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Review

Food Waste as Feedstock for Anaerobic Mono-Digestion Process

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Abstract: There is a growing recognition that food waste (FW) comprises a significant amount of unused energy. Indeed, FW shows great potential to produce methane (CH_4)-rich biogas via an anaerobic digestion (AD) process. Nevertheless, to ensure high AD process performance, deepening the knowledge of FW characteristics is required. Furthermore, the biogas yield is strongly influenced by several operational parameters. Taking into account the above, in the current study, based on the data in the literature, the physicochemical parameters of FW generated throughout the world are presented and discussed. In addition, the performance profile of the single-stage anaerobic mono-digestion process with the use of FW as a feedstock was investigated. The performed analysis clearly demonstrated that FW is characterized by significant variations in several parameters, such as pH, the total solid (TS) and volatile solid (VS) contents, the volatile solids to total solids ratio (VS/TS), soluble chemical oxygen demand (sCOD), the concentrations of VFAs and ammonium nitrogen (NH_4^+-N), and the carbon-to-nitrogen ratio (C/N). Moreover, it was shown that the selected operational parameters, such as temperature, pH, the ratio of food waste to inoculum (I) (FW/I), and the organic loading rate (OLR), may have the most significant impact on the performance of the single-stage anaerobic mono-digestion process. In addition, it was found that most of the experimental investigations presented in the literature were conducted on a laboratory scale. Hence, in future research, more effort should be made to determine the biogas yield with the use of full-scale systems. To summarize, it should be clearly highlighted that the analysis presented in this study may have important implications for the management and application of FW as feedstock for an anaerobic mono-digestion process on an industrial scale.

Keywords: biogas; feedstock; food waste; kitchen waste; methane; mono-digestion; substrate

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1. Introduction

It has been well known for some time, based on multiple lines of evidence, that globally, about one third of the food produced for humans (1.3. billion tonnes) is lost or wasted every year [1–3]. Roughly speaking, food waste (FW) is collected from numerous sources. For example, in 2021, in the European Union, FW from households represented more than 31 million tonnes of fresh mass [4] (Figure 1). Other sectors contributing to FW included food processing (above 12 million tonnes of fresh mass), primary production (5 million tonnes of fresh mass), restaurants and food services (more than 5 million tonnes of fresh mass), and retail and food distribution (4 million tonnes of fresh mass). It should be pointed out that while the FW issue is currently on the rise, the Food and Agriculture Organization of the United Nations reported that due to economic and population growth, food production will increase by 60% by 2050 [5].

FW is defined as food that has not been ultimately consumed by humans and, as a result, is discarded or recycled [6]. It has been widely documented that FW, without an efficient treatment process, is a potential contaminant of the environment and a source of greenhouse gas emissions, contributing to both global warming and climate change [7–11].

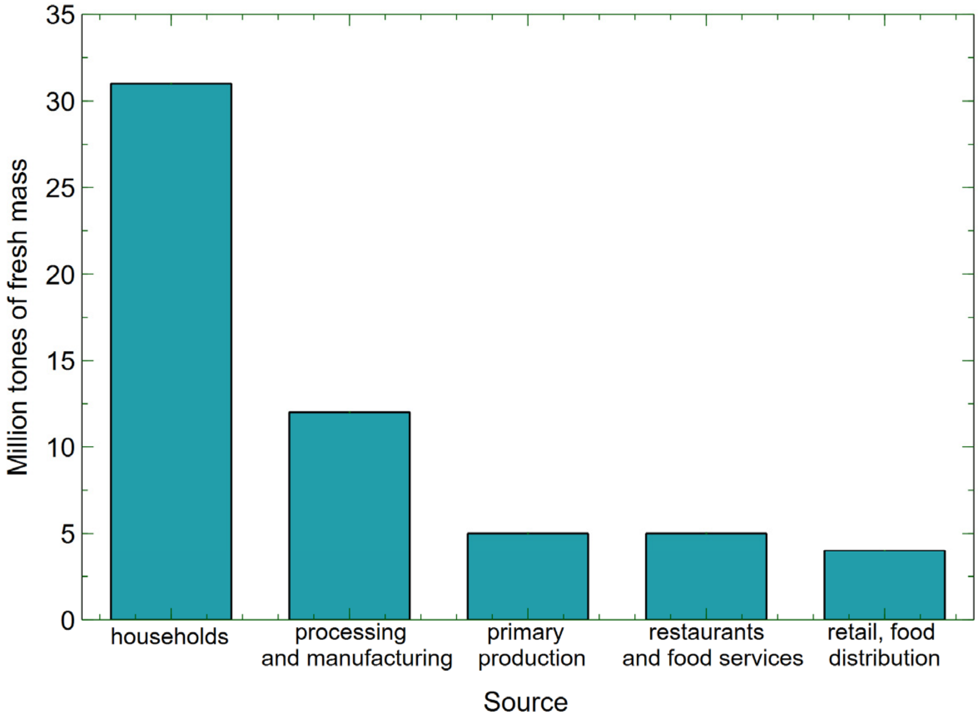

Figure 1. Sources of FW in the European Union in 2021. Based on [4].

Based on the literature review, it was noted that there is a growing recognition that FW comprises a significant amount of unused energy (Figure 2). Hence, there is no doubt that the development of sustainable and circular system solutions for FW are expected [12]. Currently, it is well known that in order to achieve sustainable environmental development, the reuse of FW by a conversion processes is essential. It is highly recommended since, as recognized in the literature, FW is a promising carbon source characterized by high methanogenic potential, biodegradability, and a high concentration of nutrient contents [13–16]. Moreover, it was highlighted by Li et al. [17] that FW is characterized by higher biogas and methane yields compared to corn stover (CS) and chicken manure (CM). At present, the main FW disposal method is anaerobic digestion (AD). AD is a low-cost and environmentally friendly biochemical process widely used for the production of methane (CH_4)-rich biogas and liquid digestate via the conversion of organic materials in the absence of oxygen. It is important to note that FW ensures a higher biogas yield than most substrates. By way of example, according to [18], FW is characterized by higher methane potential than both animal manure (AM) and municipal sewage sludge (SS). Likewise, Curry and Pillay [19] pointed out that the AD yield obtained with the use of FW leads to the production of 15 times more biogas per tonne than farm waste. The fundamentals of the AD process, including its unique advantages as well as current trends and future perspectives in biogas production, have been presented and thoroughly discussed in several recently published review articles [20–27].

The AD process may be performed in one or two/a few stages [27]. Briefly, in a single process, usually, only a continuously stirred tank reactor (CSTR) is used. Accordingly, all steps of the AD process occur in a single reactor [28]. On the other hand, a two-stage system applies two digesters and ensures the separation of acid fermentation and methanogenesis [29]. It is very essential to mention that in references [29–31], it was indicated that a two-stage AD process is characterized by more advantages than a single-reactor system. On the other hand, numerous studies have argued that the single-stage anaerobic system provides (i) higher sludge stabilization, (ii) less advanced control and operation, and (iii) minimal engineering costs [28,32]. Indeed, Capson-Tojo et al. [33] highlighted that this strategy appears as a reliable alternative due to simplicity and economic viability. It is important to point out that this solution constitutes a significant part of the systems used in Europe [13]. Indeed, Jin et al. [34], in a recently published review paper, noted that approximately 95% of AD reactors in Europe apply single-phase AD systems.

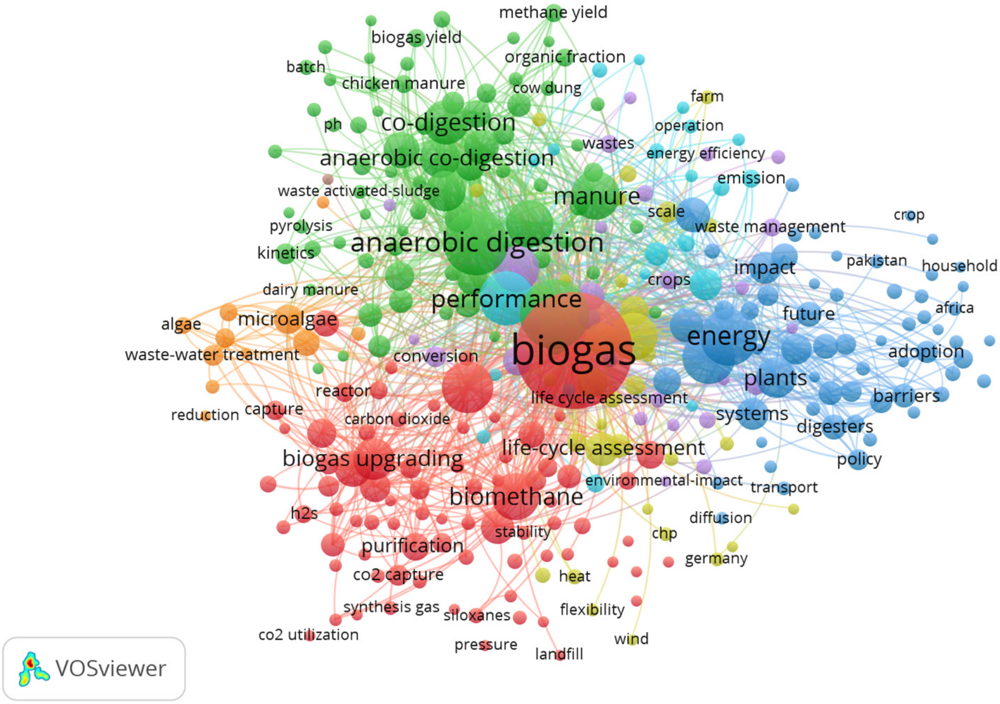

Figure 2. A bibliometric analysis of the keywords in publications of biogas (2015–2024). The analysis was performed with the use of VOSViewer software (version 1.6.20).

Another issue that must be considered is that AD can be carried out as a mono-digestion process or with the use of a mixture of two or more substrates. Co-anaerobic digestion (Co-AD) is known as the simultaneous digestion of two or more substrates [35]. The main aim of combining different feedstock types is to balance the ratio of C/N nutrients as well as macro- and micronutrients and to dilute inhibitors that decrease CH$_4$ production [36]. However, Kaur et al. [3] clearly emphasized the drawbacks of this solution. Indeed, the above-mentioned authors pointed out that in the case of Co-AD, the partial consumption of intermediate substrates decreases treatment efficiency and CH$_4$ yield. Moreover, they indicated that the reduction in the degradation of volatile fatty acids (VFAs) leads to more significant methanogenesis inhibition. As a consequence, only diluted FW may be used in the discussed strategy. In addition, choosing a suitable co-substrate with a suitable mixing ratio is of great importance [37].

According to the discussed issues, the analysis presented in the current study was limited to the single-stage anaerobic mono-digestion process. The principal objectives of this paper were to conduct a holistic investigation on the following:

(i) Physicochemical properties of FW collected from various sources, such as canteens, restaurants and cafeterias,
(ii) The performance profile of the single-stage anaerobic mono-digestion process with the use of FW as a feedstock.

The above-presented aims of this paper have been motivated by the following facts:

(i) One of the most important challenge of the FW mono-digestion is the instability of the digester [38]. Therefore, deepening the knowledge of the FW parameters is required for ensuring high process performance.
(ii) The performance of the AD process with the use of FW as a feedstock in strongly influenced by several operational parameters, such as temperature, pH, ratio between food waste and inoculum (I) (FW/I), and organic loading rate (OLR).

Hence, the findings presented in the current study provide valuable insights for the management and application of FW as a feedstock in the industrial anaerobic mono-digestion process.

2. Physicochemical Properties of Food Wastes

Due to the fact that anaerobic degradability strongly depends on the physical and chemical characteristics of the input material, the analysis of FW is one of the key important steps in designing and operating anaerobic digesters [19,39]. However, there is also general agreement that FW characteristics vary significantly. Hence, its heterogeneous nature is a great challenge in the adoption of international standards for the FW disposal and recycling [40]. FW composition can change depending on several factors such as (i) geographical location, (ii) source, (iii) season, (iv) and socioeconomic factors including consumer preferences and habits [7,40–42]. Therefore, as it has been indicated in the Introduction, there is a justified need to deepen the knowledge of the parameters of the FW used for the AD process.

It is well known that FW includes uneaten food and food preparation leftovers from various sources. Importantly, the selection of the most suitable technology for the AD process of food waste should be made taking into account, among others, its characteristics. On the basis in the present study, physicochemical properties of FW generated throughout the world were analyzed (Table 1). The analysis was conducted for FW that came mainly from university campus canteens, restaurants, cafeterias, hostels and dining halls. The investigations have been focused mainly on the following parameters: pH, total solid (TS) and volatile solid (VS) content, volatile solids to total solids ratio (VS/TS), soluble chemical oxygen demand (sCOD), concentration of VFAs, ammonium nitrogen (NH_4^+-N), and carbon-to-nitrogen ratio (C/N).

Table 1. Physicochemical properties of food wastes reported in the literature.

Source	pH [-]	TS [%] or [g/L]	VS [%] or [g/L]	VS/TS [%]	sCOD [g/L]	VFA [g/L]	NH_4^+-N [mg/L]	C [%]	N [%]	H [%]	O [%]	C/N [-]	Ref.
canteen	4.70	25.7 ± 0.03	24.0 ± 0.03	NI	NI	NI	NI	49.1 ± 0.04	2.10 ± 0.14	7.23 ± 0.15	30.2 ± 0.17	23.5 ± 1.6	[15]
canteen	4.51 ± 0.01	26.9 ± 0.3	25.2 ± 0.3	93.6 ± 0.5	NI	NI	NI	46.3 ± 0.7	2.1 ± 0.2	NI	NI	22.0 ± 1.1	[43]
canteen	NI	10.5 ± 1.5	9.1 ± 1.3	NI	84	1.882 ± 0.262	40 ± 8.2	NI	NI	NI	NI	NI	[30]
canteen	6.86 ± 0.06	22.73 ± 0.05	21.01 ± 0.04	92.42 ± 0.06	NI	NI	NI	NI	NI	NI	NI	NI	[31]
canteen	6.86 ± 0.06	22.73 ± 0.05	21.01 ± 0.04	92.42 ± 0.06	NI	NI	NI	NI	NI	NI	NI	NI	[31]
canteen	4.5 ± 0.2	19.1 ± 1.1	93.2 ± 1.4	NI	NI	NI	NI	46.1 ± 1.6	3.2 ± 0.4	7.0 ± 0.2	37.8 ± 1.6	13.7 ± 0.9	[44]
canteen	4.5 ± 0.2	19.1 ± 1.1	93.2 ± 1.4	NI	NI	NI	NI	46.1 ± 1.6	3.2 ± 0.4	7.0 ± 0.2	37.8 ± 1.6	13.7 ± 0.9	[44]
canteen	NI	NI	NI	NI	152	NI	NI	46.19	1.94	12.05	39.58	23.72	[45]
canteen	4.3	4.3 ± 0.3	NI	96.4 ± 7.6	11.0 ± 1.4	3.6 ± 0.9	NI	NI	NI	NI	NI	NI	[46]
canteen	4.5 ± 0.1	20 ± 1.2	NI	96.4 ± 0.3	71.9	NI	NI	NI	NI	NI	NI	NI	[47]
canteen	5.02	22.71	20.72	NI	NI	NI	NI	NI	NI	NI	NI	18.9	[48]
canteen	NI	16.60 ± 0.9	94.52 ± 2.9	NI	NI	NI	NI	54.05 ± 0.26	2.87 ± 0.20	6.59 ± 0.29	35.72 ± 1.6	18.83	[49]
canteen	5.2	19.9	90.2	NI	NI	NI	NI	NI	NI	NI	NI	15.9	[50]
canteen	4.1	29.4	95.3	NI	NI	NI	NI	49.58	3.53	7.32	34.88	14.2	[51]
canteen	4.41	19.71	17.04	86.45	NI	NI	NI	NI	NI	NI	NI	NI	[52]
canteen	4.51 ± 0.01	NI	NI	93.6 ± 0.5	NI	NI	-	46.3 ± 0.7	2.1 ± 0.2	NI	NI	22.0 ± 1.1	[53]
canteen	4.3	33.2	22.5	NI	NI	NI	NI	NI	NI	NI	NI	21	[54]
canteen	5.99	14.00	99.26	NI	NI	NI	NI	34.61	1.75	NI	NI	19.85	[55]
canteen	NI	17.2–24.7	NI	NI	NI	NI	NI	45.5–51.5	2.6–5.3	6.8–7.5	NI	9.7–18.1	[56]
canteen	NI	29.32	26.03	NI	NI	NI	NI	50.48	2.84	NI	NI	17.77	[57]
canteen	6.1	24.0	NI	96.2	25.2	NI	NI	NI	1.8	NI	NI	22	[58]
canteen	5.02 ± 0.03	24.30 ± 2.11	22.50 ± 1.32	NI	103.53 ± 0.31	NI	96 ± 3.5	53.39 ± 1.22	2.31 ± 0.42	6.93 ± 0.71	29.75 ± 0.25	NI	[59]
canteen	6.33 ± 0.07	24.13 ± 1.04	88.22 ± 3.78	NI	NI	0	NI	NI	NI	NI	NI	NI	[60]
canteen	5.1 ± 0.1	25 ± 0.6	21 ± 1	NI	63 ± 1	5.4 ± 0.2	NI	40.2 ± 0.3	1.5 ± 0.3	6.7 ± 0.1	NI	26.8	[61]
canteen	4.5	74,520	69,688	NI	NI	NI	NI	NI	NI	NI	NI	NI	[62]
canteen	4.40	20.23	18.16	90	NI	-	-	NI	NI	NI	NI	14.6	[63]
canteen	5.08 ± 0.07	22.17 ± 1.57	17.87 ± 1.28	80.60	NI	NI	NI	32.85	2.35	NI	NI	13.98	[64]
canteen	5.1 ± 0.4	NI	NI	93.51 ± 1.7	8.95 ± 1.24	NI [c]	16 ± 0.5	47.2	2.7	7.4	-	17.5	[65]
canteen	5.02 ± 0.03	24.30 ± 2.11	22.50 ± 1.32	NI	103.53 ± 0.31	NI	96.0 ± 3.5	53.39 ± 1.22	2.31 ± 0.42	6.93 ± 0.71	29.50 ± 0.25	NI	[66]
canteen	NI	31.70 ± 1.20	29.59 ± 2.37	93.34 ± 1.54	NI	NI	NI	47.08 ± 2.01	3.02 ± 0.32	7.04 ± 1.11	NI	15.58 ± 1.87	[67]
canteen	6.2 ± 0.2	42 ± 3	65 ± 3	NI	11.450 ± 0.002	NI	NI	NI	NI	NI	NI	NI	[68]
canteen	NI	24.87	23.87	95.98	NI	NI	NI	56.74	2.98	NI	NI	19.04	[69]
canteen	6.15 ± 0.02	22.68 ± 0.37	20.35 ± 0.29	89.77 ± 3.88	128.064 ± 0.676	NI	1319 ± 376	NI	NI	NI	NI	20.01 ± 0.09	[70]
canteen	5.63–5.96	20.66–22.29	20.04–21.62	95.82–96.70	85.880–135.808	NI	1143–1343	NI	NI	NI	NI	18.93–20.31	[70]
canteen	4.62	41.33 ± 0.28	35.41 ± 1.38	85.68	NI	NI	NI	46.20	1.89	NI	NI	24.44	[71]
canteen	5.34 ± 0.32	NI	NI	NI	NI	NI	NI	22.31 ± 0.01	2.33 ± 0.3	NI	NI	NI	[72]
canteen	5.21 ± 0.12	NI	NI	NI	NI	NI	NI	NI	NI	NI	NI	21.52 ± 3.10	[73]
restaurant	4.50 ± 0.02	16.8 ± 0.4	13.7 ± 0.1	81.5	NI	4.3 ± 0.7	NI	NI	NI	NI	NI	NI	[10]
restaurant	NI	18.1	17.1	94	NI	NI	NI	NI	NI	NI	NI	13.2	[74]
restaurant	6.5 ± 0.2	18.1 ± 0.6	17.1 ± 0.6	94 ± 1	106.6 ± 5.3	NI	NI	46.67	3.54	6.39	36.39	13.2 ± 0.2	[13]
restaurant	4.7	26.3	22.7	86.3	NI	8.4	NI	52.9	2.6	7.9	26.0	20.3	[17]
restaurant	5.9	NI	NI	NI	NI	0.49	130	NI	NI	NI	NI	37	[75]
restaurant	4.8	29.2	92.5	NI	NI	NI	NI	46.8	4.04	5.6	NI	11.6	[76]
restaurant	5.98	15.28	13.02	85.21	NI	NI	NI	7.23	0.46	NI	NI	15.72	[77]

Table 1. *Cont.*

Source	pH [-]	TS [%] or [g/L]	VS [%] or [g/L]	VS/TS [%]	sCOD [g/L]	VFA [g/L]	NH$_4^+$-N [mg/L]	C [%]	N [%]	H [%]	O [%]	C/N [-]	Ref.
restaurant	5.1 ± 0.07	29 ± 0.32	95 ± 0.04	NI	NI	NI	NI	NI	NI	NI	NI	14 ± 0.12	[78]
restaurant	4.3	9.11	8.53	93.6	NI	NI	NI	NI	NI	NI	NI	NI	[79]
restaurant	5.6 ± 0.1	NI	NI	80	NI	3.650 ± 0.235	86 ± 63	37.3 ± 2.0	1.71 ± 0.1	4.7 ± 0.30	32.7 ± 1.1	33.6	[80]
restaurant	4.53 ± 0.06	19.59 ± 1.02	15.46 ± 0.86	78.89 ± 0.57	NI	1.98 ± 0.03	NI	NI	NI	NI	NI	23.5 ± 0.45	[81]
restaurant	3.9	28.90	28.0	NI	NI	NI	NI	NI	NI	NI	NI	NI	[82]
restaurant	4.87 ± 0.05	14.3 ± 2.50	13.1 ± 2.23	91.90 ± 1.06	39.083 ± 33.276	NI	166	51.12 ± 1.0	2.74 ± 0.07	7.2 ± 0.25	30.41 ± 0.04	18.68 ± 0.11	[83]
restaurant	4.9 ± 0.1	22.621 ± 0.231	21.689 ± 0.195	NI	NI	NI	NI	NI	NI	NI	NI	NI	[84]
restaurant	4.7 ± 0.2	16.5 ± 0.3	15.2 ± 0.7	NI	47.7 ± 1.7	5.8 ± 2.3	NI	NI	NI	NI	NI	NI	[85]
restaurant	NI	25.94 ± 1.12	24.59 ± 0.84	NI	NI	NI	NI	51.1 ± 1.4	3.4 ± 0.3	7.4 ± 0.7	37.0 ± 1.6	17.5 ± 1.5	[86]
restaurant	4.5	0.725	0.048	NI	149	NI	213	NI	NI	NI	NI	121	[87]
restaurant	4.4	NI	29.3	NI	NI	NI	NI	48.4	3.8	NI	NI	NI	[88]
restaurant and cafeteria	3.94–4.85	13.95–24.30	11.47–21.44	NI	NI [a]	NI	NI [b]	43.36–53.01	2.39–4.13	6.09–7.84	NI	NI	[89]
cafeteria	4.2 ± 0.23	23.19 ± 0.54	95.69 ± 1.27	NI	NI	NI	NI	NI	NI	NI	NI	31.18 ± 1.37	[90]
cafeteria	4.93 ± 0.02	40.52 ± 0.38	39.96 ± 0.30	96.2	126.8	8.79	NI	NI	NI	NI	NI	NI	[91]
cafeteria	NI	27.45	91.99	NI	NI	NI	NI	NI	3.04	NI	NI	16.81	[92]
cafeteria	6.5 ± 0.1	24.9 ± 1.2	18.8 ± 1.1	NI	NI	NI	NI	NI	NI	NI	NI	NI	[93]
cafeteria	4.51 ± 0.01	27.59 ± 0.13	25.91 ± 0.13	93.90 ± 0.07	NI	NI	1125.08 ± 9.65	46.28 ± 0.02	2.23 ± 0.13	7.27 ± 0.02	NI	NI	[94]
cafeteria	NI	23.9 ± 0.1	21.8 ± 0.1	91.3 ± 0.3	NI	NI	NI	45.7 ± 0.1	2.8 ± 0.0	7.5 ± 0.1	NI	16.3 ± 0.2	[95]
cafeteria	5.8 ± 0.34	60.78 ± 0.73	54.12 ± 0.97	89.05	85 ± 2.32	NI	970 ± 50	45.97 ± 0.48	2.66 ± 0.24	16.44 ± 0.69	18.56 ± 0.92	17.28 ± 0.57	[96]
cafeteria	NI	31.67 ± 0.30	29.98 ± 0.31	NI	NI	NI	NI	46.47 ± 0.06	2.99 ± 0.21	7.14 ± 0.06	36.05 ± 0.15	NI	[97]
cafeteria	4.5	12.64	12.06	95.4	52.3	NI	NI	53.6	3.0	7.9	32.9	17.9	[98]
cafeteria	NI	14.8	89.5	NI	NI	NI	NI	NI	NI	NI	NI	38.2	[99]
cafeteria	NI	22.61	17.90	79.17	NI	NI	NI	30.25	2.63	NI	NI	11.50	[100]
hostel	NI	NI	NI	NI	NI	NI	NI	49.96	1.13	NI	NI	44.21	[101]
hostel	5.6	25.9	55.59	NI	NI	0.09	NI	NI	NI	NI	NI	NI	[102]
hostel	5.02–6.64	24.6 ± 3.6	20.3 ± 3.2	76–86	78.4 ± 6.2	NI	NI	NI	NI	NI	NI	NI	[103]
distribution points of big retail chains	6.84 ± 0.1	NI	NI	NI	NI	0.3601 ± 0.0071	NI	NI	NI	NI	NI	7.4 ± 0.5	[11]
distribution points of big retail chains	8.51 ± 0.2	NI	NI	NI	NI	0.1001 ± 0.0033	NI	NI	NI	NI	NI	14.7 ± 0.3	[11]
waste management company	NI	30.90 ± 0.07	26.35 ± 0.14	85.30 ± 0.65	NI	NI	NI	46.78 ± 1.15	3.16 ± 0.22	NI	NI	14.8	[39]
university	5.2 ± 0.3	18.5 ± 0.1	17.0 ± 0.1	92.0	NI	NI	NI	46.5 ± 1.5	2.2 ± 0.3	NI	NI	21.1	[104]
university	5.2 ± 0.3	NI	-	96.2 ± 0.5	5.84 ± 0.05	1.6 ± 0.1	14 ± 1.5	NI	NI	NI	NI	NI	[105]
leftovers at households	4–7.1	80–110	68–93	NI	NI	NI	NI	NI	NI	NI	NI	NI	[106]
student dorm	5.41 ± 0.13	39.67 ± 0.37	34.83 ± 0.21	NI	NI	NI	NI	NI	NI	NI	NI	NI	[107]
dining center	4.2 ± 0.2	291 ± 0.8	260 ± 0.1	NI	NI	NI	1300 ± 100	NI	NI	NI	NI	NI	[108]
dining room	4.72 ± 0.21	26.56 ± 0.6	NI	94.76 ± 3.9	NI	NI	538 ± 24	NI	NI	NI	NI	13.4 ± 0.6	[109]
dining hall	3.65 ± 0.06	7.62 ± 0.29	7.21 ± 0.29	94.6	NI	NI	NI	NI	NI	NI	NI	NI	[110]
dining hall	NI	25.5	24.1	NI	NI	NI	NI	43.2	2.4	NI	NI	18	[111]
dining hall	NI	4.24	4.10	97.0	NI	NI	NI	45.7	2.2	6.7	NI	20.8	[112]
environmental services provider	4.71 ± 0.01	23.7 ± 0.1	21.7 ± 0.1	NI	NI	NI	-	47.9 ± 0.5	3.42 ± 0.04	7.03 ± 0.26	34.3 ± 2.5	NI	[113]

Table 1. *Cont.*

Source	pH [-]	TS [%] or [g/L]	VS [%] or [g/L]	VS/TS [%]	sCOD [g/L]	VFA [g/L]	NH_4^+-N [mg/L]	C [%]	N [%]	H [%]	O [%]	C/N [-]	Ref.
garbage collection company	-	4.4	4.1	96	22	NI	NI	45	NI	NI	NI	NI	[114]
garbage collection company	-	10.5	10.1	93	20	NI	NI	45	NI	NI	NI	NI	[114]
company Jinquan Environmental Protection Co., Ltd.	5.4	29.65 ± 0.05	28.76 ± 0.05	NI	NI	NI	NI	NI	NI	NI	NI	20	[115]
Dufferin Organaics Processing Facility	4.6 ± 0.2	NI	NI	NI	60.30 ± 0.35	0.26 ± 0.02	NI	NI	NI	NI	NI	NI	[116]
digestion plant	4.96 ± 0.16	24.75 ± 0.47	22.99 ± 0.45	92.9	98.2 ± 6.5	NI [d]	0.32 ± 0.12	NI	NI	NI	NI	NI	[117]
local waste treatment facility	4.2	30.4	28.1	92.5	120.4	2.5	NI	NI	NI	NI	NI	NI	[118]
FW treatment industrial plant	3.6 ± 0.3	75.1 ± 7.1	67.5 ± 3.5	NI	NI	NI	208 ± 74	NI	NI	NI	NI	NI	[119]
FW treatment industrial plant	4.5	29.38	28.37	96.6	92.6	3.007	386	NI	NI	NI	NI	NI	[120]
municipal waste collection station	4.9 ± 0.1	NI	NI	NI	NI	NI	NI	44.9 ± 0.1	5.1 ± 0.03	NI	NI	8.8 ± 0.1	[121]
landfill site	4.0 ± 0.3	97,300 ± 28,100	82,000 ± 23,900	NI	92.4 ± 22.4	5.4 ± 2.8	630 ± 420	NI	NI	NI	NI	NI	[122]
digestion facility	4.71 ± 0.01	23.74 ± 0.08	91.44 ± 0.39	NI	NI	NI	NI	47.6 ± 0.5	3.44 ± 0.04	7.04 ± 0.63	33.3 ± 2.6		[123]
biogas plant	4.05 ± 0.28	12.02 ± 2.03	10.61 ± 1.79	NI	NI	NI	NI	NI	NI	NI	NI	NI	[124]

[a]—0.34–0.90 g/g TS; [b]—0.77–1.98 mg/g TS; [c]—1.98 ± 0.31 mM; [d]—0.32 ± 0.12 g/kg; TS—total solid; VS—volatile solid; VS/TS—volatile solids to total solids ratio; sCOD—soluble chemical oxygen demand; VFA—volatile fatty acids; NH_4^+-N—ammonium nitrogen; C—carbon; N—nitrogen; H—hydrogen; O—oxygen; C/N—carbon to nitrogen ratio; NI—no information.

Data analysis has clearly demonstrated that the properties of FW vary significantly (Table 1). Unfortunately, the reported differences pose a great challenge mainly in adopting standards, recycling as well as the valorization of FW [40]. The distributions of values of selected FW parameters in a dataset are presented in Figure 3. It should be pointed out that although in the literature data for simulated FW are available, e.g., [125–133], in the present study, investigations have been limited to the data obtained for real FW.

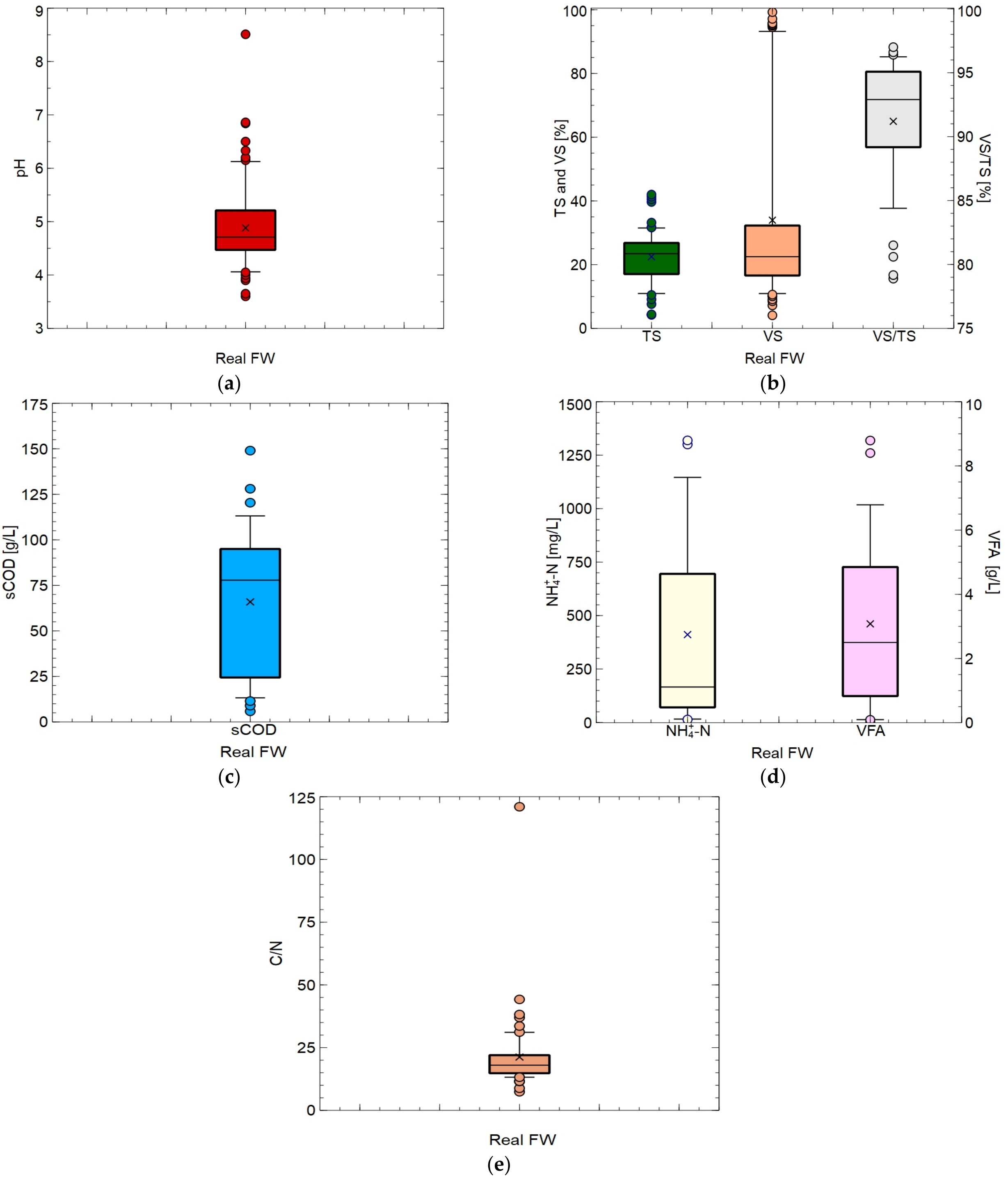

Figure 3. Physicochemical properties of FW reported in the literature: (**a**) pH (N = 71); (**b**) TS (N = 69), vs. (N = 82) and VS/TS (N = 41); (**c**) sCOD (N = 28), (**d**) NH_4^+-N (N = 22), VFA (N = 19); (**e**) C/N (N = 56). N—number of data.

As can be clearly seen in Table 1, pH is the most frequently analyzed parameter of FW. Roughly speaking, it can be attributed to the fact that pH is linked with concentrations of VFAs; hence, it plays a key role in the pH balance management during the AD process [134] (Section 3.1). According to the results of the present study, it was found that the pH values of the FW reported in the literature were in a wide range. Indeed, it was from 3.65 ± 0.06 [110] to 8.51 ± 0.2 [11] (Figure 3a). The lowest value indicated above was noted for FW collected from a dining hall, while the highest value was obtained for food waste products from the distribution points of big retail chains. It is worth noting that the average value of reported pH was 4.88, while the median was equal to 4.71.

TS is defined as the mass sum of dissolved and suspended solids [28]. In general, the AD process is classified based on the TS content in the substrate. Indeed, wet digestion is characterized by $TS < 15\%$, while for dry digestion, $TS \geq 15\%$ [120,135]. Hence, it must be stressed that in the case of a wet process performed with the use of FW characterized by high TS content, the addition of a large amount of water is required [91]. Forster-Carneiro et al. [75] pointed out that conventional anaerobic digesters require feed material with the TS concentration below 10%, while modern systems can be operated with the feed characterized by TS content higher than 20%. A similar indication was presented by Wang et al. [91] who suggested that the AD process is usually conducted with the application of substrates with the TS content below 10%. Paramaguru et al. [45] investigated the impact of TS on the biogas production via the single-stage anaerobic mono-digestion process. For this purpose, the FW calleted from the canteen was used (Table 1). The process was performed at a temperature of 30 °C. The obtained biogas production rate was equal to 0.150, 0.162, 0.143, 0.129 and 0.109 L/day for the solid concentrations of 5%, 10%, 15%, 20% and 25%, respectively. Hence, it can be concluded that the above-mentioned authors have demonstrated that the use of FW with 10% ensures the highest biogas yield. Finally, it should be pointed out that analysis presented in the current study has shown that the values of TS reported in the literature were from 4.24% [112] to 42% [68] (Figure 3b). In addition, it has been determined that the average value and median of the TS were equal to 22.49% and 23.45%, respectively. It is interesting to note that different values were indicated in a study [13] wherein it has been pointed out that the typical FW contains 7–31% of total solids. Hence, it should be pointed out that the TS content should be controlled since it may strongly affect the biogas performance. In addition, technically, a too high TS concentration may result in insufficient mixing during the AD process and finally, an expensive mixing procedure may be a challenge [25].

VSs are known as a part of the TSs present in the substrate [136]. As recognized in the literature, the VS content is another parameter determining the biogas yield during the AD of food waste. Indeed, its high content may lead to the rapid hydrolysis process and, finally, a severe acidification and inhibition of methanogenesis may occur [64]. The dataset created in the present study indicated that the VS values documented in the literature were in the wide range. Indeed, the noted vales of VS were from 4.1% [112,114] to 99.26% [55] (Figure 3b). The average VS value was equal to 33.95%, while the median was 22.50%. The analysis of the VS/TS clearly showed that it was in the range from 78.89% [81] to 97% [112] (Figure 3b). Moreover, it has been found that the average value and median of the VS/TS were equal to 91.19% and 92.90, respectively. It is worthy of note that this finding is in agreement with the indication presented by Li et al. [56] who demonstrated that typically, the VS/TS ratio ranges from 80 to 97%. On the other hand, the range reported in the present study was slightly wider than that shown by Paramaguru et al. [45]. Indeed, the above-mentioned authors pointed out that usually, the VS/TS is from 85% to 96%.

COD is a very useful and important parameter. Indeed, it allows to determine the amount of available organic matter as well as calculate the digestion efficiency [137]. In the present study, it was recognized that the values of sCOD in the FW collected from various sources was in the range from 5.84 ± 0.05 [105] to 152 g/L [45], while the average and median were equal to 65.92 and 77.85 g/L, respectively (Figure 3c).

Volatile fatty acids are intermediate products of the AD process containing mainly short-chain fatty acids, such as the fatty acids acetate, propionate and iso-butyrate. As it has been indicated in [134], VFAs are produced from monomers in the acidogenesis step. VFAs can be used as a source in the biological nutrient removal (BNR) process [126]. It is well known that FW is a highly biodegradable feedstock that tends to accumulate large amounts of VFAs. Consequently, it leads to a decrease in pH and inhibition of the AD process [37,120,138]. As a result, it may buffer the AD system capacity and lead to its failure [72]. Xu et al. [139] studied the impact of VFAs on the biogas production via the AD process of kitchen wastes. The above-mentioned authors have found that CH_4 generation has been completely limited when the VFAs concentration was from 5.8 to 6.9 mg/L. In turn, the results obtained in the present study have demonstrated that the VFAs concentration in the FW collected from various sources around the world was up to 8.79 g/L [91] (Figure 3d). The average value and median of this parameter were equal to 2.76 and 2.5 g/L, respectively.

Roughly speaking, during the AD process, ammonia is generated via the degradation of the nitrogenous matter present in the feedstock [140]. It is generally acknowledged that ammonia plays a key role during the AD process. Indeed, it is a nutrient required for the growth of bacteria involved in the AD process. In addition, NH_4^+N allows to maintain the required alkalinity and consequently ensures sufficient buffering capacity for the system [59,132,140]. Nevertheless, according to [94,132,140,141], a higher concentration of NH_4^+N inhibits the enzymatic activity of the methanogens, leading to a decrease in the CH_4 production. In [59,94], it has been highlighted that the inhibition effect of ammonium would occur under its concentration in a reactor higher than 2 g/L. Therefore, in the present study, the analysis of NH_4^+N concentration in the FW collected from various sources has been performed. It has been found that it was in the range from 14 [105] to 1143–1343 mg/L [70] with the average value and median equal to 411 and 166 mg/L, respectively (Figure 3d).

The C/N ratio is an indicator of the availability of nutrients present in a substrate [96]. According to the literature, it is a key parameter which affects the microorganisms' activity. Generally, low values of this parameter are not suitable for the AD process mainly due to the inhibition from total ammonia nitrogen present in FW [48]. In a paper by Abreu et al. [14], it has been pointed out that in general, FW is characterized by a C/N equal to 9–21. On the other hand, Ferdes et al. [137] showed that for FW, this parameter is in the range of 9.3–24.5. In a study by Song [133], it has been indicated that the C/N of food waste is in the range between 2 and 30. However, the above-presented indications are not in agreement with the finding presented in the present study. Indeed, it has been demonstrated that the C/N of the FW generated throughout the world was in the range from 7.4 to 121 (Figure 3e). As it has been pointed out by the above-mentioned authors, the values of C/N vary by regions due to different eating habits. A detailed analysis showed that the average value and median of this parameter were equal to 19.46 and 18, respectively. Moreover, it should be pointed out that performing the literature review allowed to demonstrate that the data on the optimum values of C/N for the AD are inconsistent. For instance, Fisgativa et al. [134] reported that the most suitable value of C/N is between 15 and 30. In turn, according to [92,142], the optimum is in the range of 25–30. Leung and Wang [28] indicated that the optimal ratio of carbon to nitrogen is from 30 to 35. If changing the C/N ratio is required, adding the carbon (carbohydrate) or nitrogen (urea) can be performed.

To sum up, it should be pointed out that the detailed analysis performed in the current study on the FW characteristics documented in the literature showed significant variations of several parameters. It can be explained by the fact that the FW used for the AD process has been collected from various sources. In addition, as indicated above, the FW parameters are affected by several other factors, such as season and socio-economic factors. Hence, it should be indicated that an analysis of the FW parameters should be conducted, since it may have a significant impact of the AD performance.

3. Performance Profile of Single-Stage Anaerobic Mono-Digestion Process

Investigations on the co-AD process of FW have been widely reported in the literature. Indeed, a considerable amount of research has been focused on the co-digestion of FW with such degradable co-substrates as (i) sewage sludge [49,61,72,112,136], (ii) dairy manure [88,108,143,144], (iii) pig manure [91,98,120], (iv) yard waste [14,36,79], (v) rice husk [92,145], (vi) poultry manure [101,146], (vii) municipal biowaste [138], (ix) bovine manure [76], and (ix) olive mill wastewater [10]. On the other hand, information in the literature pertaining to the anaerobic mono-digestion process is limited (Table 2). Moreover, the most important limitation lies in the fact that the vast majority of experimental studies were carried out using laboratory-scale reactors. Hence, in the future, more attention should be paid to determine the biogas yield with the use of full-scale systems.

For instance, in a study by Oduor et al. [96], FW from a cafeteria has been used (Table 1). The AD process has been conducted in a laboratory-scale reactor under a temperature and FW/I ratio equal to 37 °C and 1:1, respectively (Table 2). The significant differences in the reported values of the performance of single-stage anaerobic digestion of FW (Table 2) are related to the fact that it is strongly influenced by both FW composition and several operational parameters. Among them are mainly the temperature, pH, food waste to inoculum (I) ratio (FW/I), organic loading rate (OLR), and so on.

Table 2. Performance profile of the single-stage anaerobic digestion of food waste: literature data.

Scale	AD Conditions				Process Performance				Ref.
	FW/I on a VS Basis	T [°C]	pH	OLR [g VS/L] or [g VS/L/d]	Biogas Production Rate [L/d] or [L/L/d]	Specific Biogas Yield [L/g VS]	CH_4 Content in Biogas [%]	Specific CH_4 Yield [L/g VS]	
lab	1.5; 3.0	37	8.0→7.4	3	NI	1.142	60	about 0.180; 0.670	[17]
lab	NI	50 ± 2	7.57	6.8; 10.5	NI	NI	73.14 ± 3.64	0.425; 0.445	[39]
lab	NI	30	NI	NI	0.150; 0.162; 0.143; 0.129; 0.109	NI	60.2–64.9	NI	[45]
lab	1:3	37	NI	NI	NI	NI	NI	0.314; 0.358; 0.467	[51]
lab	NI	35; 36–40; 41–45; 46–50; 51–55; 55	7.48→6.93; 6.95 ± 0.10; 7.0–7.5; 7.14→4.73;7.82→7.46; 7.27 ± 0.12; 7.0–7.5; 7.68–7.09	0.0667–0.5336	0.057 ± 0.020; 0.082 ± 0.024; 0.233 ± 0.063; 0.528 ± 0.132; 0.610 ± 0.165; 0.615 ± 0.120; 0.574 ± 0.074; 0.507 ± 0.091; 0.349 ± 0.087; 0.609 ± 0.167; 0.542 ± 0.101; 0.502 ± 0.152; 0.237 ± 0.075; 0.130 ± 0.027; 0.318 ± 0.344; 0.192 ± 0.023; 0.119 ± 0.034; 0.143 ± 0.052; 0.193 ± 0.039; 0.068 ± 0.064; 0.109 ± 0.029; 0.133 ± 0.030; 0.316 ± 0.072; 0.531 ± 0.167; 0.584 ± 0.122; 0.619 ± 0.185; 0.519 ± 0.147; 0.505 ± 0.087; 0.498 ± 0.033; 0.693 ± 0.203; 0.505 ± 0.132; 0.576 ± 0.141; 0.395 ± 0.158; 0.194 ± 0.032; 0.447 ± 0.397; 0.365 ± 0.120; 0.632 ± 0.203; 0.511 ± 0.118; 0.413 ± 0.116	NI	NI	NI	[54]
lab	1:2	37	7.79–7.99	NI	NI	NI	NI	0.385–0.627	[56]
lab	1:2	35 ± 1	NI	NI	NI	NI	NI	0.285 ± 0.008; 0.308 ± 0.031; 0.530 ± 0.197; 0.466 ± 0.106; 0.418 ± 0.119; 0.618 ± 0.012; 0.696 ± 0.043; 0.639 ± 0.174	[60]
lab	NI	37 ± 1; 55 ± 1	NI	1.5; 1; 1.5; 2.5; 5; 7.5; 10	0.3; 0.4; 0.03; 0.03; 0.150; 0.100	NI	56.0−58.0; 54.0; 56.0; 3.4; 2.3; 1.8; 0.1; 55.0−57.0; 55.0; 56.7; 59.0; 58.6; 57.0; 55.7	0.38673; 0.37057; 0.51267; 0.55140; 0.54139; 0.44393; 0.401	[66]

Table 2. *Cont.*

Scale	AD Conditions				Process Performance				Ref.
	FW/I on a VS Basis	T [°C]	pH	OLR [g VS/L] or [g VS/L/d]	Biogas Production Rate [L/d] or [L/L/d]	Specific Biogas Yield [L/g VS]	CH_4 Content in Biogas [%]	Specific CH_4 Yield [L/g VS]	
lab	1:10	37 ± 2	6.5–7.5	NI	NI	0.249 ± 0.00022	69 ± 0.32	0.086 ± 0.00061	[78]
lab	1	37	7.0	0.15; 0.30; 0.45; 0.60; 0.90	NI	NI	NI	0.869; 0.348–0.837; 0.740; 0.654; 0.348	[81]
lab	1	55	7.0	0.15; 0.30; 0.45; 0.60; 0.90	NI	NI	NI	0.735; 0.670; 0.568; 0.500; 0.338	[81]
lab	2	37	NI	NI	NI	NI	52	NI	[82]
lab	NI	37	7.6 ± 0.21	1.42→2.10	NI	NI	NI	0.30952	[85]
lab	1:300; 1:150; 1:100; 1:75; 1:60; 1:30	38 ± 2	7.05; 6.98; 7.01; 6.97; 6.99; 7.14	0.38; 0.77; 1.15; 1.53; 1.92; 3.83	NI	NI	70; 51; 65; 79; 81; 52	NI	[87]
lab	1:300; 1:150; 1:100; 1:75; 1:60; 1:30	38 ± 2	6.6–6.7	1.3; 2; 4; 6; 7; 8	NI	NI	72; 68; 63; 85; 42; 42; 36	NI	[87]
lab	0.6	37	NI	NI	NI	NI	NI	0.4911; 0.4361; 0.3532; 0.4824; 0.4397; 0.5384; 0.5652	[89]
lab	0.6	55	NI	NI	NI	NI	NI	0.4971; 0.4308; 0.3739; 0.5127; 0.4445; 0.5512; 0.5747	[89]
lab	NI	35 ± 1	7.0 ± 0.1	NI	NI	NI	NI	0.2533; 0.1977; 0.0503; 0.0227	[93]
lab	1:1	37	NI	NI	NI	0.35785 ± 0.024	53 ± 4.35	NI	[96]
lab	NI	50	7.0	NI	NI	NI	62.03	NI	[101]
lab	NI	30 ± 2; 50 ± 2; 15 ± 2	NI	NI	NI	NI	NI	NI [a]	[102]
lab	NI	37 ± 1	7.1–7.5	8; 10	NI	NI	NI	0.251; 0.197; 0.1948; 0.1562; 0.1202	[105]
lab	NI	35	7.39 ± 0.08; 7.68 ± 0.06; 7.82 ± 0.09	2.35; 7.01; 9.41	NI	0.70 ± 0.02; 0.76 ± 0.01; 0.87 ± 0.02	52.5 ± 2.1; 54.2 ± 2.7; 55.1 ± 2.6	0.37 ± 0.01; 0.41 ± 0.01; 0.48 ± 0.01	[109]
lab	NI	36 ± 1	NI	NI	NI	NI	NI	0.475 ± 0.031	[113]
lab	1:2	37	7.7; 7.3 ± 0.01; 7.7 ± 0.03; 7.6 ± 0.03; 7.7 ± 0.01	NI	NI	NI	NI	0.435	[117]
lab	NI	50 ± 1	7.6 ± 0.1; 7.7 ± 0.1; 7.7→7.3; 7.6 ± 0.1	4.2→5.4; 7.3; 10.0; 10.0	2.6 ± 0.2; 3.9 ± 0.2; 5.4→4.4; 5.3 ± 0.2	NI	59.0 ± 1.1; 58.0 ± 0.5; 54.4 ± 0.2; 55.1 ± 0.4	NI [b]	[119]

Table 2. *Cont.*

Scale	AD Conditions				Process Performance				Ref.
	FW/I on a VS Basis	T [°C]	pH	OLR [g VS/L] or [g VS/L/d]	Biogas Production Rate [L/d] or [L/L/d]	Specific Biogas Yield [L/g VS]	CH_4 Content in Biogas [%]	Specific CH_4 Yield [L/g VS]	
lab	NI	40	NI	0.6; 1.2; 1.7; 2.3; 3.5; 4.9; 5.3; 6.0; 6.7; 7.3; 9.1; 12.8; 16.4; 20.1	NI	NI	NI	0.431 ± 0.122; 0.336 ± 0.044; 0.509 ± 0.082; 0.437 ± 0.048; 0.315 ± 0.020; 0.302 ± 0.022; 0.408 ± 0.053; 0.483 ± 0.057; 0.500 ± 0.106; 0.503 ± 0.026; 0.377 ± 0.094; 0.315 ± 0.037; 0.284 ± 0.023; 0.154 ± 0.075	[124]
lab	NI	40	NI	0.5; 1.1; 1.6; 2.7; 3.8; 5.2; 6.6; 8.2; 10.1; 12.4; 14.6	NI	NI	NI	0.208 ± 0.052; 0.211 ± 0.029; 0.248 ± 0.034; 0.287 ± 0.031; 0.332 ± 0.056; 0.405 ± 0.050; 0.391 ± 0.059; 0.440 ± 0.033; 0.403 ± 0.046; 0.321 ± 0.024; 0.233 ± 0.075	[124]
lab	1:2	39 ± 1	7.3–7.8	NI	NI	NI	66	0.3286	[125]
lab	1; 3	37	uncontrolled; 4; 5; 6	1.0	NI	NI	NI	0.0003; 0.0003; 0.017; 0.0008; 0; 0001; 0.0001; 0.0001; 0.0006; 0.0033; 0.0062; 0.00009; 0.0004; 0.0004	[127]
lab	0.5: 1; 2; 3; 4; 5; 6	35 ± 0.5	7.84→7.21; 7.79→7.19; 7.70→7.19; 7.71→7.37; 7.58→7.52; 7.47→7.60; 7.45→7.86	NI	NI	0.46401; 0.67437; 0.63888; 0.55513; 0.57014; 0.55158; 0.55678	NI	NI	[128]

Table 2. *Cont.*

Scale	AD Conditions				Process Performance				Ref.
	FW/I on a VS Basis	**T [°C]**	**pH**	**OLR [g VS/L] or [g VS/L/d]**	**Biogas Production Rate [L/d] or [L/L/d]**	**Specific Biogas Yield [L/g VS]**	**CH_4 Content in Biogas [%]**	**Specific CH_4 Yield [L/g VS]**	
lab	NI	mesophilic conditions	7.2	NI [c]	19.6 ± 3.0; 36.3 ± 4.5; 54.0 ± 6.0; 67.5 ± 9.0	NI	60.9 ± 0.2; 60.5 ± 0.3; 59.1 ± 0.4; 58.9 ± 0.3	NI [d]	[129]
lab	NI	40; 45; 50; 55	NI	NI	7.3; 6.1; 8.7; 7.4; 10.4; 8.6; 6.8; 5.6	NI	61.6; 65.6; 63.2; 66.2; 64.4; 67.4; 54.4; 58.9	NI [e]	[147]
lab	NI	37; 55	7.7 ± 0.1; 8 ± 0.1; 7.8 ± 0.2; 8 ± 0.1	1–3	NI	NI	63; 62; 62, 58	0.480 ± 0.033; 0.475 ± 0.029; 0.448 ± 0.044; 0.401 ± 0.045	[148]
lab	1.6; 3.1; 4.0; 5.0	50 ± 2	7.2→7.6; 7.3→7.4; 7.3→7.6; 7.2→7.6; 7.4→7/6	6.5; 12.5; 16; 20; 12.5	NI	0.778; 0.742; 0.784; 0.396; 0.430	65.6; 67.6; 66.1; 63.7; 56.9	0.510; 0.502; 0.518; 0.252; 0.245	[149]
industrial	3	39; 42; 54; 52→38	7.9 ± 0.1; 8.1 ± 0.04; 7.9 ± 0.1; 8.0 ± NI; 8.3 ± 0.1	6.4; 5.5; 5.9; 8.3; 5.8	NI	NI	58 ± 0.2; 59 ± 0.4; 61 ± 0.1; 61 ± 0.1; 57 ± 0.2	0.44 ± 0.15; 0.40 ± 0.01; 0.52 ± 0.05; 0.60 ± 0.12; 0.42 ± 0.12	[150]

[a]—0.44; 0.57; 0.72; 0.88; 0.37; 0.42; 0.53; 0.62; 0.30; 0.39; 0.58; 0.73 L CH_4/g COD; [b]—0.49 ± 0.03; 0.55 ± 0.03; 0.54→0.41; 0.54 ± 0.02 m^3/kg COD; [c]—2.43, 4.86, 7.29, 9.72 g COD/L/d; [d]—0.33 ± 0.05; 0.30 ± 0.03; 0.29 ± 0.02; 0.28 ± 0.02 L CH_4/g COD; [e]—145; 154; 177; 187; 216; 223; 119; 129 L/kg sCOD;. FW/I—food waste to inoculum ratio; I—inoculum; FW—food waste; OLR—organic loading rate; NI—no information.

3.1. Temperature and pH

Invariably, the AD process can be conducted under different temperature conditions, such as (i) psychrophilic (12–16 °C), (ii) mesophilic (35–37 °C) and (iii) thermophilic (50–60 °C). Among them, mesophilic and thermophilic conditions are more favorable since a higher temperature may result in a higher hydrolysis rate [28]. Moreover, it has been widely acknowledged that the operating temperature has a significant impact on the biogas stability and the bacterial and methanogenic communities [151,152]. More precisely, it affects the activity of both enzymes and coenzymes as well as hydrolysis development [22]. It is important to note that although the thermophilic AD process is known to be more efficient than mesophilic one [25,66,75], the anaerobic mono-digestion of FW was operated mainly under mesophilic conditions (about 35 °C) (Table 2). On the other hand, thermophilic conditions were applied in the studies [39,54,81,89,101,102,119,147–150]. The performance of the process under mesophilic conditions is generally more stable than that obtained for a thermophilic AD process [86]. The advantages and disadvantages of the above-mentioned conditions have been thoroughly discussed in the study [27]. It is important to note that performing the literature review allowed to find that investigations on the biogas production via an anaerobic mono-digestion process under psychrophilic conditions (below 20 °C) are unavailable. Hence, a review of the relevant literature found that the existing knowledge in this area is incomplete.

As it has been indicated earlier, pH is the important parameter governing the AD process performance. Indeed, this finding has been clearly indicated in a number of publications, e.g., [69,90,126,134]. Roughly speaking, pH has a significant impact on the microorganisms' growth and the hydrolysis of particulate organic matter [126]. For the degradation of carbohydrate and proteins, the most suitable pH is in the range between 6–9 and 7–8, respectively [134]. As already stated in the literature, in order to ensure the stability of the AD process, the adjustment of initial pH and its continuous control are required [105]. Based on the data presented in Table 2, it can be clearly seen that the AD experiments presented in the literature were performed under a range of pH values between 4 [127] and 8.3 ± 0.1 [150]. According to [28,142], the optimum values of biogas production via the AD process are around 7. As demonstrated in Section 2, most of the FW generated throughout the world and analyzed in the present study was characterized by pH values lower than 7. Therefore, it is important to point out that according to previous research, if in the continuous reactor, the controlling of pH is required, sodium bicarbonate ($NaHCO_3$) and sodium hydroxide (NaOH) can be added to the system [142]. For instance, investigations performed by Valenca et al. [78] clearly highlighted that $NaHCO_3$ is an effective alkalizing and buffering agent for the AD of food waste. Indeed, it interacts with large amounts of acids produced during the process, relieving the inhibition effects.

3.2. Food Waste to Inoculum Ratio

The results presented in Table 2 clearly demonstrate that the experiments reported in the literature were conducted under a wide range of FW/I ratios. Elbeshbishy et al. [116] pointed out that this parameter plays a vital role in the batch high-solids AD process and in the assessment of the anaerobic biodegradability of solid wastes. Furthermore, it affects its biochemical pathways and kinetics. Wu et al. [111] indicated that the optimization of this parameter should be based mainly on the composition of the fermentation substrate. In turn, according to Li et al. [17], the FW/I ratio is especially important in the large-scale batch reactors used for biogas production. Hence, it can be clearly indicated that investigating the most suitable value of this parameter is necessary to provide the highest methane yield obtained during the AD process of FW. From Table 2, it can be seen that the impact of the FW/I ratio on the performance of FW mono-digestion has been considered in several studies [17,87,127,128,149] (Table 2).

For instance, Khadka et al. [128] demonstrated the impact of the FW/I ratio on the performance and kinetics of the lab-scale batch AD of food waste. The process was under mesophilic conditions (35 ± 0.5 °C) for 57 days. The applied FW/I ratio was equal to 0.5:1;

2; 3; 4; 5; and 6 based on the VS compositions. The above-mentioned authors showed that among the applied FW/I values, the ratio equal to 1 ensured the highest average biogas yield (674.40 ± 29.10 L/g VS). In turn, the lowest process performance (24.61 L/g VS/d) was reported for the FW/I ratio of 6. This findings confirmed the fact that the FW/I ratio is one of the key factors affecting the AD process yield. In a subsequent paper [17], it has been documented that the methane production performance for the mono-digestion process of kitchen waste (KW) conducted under mesophilic temperature (37 °C) and an FW/I ratio of 3.0 was 74% lower than that obtained for an FW/I ratio equal to 1.5. It has been indicated that higher values of FW/I result in more serious acidification processes and consequently, biogas production is noticed. Similar values of this parameter (1 and 3) have been applied in a following paper [127], wherein AD experiments were performed under a temperature of 37 °C. An interesting finding presented in the above-mentioned study demonstrated that for the processes conducted under an FW/I of 3, the methane production was suppressed by itself. With regard to thermophilic conditions, the effect of FW/I on the biogas yield for the AD process of FW was presented in [149]. The investigations were conducted under various values of the FW/I: 1.6; 3.1; 4.0; and 5.0. In the above-mentioned paper, the highest values of the biogas yield (0.784 L/g VS) and methane yield (0.518 L/g VS) have been reported for the studies performed under an FW/I of 4. Increasing the FW/I to 5 resulted in a significant decrease in the process performance. The above-mentioned authors have pointed out that this finding can be attributed to the inhibition of methanogenic bacteria that occurred under an FW/I of 5.

To sum up, the results discussed above may be useful for selecting the most suitable FW/I ratio for the single-stage anaerobic mono-digestion process of FW.

3.3. Organic Loading Rate

OLR is defined as the amount of substrate to be added with the digester volume and time [85]. Roughly speaking, it is a key parameter influencing both the stability and performance as well as the cost of the AD process [153]. An increase in the OLR up to a most suitable point may result in an increase in the AD process performance. In contrast, too high OLR values may lead to an accumulation of VFAs in the system, causing in the process inhibition and a significant reduction in the CH_4 content [119,153,154]. In a review paper by Agyeman [88], it was indicated that the long-term mono-digestion of FW is typically limited to OLR values below 2.5 g VS/L/d. However, the analysis of data available in the literature allowed to demonstrate that values of OLR applied during this process were in the range from 0.0667 g VS/L/d [54] to 20.1 g VS/L/d [124] (Table 2).

However, Zhang et al. studied [39] the AD process of the FW from a waste management company (Table 1) under thermophilic conditions (50 ± 2 °C) with the application of two values of initial OLR (Table 1). Interestingly, it has been determined that for an OLR of 6.8 and 10.5 g VS/L, the average methane yield was approximately 425 and 445 mL/g VS, respectively. Hence, it was clearly indicated that this parameter did not have a significant impact on the process performance. It is important to mention that the impact of OLR on the methane yield during the single-stage anaerobic mono-digestion process of FW was reported in [129]. In the above-mentioned study, the hollow fiber anaerobic membrane bioreactor (HF-AnMBR) was operated at mesophilic conditions and a pH around 7.2 (Table 2). In turn, the applied values of OLR were equal to 2.43, 4.86, 7.29, 9.72 and 14.58 g COD/L/d. It has been documented that under an OLR in the range from 2.43 to 9.72 g COD/L/d, the CH_4 content in biogas was stable (between 58.9 ± 0.3 and 60.9 ± 0.2%). However, further increasing this parameter to 14.58 g-COD/L/d led to a significant drop of the pH to 5.3. Consequently, a decrease in the methane content (34.05%) was noted. These results indicated that increasing the OLR resulted in the inhibition of the AD process.

4. Conclusions and Perspectives

Obviously, to ensure a high biogas yield, knowledge of the FW parameters is required. Hence, in the present study, the analyses were focused on the characteristics of FW collected from various sources throughout the world. To the best of the author's knowledge, this paper is the first to demonstrate the distributions of the selected parameters of raw FW reported in the literature. It has been found that all of the analyzed parameters varied significantly. It can be attributed to the fact that the FW properties are strongly dependent on the geographical location, source, and season as well as consumer preferences and habits.

It is well known that the AD process is affected by operational conclusions. In the current study, the impact of temperature, pH, FW/I and OLR was discussed. It allowed to demonstrate the performance profile of the single-stage anaerobic mono-digestion process with the use of FW as a feedstock.

Finally, the literature review revealed that most of the studies focused on the use of FW as a feedstock for the single-stage anaerobic mono-digestion process were conducted at the laboratory scale. Hence, further studies are needed to determine the biogas yield using full-scale systems.

To sum up, it should be pointed out that the results presented in this study provide valuable insights for the management and application of FW as a feedstock anaerobic mono-digestion process at the industrial scale.

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Abbreviations

AD	anaerobic digestion
AM	animal manure
BNR	biological nutrient removal
C	carbon
C/N	carbon to nitrogen ratio
Co-AD	co-anaerobic digestion
CS	corn stover
CSTR	continuously stirred tank reactor
CM	chicken manure
C/N	carbon to nitrogen ratio
FW	food waste
FW/I	ratio between food waste to inoculum
H	hydrogen
HF-AnMBR	hollow fiber anaerobic membrane bioreactor
I	inoculum
KW	kitchen waste
N	nitrogen
NH_4^+-N	ammonium nitrogen
NI	no information
O	oxygen

OLR	organic loading rate
sCOD	soluble chemical oxygen demand
SS	sewage sludge
TS	total solids
VFA	volatile fatty acids
VS	volatile solids
VS/TS	ratio of volatile solids to total solids

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