food waste (103 kg·capita^{-1}·year^{-1} of avoidable fractions) [18].

Considering bio-waste from other sources (sinks, toilets, animals, compost, etc.) at a level of 29% [25], this amount estimated for Warsaw has increased to the level of 92.4 kg·capita^{-1}·year^{-1}. This value is higher compared to the data published by [49]—76 kg·capita^{-1}·year^{-1} and [50]—61 kg·capita^{-1}·year^{-1} for Eastern Europe.

According to data presented in [28], the recycling of bio-waste in Poland in 2017 was at a level of 12–29 kg·capita^{-1}·year^{-1}. Due to the requirements related to the preparation for reuse and recycling of municipal waste, the organization of the bio-waste collection system should be much more efficient. With the content of plant fractions in food waste at a level of approximately 63.6 kg·capita^{-1}·year^{-1} (according to the data in Table 3), recycling of this waste should reach a level of approximately 35.0 kg·capita^{-1}·year^{-1} in 2025 and 38.2 kg·capita^{-1}·year^{-1} in 2030. With 6% contaminant content in food waste collected from households in Warsaw, this translates into the need for selective collection of a minimum 37.2 kg·capita^{-1}·year^{-1} in 2025 and 40.6 kg·capita^{-1}·year^{-1} in 2030, i.e., an approximately two-fold increase in relation to the results obtained during the study under discussion. This involves the need to increase the level of selective collection of food waste from households in Warsaw to almost 25% per year in the first 3 years of the system's development (until 2025), and then about 2% per year (until 2030) [27]. Study [51] indicates even higher shares of contaminants in bio-waste coming from households in the Lubuskie Voivodeship (in western Poland)—16.6% in multi-family buildings and 10.0% in rural areas and cities with single-family housing. This would mean the need to achieve even higher collection rates for the sake of sustainability.

Although the direct research method used in the study managed to obtain actual data on food waste collection rates and collection efficiency, it should be considered that this method has also limitations, which apply to the scale and accuracy of the study results. Obtaining data from direct measurement and data regarding residents is very difficult, and requires active cooperation between waste collection companies and local authorities. For this reason, it has been possible to carry out this pilot study for two districts in Warsaw so far. The other disadvantage of the direct method used is that only food waste entering the municipal waste stream is analyzed. Thus, this type of analysis may exclude food waste that is fed to animals or is home composted [52].

5. Conclusions

The results of the study allowed us to determine that the average food waste collection efficiency rate from Warsaw households is at a level of 32%. The food waste collection efficiency from multi-family buildings (28%) is less than half that from single-family buildings (59%). The average food waste collection rate from households in Warsaw was determined to be at a level of 19.6 kg·capita^{-1}·year^{-1}. In multi-family buildings, which are dominant in Warsaw, this rate is half as pronounced (17.3 kg·capita^{-1}·year^{-1}) compared to single-family buildings (36.2 kg·capita^{-1}·year^{-1}). The coefficient of variation for monthly kitchen waste collection in Warsaw is 16%, and the annual unevenness is 11%. To meet legal requirements regarding the recycling of municipal waste, recycling of food waste collected from households in Warsaw should be executed at a level of approximately 35 kg·capita^{-1}·year^{-1} in 2025 and 38 capita^{-1}·year^{-1} in 2030. This translates into the need for an approximately two-fold increase in the selective collection of food waste in relation to the current rates, which will require almost a 25% increase per year for the first 3 years of system development (until 2025). In turn, in bio-waste generated in Warsaw households, one can expect 33.4 kg·capita^{-1}·year^{-1} of avoidable food waste, which accounts for nearly 47% of all food waste generated. This indicates that a significant challenge is not only to improve the

effectiveness of selective collection but, above all, to follow the waste hierarchy, and to increase activities to minimize food waste generation.

The results of the current and previous studies [28] indicate that there is a growing need for improvements in policy tools that support food waste prevention, and in collection solutions for household food waste in urbanized areas.

Recognizing the limitations of the current study, a more complex study could cover a larger bio-waste collection region and extend the direct method with a survey, which would fill the gaps from the direct study and determine the characteristics of households participating in the study.

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

Funding: Grant from the discipline of Environmental Engineering, Mining and Energy—research on the accumulation rate of selected municipal waste fractions—Warsaw University of Technology, Faculty of Building Installations, Hydrotechnics, and Environmental Engineering, 2022. Grant leader: Piotr Manczarski.

Data Availability Statement: The data presented in this study are available on request from the corresponding author. The data are not publicly available due to the research project in progress.

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

References

1. de Sadeleer, I.; Brattebø, H.; Callewaert, P. Waste prevention, energy recovery or recycling—Directions for household food waste management in light of circular economy policy. *Resour. Conserv. Recycl.* **2020**, *160*, 104908. [CrossRef]
2. Przydatek, G. Assessment of changes in the municipal waste accumulation in Poland. *Environ. Sci. Pollut. Res.* **2020**, *27*, 25766–25773. [CrossRef] [PubMed]
3. Dahlén, L.; Lagerkvist, A. Methods for household waste composition studies. *Waste Manag.* **2008**, *28*, 1100–1112. [CrossRef] [PubMed]
4. Liikanen, M.; Sahimaa, O.; Hupponen, M.; Havukainen, J.; Sorvari, J.; Horttanainen, M. Updating and testing of a Finnish method for mixed municipal solid waste composition studies. *Waste Manag.* **2016**, *52*, 25–33. [CrossRef] [PubMed]
5. Cappelletti, F.; Papetti, A.; Rossi, M.; Germani, M. Smart strategies for household food waste management. *Procedia Comput. Sci.* **2022**, *200*, 887–895. [CrossRef]
6. Peng, W.; Pivato, A. Sustainable Management of Digestate from the Organic Fraction of Municipal Solid Waste and Food Waste Under the Concepts of Back to Earth Alternatives and Circular Economy. *Waste Biomass Valor.* **2019**, *10*, 465–481. [CrossRef]
7. Dubois, M.; Sims, E.; Moerman, T.; Watson, D.; Bauer, B.; Bek, J.B. Guidance for separate collection of municipal waste. In *European Commission, Directorate-General for Environment Publications Office*; European Commission: Brussels, Belgium, 2020. https://data.europa.eu/doi/10.2779/691513.
8. De Laurentiis, V.; Corrado, S.; Sala, S. Quantifying household waste of fresh fruit and vegetables in the EU. *Waste Manag.* **2018**, *77*, 238–251. [CrossRef] [PubMed]
9. Beretta, C.; Stoessel, F.; Baier, U.; Hellweg, S. Quantifying food losses and the potential for reduction in Switzerland. *Waste Manag.* **2013**, *33*, 764–773. [CrossRef]
10. Östergren, K.; Gustavsson, J.; Bos-Brouwers; Timmersman, T.; Hansen, O.-J.; Moller, H.; Anderson, G.; O'Connor, C.; Soethoudt, H.; Quested, T.; et al. FUSIONS Definitional Framework for Food Waste. Full Report; Fusions. 2014. Available online: https://www.eu-fusions.org/phocadownload/Publications/FUSIONS%20Definitional%20Framework%20for%20Food%20Waste%202014.pdf (accessed on 10 December 2023).
11. Thyberg, K.L.; Tonjes, D.J. A Management Framework for Municipal Solid Waste Systems and Its Application to Food Waste Prevention. *Systems* **2015**, *3*, 133–151. [CrossRef]
12. Oláh, J.; Kasza, G.; Szabó-Bódi, B.; Szakos, D.; Popp, J.; Lakner, Z. Household Food Waste Research: The Current State of the Art and a Guided Tour for Further Development. *Front. Environ. Sci.* **2022**, *10*, 916601. [CrossRef]
13. Grazhdani, D. Assessing the variables affecting on the rate of solid waste generation and recycling: An empirical analysis in Prespa Park. *Waste Manag.* **2016**, *48*, 3–13. [CrossRef] [PubMed]
14. Konstantinos-Georgios, N.; Dimitrios, K. Influence of four socioeconomic indices and the impact of economic crisis on solid waste generation in Europe. *Waste Manag.* **2019**, *89*, 190–200. [CrossRef]

15. Commission Delegated Decision (EU) 2019/1597. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=CELEX:32019D1597 (accessed on 10 July 2023).
16. Elimelech, E.; Ayalon, O.; Ert, E. What gets measured gets managed: A new method of measuring household food waste. *Waste Manag.* **2018**, *76*, 68–81. [CrossRef] [PubMed]
17. Food Waste and Food Waste Prevention. Available online: https://ec.europa.eu/eurostat/databrowser/product/view/ENV_WASFW?lang=en (accessed on 14 July 2023).
18. Maklawe, E.E.; Petersen, C.; Scheutz, C.; Astrup, T.F. Food waste from Danish households: Generation and composition. *Waste Manag.* **2016**, *52*, 256–268. [CrossRef]
19. Koivupuro, H.-K.; Hartikainen, H.; Silvennoinen, K.; Katajajuuri, J.-M.; Heikintalo, N.; Reinikainen, A.; Jalkanen, L. Influence of socio-demographical, behavioural and attitudinal factors on the amount of avoidable food waste generated in Finnish households. *Int. J. Consum. Stud.* **2012**, *36*, 183–191. [CrossRef]
20. Giordano, C.; Alboni, F.; Falasconi, L. Quantities, Determinants, and Awareness of Households' Food Waste in Italy: A Comparison between Diary and Questionnaires Quantities. *Sustainability* **2019**, *11*, 3381. [CrossRef]
21. Szabó-Bódi, B.; Kasza, G.; Szakos, D. Assessment of household food waste in Hungary. *Br. Food J.* **2012**, *120*, 625–638. [CrossRef]
22. Djekic, I.; Miloradovic, Z.; Djekic, S.; Tomasevic, I. Household food waste in Serbia—Attitudes, quantities and global warming potential. *J. Clean. Prod.* **2019**, *229*, 44–52. [CrossRef]
23. Szakos, D.; Szabó-Bódi, B.; Kasza, G. Consumer awareness campaign to reduce household food waste based on structural equation behavior modeling in Hungary. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24580–24589. [CrossRef]
24. Abeliotis, K.; Lasaridi, K.; Boikou, K.; Chroni, C. Food waste and composition in households in Greece School of Environment. *Geogr. Appl. Econ.* **2019**, *21*, 399–404. [CrossRef]
25. Papamonioudis, K.; Zabaniotou, A. Exploring Greek Citizens' Circular Thinking on Food Waste Recycling in a Circular Economy—A Survey-Based Investigation. *Energies* **2022**, *15*, 2584. [CrossRef]
26. 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] [PubMed]
27. Rolewicz-Kalińska, A.; Lelicińska-Serafin, K.; Manczarski, P. The Circular Economy and Organic Fraction of Municipal Solid Waste Recycling Strategies. *Energies* **2020**, *13*, 4366. [CrossRef]
28. 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]
29. Laba, S.; Łaba, S.R.; Bilska, K.; Tomaszewska, B.; Tul-Krzyszczuk, M.; Kosicka-Gębska, A.; Kołożyn-Krajewska, D. Próba oszacowania strat i marnotrawstwa żywności w Polsce. *Przemysł Spożywczy* **2020**, *74*, 10–18. (In Polish) [CrossRef]
30. Favoino, E.; Giavini, M. Bio-Waste Generation in the EU: Current Capture Levels and Future Potential. Bio-Based Industries Consortium (BIC) 2020. Available online: https://zerowasteeurope.eu/wp-content/uploads/2020/07/2020_07_06_bic_zwe_report_bio_waste.pdf (accessed on 20 August 2023).
31. Regulation of the Minister of the Climate and Environment on the Method of Selective Collection of Selected Fractions of Waste. Available online: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20210000906/O/D20210906.pdf (accessed on 27 August 2023). (In Polish)
32. Website of the Warsaw City Hall. Rules of Municipal Waste Management in the City. Available online: https://warszawa19115.pl/documents/20184/1342879/Flyer/4ac01b3f-3606-4aa5-bf3e-fdcb6e15b705 (accessed on 15 October 2023).
33. Analizy Zamieszkania. Available online: https://miastojestnasze.org/jak-mieszkamy-w-warszawie/ (accessed on 15 July 2023).
34. Goel, S.; Ranjan, V.P.; Bardhan, B.; Hazra, T. Forecasting Solid Waste Generation Rates. In *Modelling Trends in Solid and Hazardous Waste Management*; Sengupta, D., Agrahari, S., Eds.; Springer: Singapore, 2017. [CrossRef]
35. Rada, E.C.; Zatelli, C.; Cioca, L.I.; Torretta, V. Selective Collection Quality Index for Municipal Solid Waste Management. *Sustainability* **2018**, *10*, 257. [CrossRef]
36. Nachar, N. The Mann-Whitney U: A Test for Assessing Whether Two Independent Samples Come from the Same Distribution. *Tutor. Quant. Methods Psychol.* **2008**, *4*, 13–20. [CrossRef]
37. Kader, G.D.; Perry, M. Variability for Categorical Variables. *J. Stat. Educ.* **2007**, *15*, 2. [CrossRef]
38. Waszczyłko-Miłkowska, B.; Kamińska-Borak, J.; Bernat, K. The Real Share of the Morphological Components of Municipal Waste Generated in Municipal Systems in Poland. *Environ. Prot. Nat. Resour.* **2022**, *33*, 13–18. [CrossRef]
39. Food Waste by Sector of Activities. 2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/images/1/14/Food_waste_by_sector_of_activities,_2021_(tonnes_of_fresh_mass)V1.png (accessed on 20 October 2023).
40. Kolanowska, J.; Skwara, A. Households Biological Waste from Different Urban Environments—Technological and Survey Research and Proposed Solutions in Regard to Their Selective Collection in the Capital City of Warsaw. Master's Thesis, Warsaw University of Technology, Faculty of Building Installations, Hydrotechnics and Environmental Engineering, Warsaw, Poland, 2021.
41. Gallardo, A.; Bovea, M.D.; Colomer, F.J.; Prades, F.J. Analysis of collection systems for sorted household waste in Spain. *Waste Manag.* **2021**, *32*, 1623–1633. [CrossRef]
42. Abeshev, K.; Koppenborg, F. More than just organics: Boosting separate collection of dry recyclables with door-to-door bio-waste collection in EU capitals. *Waste Manag.* **2023**, *161*, 156–165. [CrossRef] [PubMed]
43. Friege, H.; Eger, Y. Best practice for bio-waste collection as a prerequisite for high-quality compost. *Waste Manag Res.* **2022**, *40*, 104–110. [CrossRef] [PubMed]

44. Solano, G.; Rojas-Gätjens, D.; Rojas-Jimenez, K.; Chavarría, M.; Romero, R.M. Biodegradation of plastics at home composting conditions. *Environ. Chall.* **2022**, *7*, 100500. [CrossRef]
45. Abeliotis, K.; Lasaridi, K.; Costarelli, C.K.; Chroni, C. The implications of food waste generation on climate change: The case of Greece. *Sustain. Prod. Consum.* **2015**, *3*, 8–14. [CrossRef]
46. Ilakovac, B.; Voca, N.; Pezo, L.; Cerjak, M. Quantification and determination of household food waste and its relation to sociodemographic Characteristics in Croatia. *Waste Manag.* **2020**, *102*, 231–240. [CrossRef] [PubMed]
47. Djekic, I.; Operta, S.; Djulancic, N.; Lorenzo, J.M.; Barba, F.J.; Djordjević, V.; Tomasevic, I. Quantities, environmental footprints and beliefs associated with household food waste in Bosnia and Herzegovina. *Waste Manag. Res.* **2019**, *37*, 1250–1260. [CrossRef] [PubMed]
48. Hanssen, I.; Syversen, F.; Stø, E. Edible food waste from Norwegian households—Detailed food waste composition analysis among households in two different regions in Norway. *Resour. Conserv. Recycl.* **2016**, *109*, 146–154. [CrossRef]
49. Monier, V.; Mudgal, S.; Escalon, V.; O'Connor, C. *Preparatory Study on Food Waste Across EU 27 (Final Report)*; European Commission [DG ENV—Directorate C]; BIO Intelligence Service: Paris, France, 2010. [CrossRef]
50. UNEP Food Waste Index Report. 2021. Available online: https://wedocs.unep.org/bitstream/handle/20.500.11822/35280/FoodWaste.pdf (accessed on 19 July 2023).
51. Dronia, W.; Połomka, J.; Jędrczak, A. Morphological composition of bio-waste collected selectively in towns and villages during autumn and winter. *J. Air Waste Manag. Assoc.* **2023**, *73*, 313–320. [CrossRef]
52. Quested, T.E.; Palmer, G.; Moreno, L.C.; McDermott, C.; Schumacher, K. Comparing diaries and waste compositional analysis for measuring food waste in the home. *J. Clean. Prod.* **2020**, *262*, 121263. [CrossRef]