energies

Article

An Insight into Post-Consumer Food Waste Characteristics as the Key to an Organic Recycling Method Selection in a Circular Economy

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

Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, 00-653 Warsaw, Poland
* Correspondence: anna.kalinska@pw.edu.pl

Abstract: Reducing the phenomenon of food waste and effective management of already wasted food in the form of post-consumer waste, included in the source-separated organic fraction of municipal solid waste (SS-OFMSW) from households and catering facilities, are some of the key challenges of the circular economy (CE), in particular in highly urbanized areas. The basis for the effective use of this waste is the knowledge of its physical and chemical properties. The main objective of the paper is to identify the key technological and organizational parameters for selective collection determining the characteristics of the SS-OFMSW and, consequently, the optimal path for its management. This paper presents the results of qualitative research of SS-OFMSW generated in the capital of Poland—Warsaw—coming from three sources: multi- and single-family housing and catering facilities. The collection efficiency of this waste was determined in the form of quality in container rate (QCR = 92–97%) and variability in terms of impurities and admixtures present in it (CV = 56–87%). High variability indicates that the system of selective waste collection in Warsaw is immature, which may hinder undertaking activities in the field of waste management planning. The study confirmed the suitability of the tested SS-OFMSW for organic recycling, especially using anaerobic digestion (AD), to which it is predisposed by water content, C/N, and biomethane potential (BMP). All tested food waste is characterized by a high yield of biogas in the range of 384–426 m^3/Mg VS and an average share of methane in biogas at the level of 52–61%. Fertilizer properties, moisture, and its gas potential show little variability (CV $\leq$ 16%), which means that these data can be treated as stable data. The obtained results indicate the optimal direction for the collection and processing of SS-OFMSW based on post-consumer food waste in urbanized areas.

Keywords: biowaste; biogas; fermentation; food waste; organic recycling; physical–chemical characteristics; waste valorization

check for updates

Citation: 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. https://doi.org/10.3390/en16041735

Academic Editors: Naresh Kumar Amradi, Venkateswer Reddy Motakatla and Omprakash Sarkar

Received: 16 January 2023
Revised: 31 January 2023
Accepted: 6 February 2023
Published: 9 February 2023

1. Introduction

Food waste from the municipal waste stream is one of the priority challenges for the European Union's (EU) 2020 circular economy action plan [1]. First, it is important to define the nomenclature and systematics for the waste stream analyzed in this study. The focus of the article is the source-separated organic fraction of municipal solid waste (SS-OFMSW) from households and catering, collected in a bin or bag system for brown bins (according to the selective municipal waste collection system in force in Poland) [2]. According to data on municipal solid waste (MSW) generated in Poland, the organic fraction of municipal solid waste (OFMSW) accounts for 26.68% [3]. In this stream, the dominant share is plant-based food waste [4]. In this context, it will be mainly food waste, as defined by Directive (EU) 2018/851 [5]. The SS-OFMSW analyzed in the paper does not include green waste. Food waste is recognized as one of the leading global issues in sustainable development strategy [6]. Reducing food waste and effectively utilizing the value from biowaste generated from food already wasted are some of the key challenges of the CE, which is confirmed by numerous scientific studies indicating the importance of the topic of CE-based food waste management. Although there are many reports and studies on the use of food waste in various conduct strategies [7–9], it is impossible to determine clearly which scheme for handling SS-OFMSW consisting mainly of food waste will have the best application locally, since the properties of individual food products have a great influence in determining which waste management option is most favorable [10].

The suitability and applicability of the value of food waste is closely dependent on the stage of the food chain at which it was produced [11]. According to Commission Decision (EU) 2019/1597, food waste is identified separately for the following stages of the food supply chain: primary production, processing and manufacturing, retail and other food distribution, restaurants and catering services, and households [12].

SS-OFMSW (household and catering waste) is categorized as post-consumer food waste, and due to its properties it is mainly used in traditional organic recycling processes such as composting and anaerobic treatment using methane fermentation. Value recovery in biorefineries, especially as a source of bioproducts, is still rather applicable for more heterogenous food waste from the pre-consumer stage of the food chain [13]. Nevertheless, the fermentation process is a key technology in most microbial biorefineries due to its efficiency in converting organic waste into easily assimilable organic compounds [14]. The stability of the physical and chemical properties of food waste is a key factor necessary for its effective use in recycling technologies.

The composition, and hence the properties, of food waste generated in the SS-OFMSW stream are determined mainly by seasonality and housing types [15]. Food waste generally consists of carbohydrates (41–62%), protein (15–25%), and fats (13–30%). The exact composition of the waste depends on its blend, in particular the proportion of each food type in the waste. Studies by Wainaina et al. report that food waste consists mainly of fruit and vegetables (79%), meat and fish (8%), pasta and rice (5%) bread and bakery products (6%), and dairy (2%) [16]. For example, meat, fish, and eggs are primarily sources of fats and protein, while vegetables, fruit, rice, and pasta are sources of carbohydrates [17]. The main parameters characterizing the technological properties of food waste include: water content (74–90%), carbon-to-nitrogen ratio—C/N ratio (14.7–36.4), total solids content—TS (17–29%), and volatile solid content—VS (17–26%) [18–20]. Another important technological parameter is the potential for methane production, which for food waste can vary widely, and Slopiecka et al. report a range from 216 to 1476 mL CH_4/g VS [17].

As studies show, not only are the properties of waste and the choice of direct processing technology important for the efficiency of the organic recycling process, but a very important factor is also the time of storage of waste before it undergoes processing [21]. In this context, the organization of a system for selective collection of biowaste is very important. A study by Dolci et al. showed that the type of waste bag used (plastic vs. paper bag) can result in significant differences in the properties of the SS-OFMSW when collected and at its processing stage [22]. Contamination of OFMSW with undesirable fractions results in a reduction in the end result of the recycling process, affecting, among other things, the contamination and quality of the compost produced [23], as well as worse parameters of the energy yield process during fermentation [17,24]. Source separation of OFMSW is a key process as it reduces the content of inorganic substances and thus the share of impurities [25]. The efficiency of a separate collection system can be expressed by the quality in container rate (QCR), which determines the proportion of SS-OFMSW, 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) [26].

This study presents the results of qualitative research on municipal food waste from the selective collection system in Warsaw from three sources: single- and multi-family households and catering facilities. The purpose of the article is to identify the key technological and organizational parameters for conducting selective collection of SS-OFMSW in Warsaw conditioning the selection of the optimal path for its management. In particular, in this paper, the authors aim to fill considerable data gaps and explore the status of SS-OFMSW in urbanized areas with a developing system of source separation of food waste (up to 5 years of operation), using Warsaw as a case study. Such a study seems significant and important in the context of the organic fraction municipal solid waste separate collection mandatory for all EU member states by the end of 2023.

2. Materials and Methods

2.1. Tested Waste and Organization of Research

SS-OFMSW coming from the capital city of Warsaw—from multi-family housing (M), single-family housing (S), and food service from mass catering facilities (C) collected selectively in containers and bags—was subjected to qualitative research. 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 SS-OFMSW. Animal residues should not be included in the biowaste stream, as required by the system [27]. The investigated waste stream does not include green waste.

The research was carried out in the cycle from September 2021 to June 2022 in 12 measurement series, in which 24 samples were collected (18 for SS-OFMSW from residential developments and 6 from catering). First, a daily sample (coming from the daily collection route of a given type of waste) of about 100 kg was taken at the base of the collection company. The waste was mixed and averaged. A 10 kg sample was taken for further testing using the quartering method. Detailed methodologies are indicated in Section 2.2.

The technological properties of the SS-OFMSW were tested, and the scope of the study included: morphological composition, organic matter content (volatile solids, VS), dry matter (total solids, TS), total organic carbon (TOC), nutrients (N, P), and the biomethane potential (BMP). The efficiency of biogas yield, including methane from particular types of food waste, was determined by the reactor load and the inoculum to substrate ratio (ISR) parameter according to [28].

The definition of some food waste characteristics may be different in various publications and, in particular, different terms are often used for the content of organic matter (organic matter (OM) or volatile solids (VS)) and for the content of dry matter (dry matter or total solids (TS)) [23]. This paper uses the terms TS and VS, which are expressed in Equations (1) and (2) as defined in [29].

$$\text{TS}\ (\%) = \frac{\text{dried weight at } 105\ ^\circ\text{C}}{\text{wet weight}} \cdot 100 \quad (1)$$

$$\text{VS}\ (\%) = \frac{\text{dried weight at } 105\ ^\circ\text{C} - \text{dried weight at } 550\ ^\circ\text{C}}{\text{dried weight at } 105\ ^\circ\text{C}} \cdot 100 \quad (2)$$

All the research was carried out in triplicate, and the individual results in a given measurement series were the arithmetic mean of the replicates, the variability of which did not exceed 5%. Averaged results for each measurement series are presented along with standard deviation (SD) and coefficient of variation (CV), which is defined as the ratio of the standard deviation to the mean. The greater the value of the coefficient, the stronger the differentiation.

The results were statistically analyzed using a Kruskal–Wallis test followed by Dunn's post hoc test for multiple comparisons. The Kruskal–Wallis test is a non-parametric alternative to the analysis of variance test and was used when the assumptions of the parametric tests were not met [30,31].

2.2. The Analytical Methods

The methods used for research are compliant with generally accepted standards used in laboratory tests of MSW. The following research methodologies were used:

EN 15002 VDI 4630 Sampling procedures. Preparation of samples for analysis.

EN 14346 Determination of the dry residue and the water content.

EN 13137 Determination of Total Organic Carbon (TOC) in waste, sludge and sediment.

EN 15169 Determination of loss on ignition of waste, sludge and sediments.

PN-Z-15011 EN15002 Content of organic substances, organic carbon, nitrogen, phosphorus in biowaste.

To determine the morphological composition of the waste tested, methodology modified for the needs of the research and due to their specificity was used, based on PN-93/Z-15006—Determination of municipal solid waste (MSW) morphological composition [32].

The biomethane potential (BMP) was measured by a respirometric measuring system (OxiTop-IDS) equipped with 6 measuring units (1000 mL bottles), 6 OxiTop-IDS/B wireless measuring heads with Bluetooth technology, a MultiLine Multi 3630 IDS multi-parameter portable meter, TS-WTW thermostatic cabinets (at 35 °C), and an IS 6-Var stirring platform.

3. Results

3.1. Fertilizing Properties and Other Parameters of the SS-OFMSW Studied

Table 1 presents the averaged values of the parameters tested along with the standard deviation (SD) and coefficient of variation (CV) for each source of SS-OFMSW.

Table 1. Mean values of the tested SS-OFMSW parameters from multi-family (M) and single-family housing (S) and catering (C).

Parameter	M			S			C		
	Mean	**SD**	**CV [%]**	**Mean**	**SD**	**CV [%]**	**Mean**	**SD**	**CV [%]**
VS [%]	85.91	±1.18	1	84.42	±7.00	8	87.82	±4.05	5
TOC [%]	35.80	±4.35	12	32.61	±5.73	18	33.99	±6.77	20
C/N [-]	18	±2	9	17	±5	26	17	±5	30
C/P [-]	59	±14	24	48	±7	14	42	±13	32
Water content [%]	76.9	±3.3	4	78.1	±3.6	5	81.7	±2.9	3

The analysis conducted with the use of the Kruskal–Wallis test shows that for the assumed significance level ($\alpha = 0.05$), the test statistic for SS-OFMSW morphological research from three sources, for the share of plant origin waste in biowaste (H = 5.7289, $p = 0.05701$, $\eta^2 = 0.18$), the share of animal origin waste in biowaste (H = 0.4307, $p = 0.8063$, $\eta^2 = 0.075$), the share of plastics in biowaste (H = 2.3928, $p = 0.3023$ $\eta^2 = 0.019$), and for total admixtures (H = 5.7289, $p = 0.05701$, $\eta^2 = 0.18$), indicate that there are no grounds to conclude that there are statistically significant differences between the share of these admixtures in SS-OFMSW from three types of sources (single-family housing, multi-family housing, and catering). However, the analysis showed a statistically significant difference in water content and C/P ratio for different sources. The following statistical values for water content were obtained H = 6.316, $p = 0.042$, $\eta^2 = 0.21$, and Dunn's post hoc test with the Bonferroni correction of 0.017 showed that the rank average for the fraction from multi-family housing and catering is significantly different. For the C/P parameter, the values of the statistic are H = 6.257, $p = 0.044$, $\eta^2 = 0.2$, with a pairwise comparison.

3.2. Morphological Composition of the Studied SS-OFMSW—Admixtures and Impurities

Table 2 presents the averaged composition of SS-OFMSW from multi-family, single-family, and catering developments. Table 3 shows the average proportion of basic impurities in SS-OFMSW, and Figure 1 presents the averaged morphological composition of the impurities.

Table 2. Average composition of SS-OFMSW from different sources (M, S, C).

Component [%]	M			S			C		
	Mean	SD	CV [%]	Mean	SD	CV [%]	Mean	SD	CV [%]
Plant origin waste	93.53	±4.01	4	92.11	±4.48	5	97.08	2.44	2
Animal origin waste	0.68	±0.98	144	1.29	±1.81	140	0.59	±0.65	110
Impurities	5.79	±3.58	62	6.60	±3.72	56	2.34	±2.03	87

Table 3. Average share of impurities in SS-OFMSW from various sources (M, S, C).

Impurities [%]	M			S			C		
	Mean	SD	CV [%]	Mean	SD	CV [%]	Mean	SD	CV [%]
Paper	0.87	±0.71	82	1.17	±0.74	64	0.31	±0.41	136
Plastics	2.11	±1.26	60	2.45	±1.54	63	1.62	±2.10	130
Glass	0.25	±0.49	193	1.08	±2.10	195	0.03	±0.03	112
Metals	0.06	±0.10	157	0.33	±0.57	170	0.01	±0.02	135
Others	2.50	±3.41	136	1.57	±1.58	101	0.37	±0.36	99

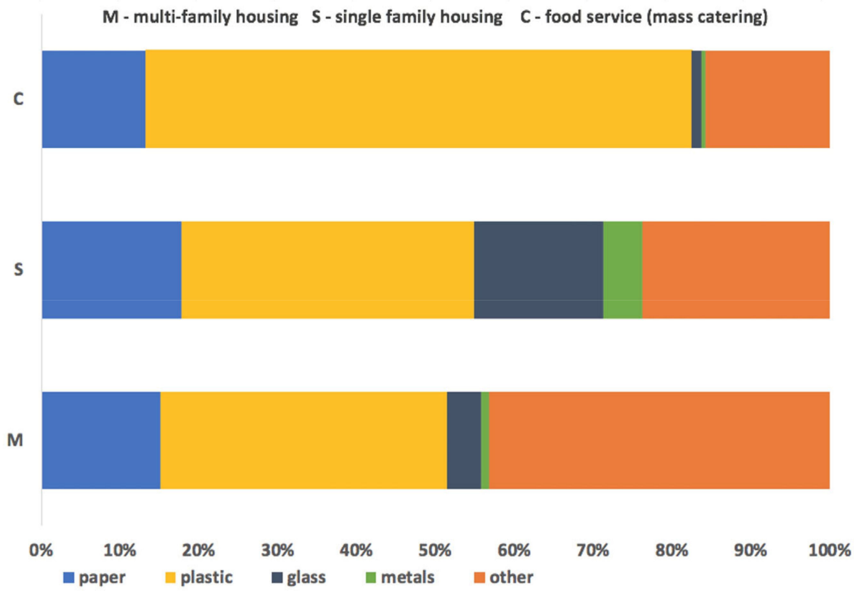

Figure 1. Average composition of impurities in SS-OFMSW from different sources (M, S, C).

In other impurities, the presence of the following was noted: soil, diapers, tea bags, packaged liquid waste (e.g., soups). Figure 2 presents impurities' distribution for individual SS-OFMSW generation sources (M, S, C). Interquartile range (IQR) takes the lowest value for catering (C) and, in the case of multi-family housing (M) and single-family housing (S), these values are similar. Based on the analysis of the graph, it can be observed that in all samples from food services, the share of impurities was the lowest and most stable.

The analysis conducted with the use of the Kruskal–Wallis test for morphological research results allows us to conclude that for the adopted level of significance ($\alpha = 0.05$), the test statistics for SS-OFMSW from the three sources, for the share of plant origin waste in biowaste ($H = 5.73$, $p = 0.057$, $\eta^2 = 0.18$), the share of animal origin waste in biowaste ($H = 0.43$, $p = 0.806$, $\eta^2 = 0.\ 075$), the share of plastics in biowaste ($H = 2.39$, $p = 0.302$, $\eta^2 = 0.019$), and for admixtures combined ($H = 5.73$, $p = 0.057$, $\eta^2 = 0.18$), indicate that there is no basis for concluding that there are statistically significant differences between the share of these admixtures in SS-OFMSW from the three types of sources (single-family housing, multi-family housing, and catering).

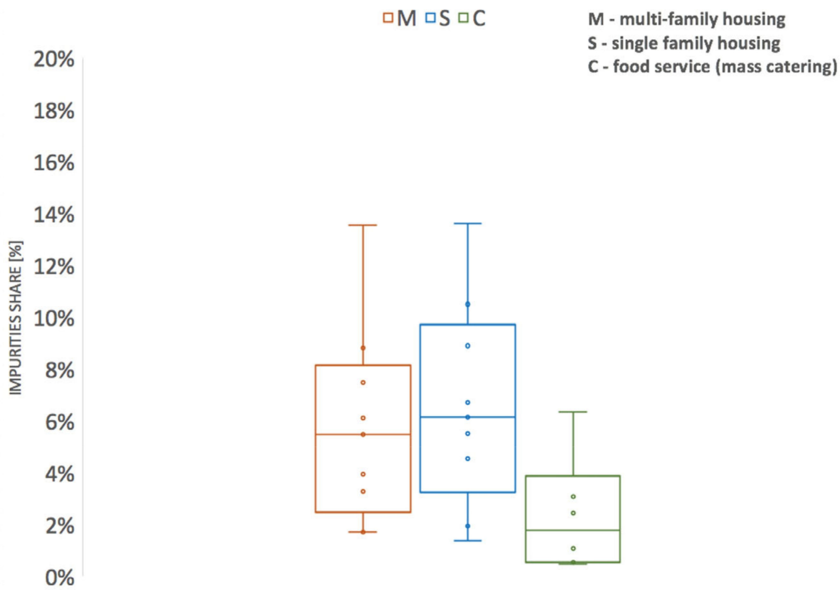

Figure 2. Impurities' share distribution for various sources (M, S, C).

3.3. Biomethane Potential (BMP) of the SS-OFMSW Tested

Table 4 shows the parameters associated with the biogas yield of the SS-OFMSW tested.

Table 4. Average biogas yields and biomethane from SS-OFMSW generated in different sources (M, S, C).

Parameter [%]	M			S			C		
	Mean	SD	CV [%]	Mean	SD	CV [%]	Mean	SD	CV [%]
Biogas yield [$m^3 \cdot Mg^{-1}$ VS]	384	±57	15	422	±96	23	426	±90	21
CH_4 share [%]	57	±4	7	61	±8	12	52	±8	16

Reactor load within the range of 2.0660–3.0884 g $VS \cdot L^{-1}$ and ISR = 3–4.

Figure 3 presents CH_4 distribution for SS-OFMSW generation sources (M, S, C). Interquartile range (IQR) takes the lowest value for catering (C) and, in the case of (multi-family housing (M) and single-family housing (S), these values are similar. Despite the greatest dispersion, both the lower and upper quartiles have the highest values for samples from single-family housing (S).

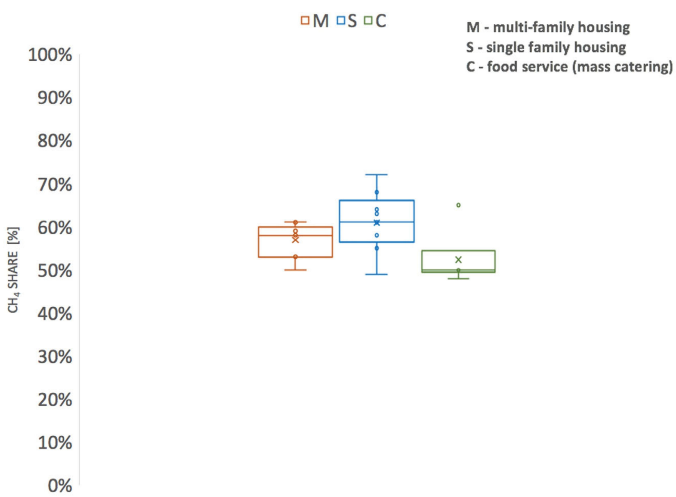

Figure 3. CH_4 in biogas share distribution for SS-OFMSW from various sources (M, S, C).

The analysis carried out with the Kruskal–Wallis test allows us to conclude that for the adopted level of significance ($\alpha = 0.05$), the test statistic for the study of the efficiency of biogas yield from SS-OFMSW from the three sources is H = 1.634, $p = 0.442$, $\eta^2 = 0.0170$ and for the methane content of biogas it is H = 5.44, $p = 0.066$, $\eta^2 = 0.16$. The differences between the values of biogas production efficiency and methane content in the biogas obtained from SS-OFMSW from different sources are not statistically significant.

4. Discussion

Research conducted from September 2021 to June 2022 indicates that in the SS-OFMSW stream, the QCR is 93.5%, 92.1%, and 97.1% for waste collected in multi-family, single-family, and catering developments, respectively. The research conducted shows a higher level of efficiency of selective food waste collection compared to the result obtained in 16 municipalities in southern Poland of 69.3% (including green waste collection) [33] and during research conducted in Catalonia with efficiency of biowaste collection of 78% [34]. The samples tested contained admixtures of waste of animal origin, which, in accordance with the requirements in force in Warsaw, should go to the stream of mixed MSW. The share of food waste of animal origin in SS-OFMSW from multi-family housing and catering is at a similar level (on average 0.6–0.7%), while in SS-OFMSW from single-family housing it is twice as much (on average 1.3%). In the pilot study conducted by the authors in 2019, this share was on average 1.44% for all types of developments [4]. In research conducted by Seruga et al., this fraction was not shown. The share of paper in single-family housing in Warsaw (1.2%) corresponds to the share of this fraction in the SS-OFMSW tested by Seruga et al. (1.3%). SS-OFMSW from multi-family housing, and especially from catering, in Warsaw contains fewer impurities in the form of paper, 0.9% and 0.3%, respectively [33]. In contrast, in a pilot study of SS-OFMSW cleanliness conducted in Spain, its paper contamination ranged from 2.18% to 3.48% [26]. The share of plastic impurities in Warsaw remains within the range of 1.6–2.5%, obtaining the lowest value in the waste stream from catering, and the highest in that coming from single-family housing. These values are significantly lower than those presented in the work of Seruga et al. (5.4%) and Gallardo et al. (4.66–6.46%) [26,33]. Other impurities found in SS-OFMSW in Warsaw (both in multi-family and single-family housing) have similar contents (within the range of 2.8–3.0%), and from catering they are seven times lower (0.4%). In the results of morphological research of food waste collected selectively in Warsaw, the presence of citrus fruits deserves attention. They constitute a share of 5.7–8.6%, the largest in single-family housing and the lowest in multi-family housing. In the paper [17], the carbon-to-nitrogen ratio for this fraction has been determined. It is characterized by a low value (C/N < 10), hence their presence in biowaste being subject to biological processing is problematic.

Very high variability in the occurrence of impurities—both in terms of total content (CV = 59–74%) and the share of individual admixtures—was recorded in the SS-OFMSW tested. The highest variability was observed for the fractions present in the smallest amounts—glass (share 0.03–1.1%, CV = 112–195%) and metals (share 0.01–0.3%, CV = 112–170%)—as well as the animal origin fraction (CV = 125–145%). For paper and plastic admixtures, the variability is also high, within the ranges of CV = 82–136% and CV = 60–130%, respectively. In the case of paper and plastic admixtures, the highest variability is in biowaste from catering. On the other hand, in the case of glass and metals, higher variability was recorded for household waste. The high variability and diversity of contaminants found in SS-OFMSW is confirmed by the results of the research [33], according to which even up to 30% plastics were found in biowaste from multi-family housing in the Lower Silesian province. The variability of food waste quality is also discussed in the paper [19], indicating that 24% of these variations may be explained by the geographical origin, the type of collection source, and the season of the collection. The amount and type of impurities found in SS-OFMSW generated and collected in Warsaw clearly indicate the need to further improve the system for their selective collection.

According to the study [17], food waste has general characteristics that can be extrapolated all over the world—it has a water content of 74–90% and a high percentage of VS (around 85 ± 5%). The food waste tested confirms these characteristics—its water content is 77–82% and VS are within the range of 84–88% (86 ± 1% for multi-family housing, 84 ± 7% for single-family housing, and 88 ± 4% for catering). In the paper [19], a slightly higher value of VS of food waste from restaurants was indicated—91.6 ± 4.1%. On the other hand, the average TS value for food waste from catering and households in Warsaw was determined at the level of 18.3% and 21.9–23.1% (for single-family and multi-family developments, respectively), which is consistent with the data in the study [19]—19.1% and 23.4%.

All the SS-OFMSW tested had very good fertilizing properties, confirming its suitability for organic recycling. Similar levels of VS (indicated above) and TOC (33–36%) were reported for all three types of biowaste. However, other studies [35] indicate a higher organic carbon content in food waste from restaurants (47.35%) compared to biowaste from catering in the capital city of Warsaw (33.99%). The VS content within the SS-OFMSW generated in Warsaw is characterized by a slight variation, at a level of CV = 3–8% (the highest for food waste from single-family housing). The variability of TOC content in the tested waste is in a slightly higher range—CV = 12–20% (highest for single-family housing and catering). Carbon-to-nitrogen ratio of food waste from the capital city of Warsaw was determined at the level of C/N = 18 ± 2 (for food waste from multi-family housing) and 17 ± 5 (for food waste from single-family housing and catering). A similar level for this parameter (defined as the average value for food waste from residential developments and restaurants) was indicated in the study of Fisgativa et al.—18.5 ± 5.9 [19].

The water content of the tested SS-OFMSW indicates its greater suitability for processing in anaerobic processes. Additionally, the C/N parameter confirms this suitability for processing in anaerobic decomposition processes, for which a C/N level in the range of 10–25 is recommended, while for aerobic processes the requirement for C/N = 25–35 is indicated [35]. According to the study [36], plant origin waste is more compostable when its moisture decreases from 76% to 60% or C/N ratio increases from 12 to 24. Too low a C/N ratio can result in the formation of large amounts of ammonia, which contributes to odor nuisance and inhibits the aerobic decomposition process. The results of the study [37] also indicate that the optimal moisture content for co-composting of food waste and green waste is 60%. They also indicate that the substrate at a C/N ratio of 19.6 can be decomposed effectively. A C/N ratio between 25 and 30 is usually considered the optimum ratio for composting; however, recent studies have shown that composting can be carried out effectively at a lower C/N of 15 [38,39]. Thanks to composting at low C/N ratios, the requirement of bulking agent for adjusting the initial C/N ratio of a food waste composting mixture can be reduced. Based on the results of the research presented in the aforementioned scientific literature, SS-OFMSW from Warsaw can be organically recycled under aerobic conditions after appropriate pretreatment to correct water content and porosity.

From the point of view of anaerobic decomposition processes, the organic matter content of the digester feedstock (determined by VS and TS) is also an important parameter which is commonly used to determine the suitability of waste for the AD process [17]. For much of the food waste tested in this study, the average VS/TS value was over 80%. This parameter for SS-OFMSW coming from Warsaw also exceeds 80% and is 84% for single-family housing, 86% for multi-family housing, and 88% in the case of catering. In the research conducted by Moretti et al., a VS/TS value of 90.8% was obtained for SS-OFMSW from households (without distinguishing the type of development) and 95% for catering [40]. The high VS/TS value means that more feedstock can be consumed by the bacteria during the fermentation process. In addition, the raw material with a higher VS/TS ratio can produce more biogas and also less digestate after the digestion process.

From the point of view of anaerobic digestion processes, the C/N ratio is also an important element in process control. The optimal value of carbon-to-nitrogen ratio is usually maintained in the range of 20–30 [41,42]. If this value is exceeded, the nitrogen will be completely consumed by the bacteria and this will reduce the amount of biogas produced. If the ratio drops too much below, nitrogen will be released in the form of ammonia, and it will increase the pH of the environment. This condition may disturb the nitrogen balance and have a toxic effect on methanogenic bacteria. The problem of the toxic effects of ammonia occurs in the fermentation of raw materials with high protein content [17]. In turn, the study [18] indicates the minimum recommended C/N ratio (15) for AD. Based on these data, it can be concluded that SS-OFMSW generated in the capital city of Warsaw is characterized by the C/N parameter being at the right level for proper anaerobic treatment.

In addition, the interaction between the C/N ratio and water content was noticed in the study [35], and the best results in terms of biological treatment of waste were recorded under the conditions of low water contents and high C/N ratios, or high water contents and low C/N ratios. Food waste from restaurants tested in this study is characterized by about half the C/N ratio (8.85) compared to biowaste from catering in the capital city of Warsaw (17.20) and slightly lower water content, 70–80% and 77–86%, respectively. Even different C/N values for food service waste are reported by Moretti et al. in their study, the C/N is 13.1 [40].

On the other hand, the optimal values of the C/P parameter for biological decomposition processing of waste are indicated in the range of 70–240 [35,43]. SS-OFMSW coming from Warsaw is characterized by C/P = 42–59, which indicates too high content of total phosphorus (especially in the case of catering waste). It is therefore advisable to process it in organic recycling processes together with other organic carbon-rich biowaste.

The suitability of the tested SS-OFMSW for treatment in anaerobic processes is confirmed by biomethane potential (BMP) research. All tested food waste has high biogas yields—at similar levels within the range of 384 $m^3 \cdot Mg^{-1}$ VS to 426 $m^3 \cdot Mg^{-1}$ VS (at reactor loads of 2.0660–3.0884 g $VS \cdot L^{-1}$ and ISR = 3–4). The average proportion of methane in biogas is 52% to 61%. In the study [16], BMP was determined for many fractions of food waste. It is found in a very wide range from 232 to 1108 mL $CH_4 \cdot g^{-1}$ VS. The range of methane potential yield in carbohydrate-rich feedstock was determined to be between 226 mL $CH_4 \cdot g^{-1}$ VS and 599 mL $CH_4 \cdot g^{-1}$ VS. In addition, in the study [18] a higher BMP of FW (460 mL $CH_4 \cdot g^{-1}$ VS) was indicated, but it is characterized by high variability (CV = 88%), while the studies conducted on biogas yield from municipal biowaste from Warsaw reported a variability of gas potential at the level of CV = 15–23%, less for SS-OFMSW from multi-family housing, and more for food waste from single-family housing and catering. Similar results of biogas yield from biowaste to the Warsaw results were obtained in the study [44]—within the range of 449.6–453.3 $L \cdot kg^{-1}$ VS. On the other hand, in the paper [33], the average biogas production rate of 120 L kg^{-1} of fresh SS-OFMSW was indicated (based on tests conducted on a full technical scale under thermophilic fermentation conditions) and the average share of methane in biogas was at a level of 58%. The usefulness of food waste for processing in anaerobic processes is confirmed by the study [19], indicating that its physicochemical characteristics (especially volatile solids, chemical oxygen demand, and biomethane potential) show a good potential of FW for AD treatment, and that among the biological valorization processes, the AD of FW has been demonstrated to be one of the most advantageous technologies to maximize the substrate and energy recovery.

The results of SS-OFMSW research from Warsaw obtained confirm that the characteristics of FW present a very high CV. In the study [19], high variations in FW characteristics were demonstrated—it was indicated that some of them exceed 100% and even 200%. This high changeability of food waste produced in urbanized areas makes it difficult to undertake waste management planning activities. According to the study [23], a CV between 0% and 16% shows a low changeability, and data with such changeability can be treated as stable data.

The study [19] showed that only two FW characteristics presented there have universal values with CV lower than or close to 16%: pH and BMP. In the SS-OFMSW research from the capital city of Warsaw, more such characteristics are shown. Table 5 presents the parameters of the examined food waste from Warsaw (along with their source of origin), which present a CV lower than 16% or close to it.

Table 5. The parameters of the tested food waste from Warsaw, which present a CV ≤ 16%.

Parameter	The Source of SS-OFMSW Origin	CV [%]
VS	M, S, C	1–8
TOC	M	12
Water content	M, S, C	3–5
C/N	M	9
C/P	S	16
The share of plant origin fractions in SS-OFMSW	M, S, C	2–5
Biogas yield from SS-OFMSW	M	15
CH_4 share in biogas	M, S, C	7–16

In Table 6, selected SS-OFMSW properties tested for Warsaw in comparison with chosen European regions are summarized. Literature data availability did not allow BMP to be included in this comparative data set. This parameter is usually presented for specific types of biowaste fractions rather than distinguishing the region of their generation.

Table 6. Selected SS-OFMSW properties tested for Warsaw in comparison with chosen European regions.

Parameter	Value	The Source of SS-OFMSW Origin	Literature Source
Content of animal origin food waste in SS-OFMSW [%]	0.59–1.29	Warsaw	Own studies
	8.4	UK (from 8 cities)	[45]
	6.3	Finland (the city of Forssa)	
	8.0	Portugal (from the city of Lisbon)	
	7.6	Italy (the city of Treviso)	
Content of paper in SS-OFMSW [%]	0.31–1.17	Warsaw	Own studies
	<2.0	UK (from 8 cities)	[45]
	17.5	Finland (the city of Forssa)	
	6.3	Portugal (from the city of Lisbon)	
	13.8	Italy (the city of Treviso)	
	2.18–3.48	Spain (3 regions)	[26]
Content of plastics, metals, and other impurities in SS-OFMSW [%]	2.03–5.43	Warsaw	Own studies
	<2.0	UK (from 8 cities)	[45]
	<2	Finland (the city of Forssa)	
	9.6	Portugal (from the city of Lisbon)	
	19.5	Italy (the city of Treviso)	
TS [%]	18.3–23.1	Warsaw	Own studies
	23.70–28.62	UK (from 8 cities)	[45]
	27.02	Finland (the city of Forssa)	
	33.80	Portugal (from the city of Lisbon)	
	24.43–27.47	Italy (the city of Treviso)	
	28.4	Average of approx. 30 studies from the EU	[19]
VS [%]	84.42–87.82	Warsaw	Own studies
	91.17–94.18	UK (from 8 cities)	[45]
	92.26	Finland (the city of Forssa)	
	81.7	Lisbon	
	83.32–86.60	Italy (the city of Treviso)	
TOC [%]	32.61–35.80	Warsaw	Own studies
	48.3–51.3	UK (from 8 cities)	[45]
C/N [-]	17–18	Warsaw	Own studies
	14–17	UK (from 8 cities)	[45]

Table 6. *Cont.*

Parameter	Value	The Source of SS-OFMSW Origin	Literature Source
QCR [%]	92–97	Warsaw	Own studies
	80–90	Spain (various regions)	[26]
	89	Italy (Calabria)	
	70–90	Czech Republic (Usti nad Labem)	
	97	Belgium (Antwerp)	
	78	Spain (Catalonia)	[34]

5. Conclusions

Reducing food waste and making efficient use of post-consumer food waste is one of the CE's key challenges, particularly in highly urbanized areas. Waste from this stage of the supply chain is characterized by less homogeneity and a high amount of contamination compared to food waste from production and processing and is therefore mainly eligible for processing through traditional organic recycling processes (composting and anaerobic decomposition). The basis for its effective use is the knowledge of the physical and chemical properties specific to the given region and determined, among other things, by the characteristics of the waste generators. In this regard, its collection system is of great importance, and the effectiveness of this system is measured both quantitatively (as the amount of collected fraction in relation to potential opportunities) and qualitatively (as the share of impurities—quality in container rate). The stability of SS-OFMSW properties is also important.

This paper presents the results of a qualitative study of SS-OFMSW generated in Poland's capital—Warsaw—from three sources (multi-family and single-family residential developments and catering). The collection efficiency of this waste, measured as QCR, is high and amounts to 92–97%. At the same time, Warsaw's SS-OFMSW collection system is characterized by high variability from the point of view of impurities present in food waste, both in terms of quantity and quality. This variability is at the level of CV = 56–87%, which is characteristic of immature selective collection systems and can hinder waste management planning efforts.

All SS-OFMSW samples tested have very good fertilizing properties, especially VS and TOC. This confirms their suitability for organic recycling, especially under anaerobic conditions, for which their water content, C/N, and BMP are predisposed. All food waste tested has high biogas yields within the range of 384–426 $m^3 \cdot Mg^{-1}$ VS and an average methane content in biogas of 52–61%. Fertilizing properties, water content, and its gas potential show little variation, not exceeding 16%, which means that these data can be considered stable.

Further research should be carried out for developing collection solutions for SS-OFMSW in urbanized areas, also including food waste of animal origin and green waste, in order to choose the most efficient and sustainable processing path.

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: 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. 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. COM/2020/98 final. *Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions a New Circular Economy Action Plan for a Cleaner and More Competitive Europe*. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN (accessed on 27 December 2022).
2. Jakubus, M.; Stejskal, B. Municipal solid waste management systems in Poland and the Czech Republic. A comparative study. *Environ. Prot. Eng.* **2020**, *46*, 61–78. [CrossRef]
3. 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]
4. 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]
5. Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2008/98/EC on Waste (Text with EEA Relevance). Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32018L0851 (accessed on 27 December 2022).
6. Giordano, C.; Falasconi, L.; Cicatiello, C.; Pancino, B. The role of food waste hierarchy in addressing policy and research: A comparative analysis. *J. Clean. Prod.* **2020**, *252*, 119617. [CrossRef]
7. Imbert, E. Food waste valorization options: Opportunities from the bioeconomy. *Open Agric.* **2017**, *2*, 195–204. [CrossRef]
8. Kibler, K.M.; Reinhart, D.; Hawkins, C.; Motlagh, A.M.; Wright, J. Food waste and the food-energy-water nexus: A review of food waste management alternatives. *Waste Manag.* **2018**, *74*, 52–62. [CrossRef]
9. Cimon, C.; Kadota, P.; Eskicioglu, C. Effect of biochar and wood ash amendment on biochemical methane production of wastewater sludge from a temperature phase anaerobic digestion process. *Bioresour. Technol.* **2020**, *297*, 122440. [CrossRef]
10. Eriksson, M.; Strid, I.; Hansson, P.-A. Carbon footprint of food waste management options in the waste hierarchy – a Swedish case study. *J. Clean. Prod.* **2015**, *93*, 115–125. [CrossRef]
11. Garcia-Garcia, G.; Woolley, E.; Rahimifard, S.; Colwill, J.; White, R.; Needham, L. A Methodology for Sustainable Management of Food Waste. *Waste Biomass Valorization* **2017**, *8*, 2209–2227. [CrossRef]
12. EUR-Lex–European Union Law–Official Site. Available online: https://eur-lex.europa.eu/legal-content/PL/TXT/PDF/?uri=CELEX:32019D1597&from=EN (accessed on 29 December 2022).
13. Carmona-Cabello, M.; Garcia, I.L.; Leiva-Candia, D.; Dorado, M.P. Valorization of food waste based on its composition through the concept of biorefinery. *Curr. Opin. Green Sustain. Chem.* **2018**, *14*, 67–79. [CrossRef]
14. Vidal-Antich, C.; Peces, M.; Perez-Esteban, N.; Mata-Alvarez, J.; Dosta, J.; Astals, S. Impact of food waste composition on acidogenic co-fermentation with waste activated sludge. *Sci. Total Environ.* **2022**, *849*, 157920. [CrossRef]
15. Adelodun, B.; Kim, S.H.; Choi, K.-S. Assessment of food waste generation and composition among Korean households using novel sampling and statistical approaches. *Waste Manag.* **2021**, *122*, 71–80. [CrossRef]
16. Wainaina, S.; Awasthi, M.K.; Horváth, I.S.; Taherzadeh, M.J. Anaerobic digestion of food waste to volatile fatty acids and hydrogen at high organic loading rates in immersed membrane bioreactors. *Renew. Energy* **2020**, *152*, 1140–1148. [CrossRef]
17. Slopiecka, K.; Liberti, F.; Massoli, S.; Bartocci, P.; Fantozzi, F. Chemical and physical characterization of food waste to improve its use in anaerobic digestion plants. *Energy Nexus* **2022**, *5*, 100049. [CrossRef]
18. Zhang, R.; El-Mashad, H.M.; Hartman, K.; Wang, F.; Liu, G.; Choate, C.; Gamble, P. Characterization of food waste as feedstock for anaerobic digestion. *Bioresour. Technol.* **2007**, *98*, 929–935. [CrossRef]
19. Fisgativa, H.; Tremier, A.; Dabert, P. Characterizing the variability of food waste quality: A need for efficient valorisation through anaerobic digestion. *Waste Manag.* **2016**, *50*, 264–274. [CrossRef]
20. Zhang, C.; Su, C.H.; Baeyens, J.; Tan, T. Reviewing the anaerobic digestion of food waste for biogas production. *Renew. Sustain. Energy Rev.* **2014**, *38*, 383–392. [CrossRef]
21. Degueurce, A.; Picard, S.; Peu, P.; Trémier, A. Storage of Food Waste: Variations of Physical–Chemical Characteristics and Consequences on Biomethane Potential. *Waste Biomass Valorization* **2020**, *11*, 2441–2454. [CrossRef]
22. Dolci, G.; Catenacci, A.; Malpei, F.; Grosso, M. Effect of Paper vs. Bioplastic Bags on Food Waste Collection and Processing. *Waste Biomass Valorization* **2021**, *12*, 6293–6307. [CrossRef]
23. Rodrigues, L.C.; Puig-Ventosa, I.; López, M.; Martínez, F.X.; Ruiz, A.G.; Bertrán, T.G. The impact of improper materials in biowaste on the quality of compost. *J. Clean. Prod.* **2020**, *251*, 119601. [CrossRef]
24. 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]
25. Cerda, A.; Artola, A.; Font, X.; Barrena, R.; Gea, T.; Sánchez, A. Composting of food wastes: Status and challenges. *Bioresour. Technol.* **2018**, *248*, 57–67. [CrossRef] [PubMed]
26. Gallardo, A.; Colomer-Mendoza, F.J.; Carlos-Alberola, M.; Badenes, C.; Edo-Alcón, N.; Esteban-Altabella, J. Efficiency of a pilot scheme for the separate collection of the biowaste from municipal solid waste in Spain. *Sci. Rep.* **2021**, *11*, 11569. [CrossRef] [PubMed]
27. 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 25 December 2022).

28. Holliger, C.; Alves, M.; Andrade, D.; Angelidaki, I.; Astals, S.; Baier, U.; Bougrier, C.; Buffière, P.; Carballa, M.; De Wilde, V.; et al. Towards a standardization of biomethane potential tests. *Water Sci. Technol.* **2016**, *74*, 2515–2522. [CrossRef]
29. Kreuger, E.; Nges, I.A.; Björnsson, L. Ensiling of crops for biogas production: Effects on methane yield and total solids determination. *Biotechnol. Biofuels* **2011**, *4*, 44. [CrossRef]
30. Longjan, G.G.; Dehouche, Z. Nutrient characterisation and bioenergy potential of common Nigerian food wastes. *Waste Manag. Res.* **2018**, *36*, 426–435. [CrossRef]
31. Del Moral, M.O.; Fröhlich, N.; Figarella, K.; Mojtahedi, N.; Garaschuk, O. Effect of Caloric Restriction on the In Vivo Functional Properties of Aging Microglia. *Front. Immunol.* **2020**, *11*, 750. [CrossRef]
32. Jędrczak, A.; Szpadt, R. *Określenie Metodyki Badań Składu Sitowego, Morfologicznego i Chemicznego Odpadów Komunalnych*; Kamieniec Wrocławski: Zielona Góra, Poland, 2006. (In Polish)
33. Seruga, P.; Krzywonos, M.; den Boer, E.; Niedźwiecki, Ł.; Urbanowska, A.; Pawlak-Kruczek, H. Anaerobic Digestion as a Component of Circular Bioeconomy—Case Study Approach. *Energies* **2023**, *16*, 140. [CrossRef]
34. Alvarez, M.D.; Sans, R.; Garrido, N.; Torres, A. Factors that affect the quality of the bio-waste fraction of selectively collected solid waste in Catalonia. *Waste Manag.* **2008**, *28*, 359–366. [CrossRef]
35. Amlinger, F.; Peyr, S.; Cuhls, C. Green house gas emissions from composting and mechanical biological treatment. *Waste Manag. Res.* **2008**, *26*, 47–60. [CrossRef]
36. Xu, Z.; Li, G.; Huda, N.; Zhang, B.; Wang, M.; Luo, W. Effects of moisture and carbon/nitrogen ratio on gaseous emissions and maturity during direct composting of cornstalks used for filtration of anaerobically digested manure centrate. *Bioresour. Technol.* **2020**, *298*, 122503. [CrossRef]
37. Kumar, M.; Ou, Y.-L.; Lin, J.-G. Co-composting of green waste and food waste at low C/N ratio. *Waste Manag.* **2010**, *30*, 602–609. [CrossRef]
38. Huang, G.F.; Wong, J.W.; Wu, Q.T.; Nagar, B.B. Effect of C/N on composting of pig manure with sawdust. *Waste Manag.* **2004**, *24*, 805–813. [CrossRef]
39. Asnani, P.U.; Zurbrugg, C. *Improving Municipal Solid Waste Management in India: A Sourcebook for Policymakers and Practitioners*; World Bank Publications: Washington, DC, USA, 2007.
40. Moretti, P.; de Araujo, J.M.; de Castilhos, A.B.; Buffière, P.; Gourdon, R.; Bayard, R. Characterization of municipal biowaste categories for their capacity to be converted into a feedstock aqueous slurry to produce methane by anaerobic digestion. *Sci. Total Environ.* **2020**, *716*, 137084. [CrossRef]
41. Rabii, A.; Aldin, S.; Dahman, Y.; Elbeshbishy, E. A Review on Anaerobic Co-Digestion with a Focus on the Microbial Populations and the Effect of Multi-Stage Digester Configuration. *Energies* **2019**, *12*, 1106. [CrossRef]
42. Ghaleb, A.A.S.; Kutty, S.R.M.; Ho, Y.-C.; Jagaba, A.H.; Noor, A.; Al-Sabaeei, A.M.; Almahbashi, N.M.Y. Response Surface Methodology to Optimize Methane Production from Mesophilic Anaerobic Co-Digestion of Oily-Biological Sludge and Sugarcane Bagasse. *Sustainability* **2020**, *12*, 2116. [CrossRef]
43. Brown, K.H.; Bouwkamp, J.C.; Gouin, F.R. The Influence of C:P Ratio on the Biological Degradation Of Municipal Solid Waste. *Compos. Sci. Util.* **1998**, *6*, 53–58. [CrossRef]
44. 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]
45. Zhang, Y.; Arnold, R.; Paavola, T.; Vaz, F.; Correia, C.; Cavinato, C.; Kusch-Brandt, S.; Heaven, S. Compositional analysis of food waste entering the source segregation stream in four European regions and implications for valorisation via anaerobic digestion. In Proceedings of the 14th International Waste Management and Landfill Symposium, Cagliari, Italy, 30 September–4 October 2013. Available online: http://eprints.soton.ac.uk/id/eprint/359726 (accessed on 25 December 2022).