Anaerobic Co-Digestion of Primary Sludge and Biowastes

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Contributor: Foteini Sakaveli, Maria Petala, Vasilios Tsiridis, Efthymios Darakas

Primary sludge is a valuable substrate for anaerobic digestion as it contains a higher percentage of fatty acids and lipids compared to secondary sludge, although its carbon-to-nitrogen ratio is relatively low due to its inherent deficiency of carbon. This limiting factor of C/N ratio can be overwhelmed by the co-digestion of primary sludge with organic fractions such as agricultural byproducts and municipal solid wastes. The operating principle of this practice is based on the fact that organic fractions such as agricultural byproducts contain a high percentage of carbon and a low percentage of nitrogen, so the co-digestion of primary sludge with different organic fractions, such as animal manure, agricultural residues, organic fractions of municipal waste, or vegetable residues, may improve the balance of nutrients, provide buffering capacity, adjust the C/N ratio, reduce the concentration of ammonia, and hence its inhibitory effects, and overall promote the process of methanogenesis.

Keywords: anaerobic digestion ; primary sludge ; co-digestion ; additives

1. Introduction

Anaerobic digestion is a well-known and established practice in municipal wastewater treatment plants (WWTP), which target energy recovery through biogas production, sludge volume reduction, and sludge stabilization through the inactivation of pathogens. Sludge is then converted into a biologically stable material so that it can be safely disposed of or used in applications such as agriculture, composting, etc. In addition, as landfilling is prohibited, the large quantities of sludge that are generated during its treatment process must be accordingly handled.

2. Food Waste (FW), Fruit and Vegetable Waste (FVW), and the Organic Fraction of Municipal Solid Waste (OFMSW)

Table 1 summarizes the findings of studies that investigated the impact of the co-digestion of primary sludge with food waste (FW), fruit and vegetable Waste (FVW), and the organic fraction of municipal solid waste (OFMSW) on biogas production efficiency. Obulisamy's et al. [1] studied the anaerobic co-digestion of FW–primary sludge mixture under mesophilic and thermophilic conditions. Prior to digestion, primary sludge was further thickened using chemical agents (flocculants). The best performance as regards methane production was obtained at mesophilic conditions, while it was favored at decreased food-to-waste concentrations, i.e., decreased FW/CEPT ratio. For example, a decrease from 1:1 to 1:2 in the FW/CEPT ratio resulted in about a 40% increase in methane production per VS unit mass. Specifically, for the 1:1 FW/CEPT ratio, methane production averaged around 100 mL CH_4/g VS, while for the 1:2 ratio, it increased to approximately 140 mL CH_4/g VS. This was probably attributed to better hydrolysis of organics and enhanced efficiency of acetogenesis process. A further increase in the overall efficiency was observed in a later study of Chakraborty et al. [2] who added lime for improving the alkalinity of tested substrates and tested even lower FW-to-CEPT ratios. Kang and Liu [3] agreed well with the studies of Obulisamy et al. [1] and Chakraborty et al. [2], verifying that an increase in CEPT fraction in the substrate favors the production of biomethane and limits problems associated with increased acidogenesis inside the anaerobic digestors. Interestingly, the amount of cumulative methane produced by the 1:4 FW/CEPT mixture, which was about 2750 mL CH_4, at the end of a 20-day anaerobic digestion procedure was almost two-fold higher than the amount produced by the 3:2 FW/CEPT mixture. On the other hand, Xie et al. [4] found that anaerobic digestion of primary sludge with FW was highly efficient for methane production (799 mL CH_4/g VS) at a ratio of 1:1 for FW to PS, while Rakić et al. [5] found the highest biogas production equal to 619 mL/g VS at a FW/PS ratio equal to 3:1. Alternatively, Xie et al. [4] used paper pulp reject to improve the C/N ratio of PS; however, methane production capacity was inferior when compared to food waste/PS substrate ratio. The crucial role of alkalinity-related problems during the co-digestion of primary sludge with food waste was moreover addressed by Gomez-Lahoz et al. [6], who revealed that the addition of $NaHCO_3$ in the mixture of FVW and PS at a ratio of 1:1 significantly improved the efficiency of methane production. Lately, Elsayed et al.

[7] observed the highest methane yield (141 mL CH_4/g VS) at a FVW-to-PS ratio of 1:1 on a VS basis, while a further increase in the FVW fraction did not improve biogas production. On the contrary, Gómez et al. [8] studied the digestion of primary sludge and the co-digestion of primary sludge with fruit and vegetable wastes in ratio of around 1:3.5 and found that the addition of fruit and vegetable wastes enhanced the organic loading in the digesters and produced higher amounts of biogas when compared to single digestion of primary sludge, overlooking inhibition problems related to acidogenesis and alkalinity. Comparable results were reported by Habagil et al. [9] when a mixture of municipal organic solid wastes and primary sludge was subjected to anaerobic digestion. In this study, 404 mL CH_4/g VS/d were produced using as a substrate mixture at ratio of 4:1 FW/PS on a VS basis. Meanwhile, when Ahmed et al. [10] studied the anaerobic digestion of the organic fraction of the municipal solid wastes and primary sludge at a 1:1 ratio, their findings revealed a biogas production rate of 107 mL/g VS. In general, the term FW includes a multitude of wastes that originate from diverse sectors and activities, such as household or manufacturing, wholesale/retail, and food sale. Therefore, FW as a substrate in anaerobic digestion may be highly diverse in terms of its content of carbohydrates, fats, and proteins. Food wastes containing components such as meat, bones, cheese, and eggs are rich in proteins and fats, whereas bread, potatoes, rice, and flour are rich in carbohydrates, while legumes and fresh vegetables such as spinach present a more even composition of carbohydrate and protein content [11]. The origin of FW is critical for anaerobic digestion, considering that methane yield depends on the carbon source of the substrate; for example, lipids have a higher methane potential and can achieve 0.70 to 1.01 L CH_4/g VS, although they require a digestion time up to 50–65 days compared to proteins, whose maximal methane yield ranges between 0.42 and 0.85 L CH_4/g VS after digestion for about 15–25 days [12][13]. Based on these data, it might have been expected that an increase in FW contribution to the PS substrate would enhance the methane production yield. Yet, during the first step of hydrolysis, FW induces extended acidogenesis via lactic acid and VFA production, which inhibit methanogenesis through different pathways. For this reason, the addition of lime or the increase in PS to the substrate favors the buffering capacity of the system and the overall co-digestion of FW and PS. In addition, as suggested by Chakraborty et al. [2], the activity of various enzymes, such as the a-amylase and b-galactosidase, is limited at lower concentrations of FW in the substrate, thus enhancing the production of bioenergy. Moreover, the addition of PS advances the production of methane with less H_2S content, independently of the substrate-to-inoculum ratio [14].

Table 1. Co-digestion of primary sewage sludge with food waste, fruit and vegetable waste, and organic fraction of municipal solid wastes.

	Substrate [1]	Treatment [2]	Inoculum [3]	ISR *	Tested Conditions	Mode [4]	Scale [5]	T [6]	Efficiency [7]	Reference
1.	CEPT	-	ADS	-	OLR 2, 1.5, 2.25, and 3 g VSS/L/d	SC	L	M	-	[15]
2.	PS SS	Advanced primary separation	ADS-LAB	-	SS: 0.5 and 1.5 g/L	-	L	-	-	[16]
3.	PS	FNA (HNO_2-N)	ADS	1.5–2 *w*/*w* VS for sludge, *w*/*w* TCOD for supernatant	0.77, 1.54, 2.31, 3.08, and 3.85 mg HNO_2-N/L	B	L	M	-	[17]
4.	PS	Enzymatic treatment (P, LP)	ADS-LAB	1:1 g VSS/g VS	P/LP 3:1, 1:1, 1:3, 0:1 *w*/*w*	B	L	M	+	[18]
5.	PS	NaOH	EBS	4:1	NaOH 0.1 mol/L to 5, 10, 15% recycled sludge	SC	L	M	+	[19]
6.	PS	MCP	ADS	0.3:1 *v*/*v*	2, 4, 6, 8, and 10 min of MCP	B	L	M	+++	[20]
7.	PS	HTT	ADS	0.3:1 *w*/*w* VS	130, 150, 170, 190, and 210 °C for 30 min	B	L	M	+	[21]

[1] PS substrate, PS: primary sludge. [2] Co-substrate, CSB: corn stover biochar; WS: wheat straw; BH: buckwheat husk; FL: fallen leaves; GR: grass; SBP: sugar beet pulp; SL: sugarcane leaves; CS: Corchorus stalks; CM: cow manure; BS: brewery sludge; WH: whey. [3] Inoculum, ADS: anaerobic digested sludge; CM: cow manure; WAS: waste-activated sludge;

RC: rumen content of cattle; UASB: up-flow anaerobic sludge blanket digestion. [4] Mode, B: batch; C: continuous; SC: semi-continuous. [5] Scale, L: lab scale, [6] T: temperature; M: mesophilic; TH: thermophilic. [7] Efficiency, +: 0–40%; ++: 41–80%; +++: >81% enhancement of biomethane production compared to single digestion of primary sludge. * Inoculum-to-substrate ratio: ISR. + Organic loading rate: OLR. Total solids: TS.

The formation of VFAs significantly contributes to their accumulation in digesters that may negatively impact their operation and methane productivity. Although butyric and acetic acid favor methanogenesis through the activity of specific bacteria, propionic acid deteriorates methane productivity due to slow degradation kinetics [22]. Progressive VFA accumulation may alter the VFA distribution (acetate-to-butyrate and acetate-to-propionate ratios) and even the microbial population dynamics. An increase in PS concentration can improve the distribution of VFAs and acetoclastic microbes. To this aim, PS advances the presence of nutrients, such as iron, that are valuable elements for methanogens' viability and proliferation and related metalloenzymes that contribute to methane production. Fe contributes to the precipitation and thus the inactivation of sulfur, while it promotes the activity of specific metalloenzymes known to enhance methane production, i.e., carbon monoxide dehydrogenase (CODH) for the degradation of acetic acid and F420 co-enzyme that is involved in methanogenic reactions.

3. Agro-Industrial Wastes

Agro-industrial wastes are more homogeneous than food wastes, but they present certain constraints. The quality of such wastes depends on the type of crops found in a region, while their production occurs in specific periods. This phenomenon impacts associated logistics and storage capacities of raw materials in the anaerobic digestion unit. Though anaerobic digestion of agro-industrial wastes is quite familiar in the literature, only the last year's co-digestion of such wastes with primary sludge is conducted. According to the best of the authors′ knowledge, research studies have mainly focused on the co-digestion of agro-industrial wastes with sewage sludge and have thoroughly investigated the terms to facilitate the biological conversion of that biomass into bioenergy. Anaerobic digestion of primary sludge with wastes from agricultural and livestock activities has been mainly studied regarding corn stover biochar, wheat straw, buckwheat husk, fallen leaves, grass, leaves, cow manure, and brewery sludge. **Table 2** summarizes the outcomes of these studies in a comprehensive yet conclusive way to understand what kind of substrates are the most promising ones.

Elsayed et al. [23] studied the co-digestion of primary sludge with either wheat straw (WS) or buckwheat husk (BH) along with wheat straw (WS). The mix of primary sludge with WS at a ratio close to 1:2 on a VS basis with an organic loading of 7.5 g VS/L produced around 345 mL CH_4/g VS, while the combined use of BH and WS resulted in a higher methane yield of 481 mL CH_4/g VS at a ratio of PS/mix of WS and BH equal to 1:1 on a VS basis, with a C/N equal to 10.07 and an organic loading of 7.50 g VS/L. The obtained efficiency was three times higher than that of single PS digestion. Subsequently, Elsayed et al. [24] investigated the co-digestion of primary sludge with fallen leaves (FL) and grass (GR), focusing on the impact of the C/N ratio on methane production. The experimental results showed that a C/N ratio of 13, corresponding to a ratio of PS/mix of FL and GR almost equal to 1:2 on a VS basis, showed the highest methane yield, 352 mL CH_4/g VS, two times higher than that of primary sludge, and the shortest lag phase (about 14 d) among the C/N ratios tested. In the same context, Elsayed et al. [25] examined the impact of sugarcane leaves (SL) and Corchorus stalks (CS) on the digestion of PS. The highest methane production, almost three times higher than that of single PS, was obtained during the co-digestion of PS with the mix of SL and CS at a ratio of 2:1 (PS/mix) on a VS basis, indicating that in this case, more PS biomass was required to achieve high methane production yields. Similar results were found in a later study by Elsayed et al. [26] who investigated the co-digestion of primary sludge with sugar beet pulp (SBP). Among the examined ratios, the highest methane production was achieved at a ratio of PS/SBP equal to 7:3 *w*/*w* VS. At this ratio, methane production reached 307 mL CH_4/g VS, nearly doubling the methane yield achieved during the exclusive digestion of primary sludge. Overall, the efficiency of each substrate was related to the type of waste/additive that prescribes the characteristics of organic matter, as well as the mixing ratio of PS/additives and the overall organic loading rate in the digester.

The most essential factor to take into consideration when designing such units is the carbon source characteristics. Organic material in agro-wastes contains to a great extent lignocellulose, e.g., hemicellulose, cellulose, and lignin. Cellulose is the most abundant organic compound on earth, and its chemical structure consists of linear chains of glucose units linked by β-1,4-glycosidic bonds [27]. Hemicellulose is known as the second most abundant carbohydrate material, and in contrast to cellulose, which is a polymer of only glucose, hemicellulose is a polymer of different monosaccharides (e.g., glucose, mannose, xylose, arabinose, and fructose), and it is generally easier to degrade enzymatically than cellulose [28][29]. Finally, lignin is a polyphenolic structural constituent of wood and other native plant materials and its high crystallinity makes it difficult to be degraded, as it is composed of aromatic alcohols and their ramifications (e.g., syringyl alcohol, guaiacyl alcohol, and p-coumaryl alcohol) [30]. Even though cellulose and hemicellulose appear to be favorable substrates for degradation, it is well known that during the anaerobic digestion of lignocellulosic biomass, cellulose and hemicellulose are often surrounded by lignin, resulting in a stable polymer that is quite resistant to degradation during digestion. One promising approach for improving lignocellulose biomass hydrolysis appears to be that of organic acid pretreatment. In fact, Dharmalingam et al. [31] observed that when treating a mixed lignocellulose biomass with citric acid, biogas production was increased by fivefold over the untreated biomass. However, the resistance of lignocellulose biomass to degradation does not apply in the same way for all crops which are expected to present differences in cellulose, hemicellulose, and lignin content. From the lignocellulosic substrates used for the co-digestion of primary sludge, buckwheat husk is generally characterized by a high concentration of cellulose, 40–52%, and lower concentrations of hemicellulose and lignin, 17–32 and 27–29%, respectively [32][33]. Probably, its higher concentration of cellulose enhanced the hydrolysis rate and resulted in improved methane production when it was used at an optimal ratio of PS/mix of WS and BH equal to 1:1 on a VS basis (**Figure 1**). On the other hand, the addition of fallen leaves and grass into primary sludge resulted in lower methane production efficiency, although the concentration of lignin in this substrate was expected to be rather low [34][35]. The obtained results could be possibly attributed to other inhibitory phenomena, potentially involving the release of inhibitory compounds, such as vanillin, syringaldehyde, humic acids, etc., resulting from the degradation of the lignocellulose biomass [36]. These compounds can have an inhibitory effect on the anaerobic digestion process, leading to a reduction in methane yield [36]. A suitable measure to confront such limitations would be to increase the amount of primary sludge in the slurry to be digested. In this context, Elsayed et al. [25] investigated the co-digestion of primary sludge with the mix of sugarcane leaves and Corchorus stalks at a ratio of 2:1 on a VS basis (C/N = 18). Yet, the methane production was not further increased, indicating the impact of other operational conditions, such as the organic loading rate, the overall C/N ratio, and the type of inoculum, as shown in **Table 2**, that may affect the microbial communities inside the digester.

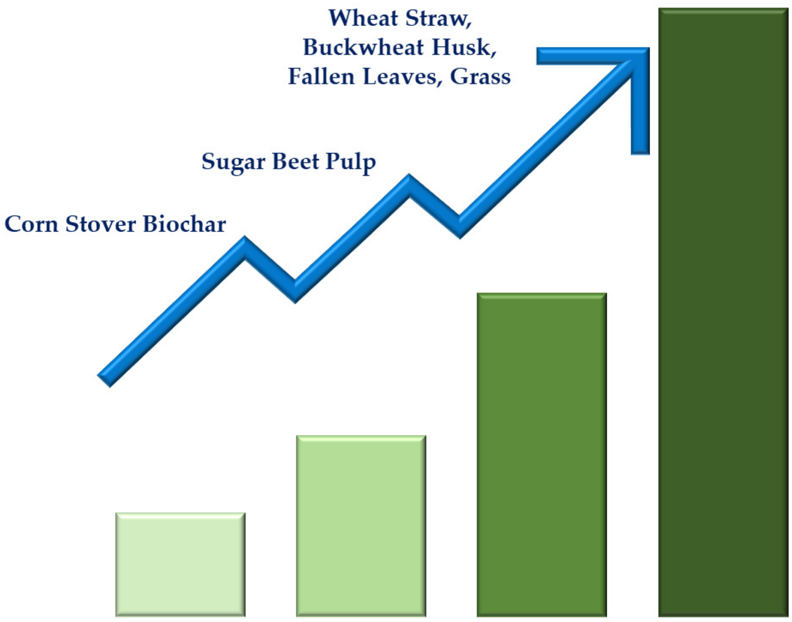

Figure 1. Performance of anaerobic co-digestion of PS with agro-industrial wastes under comparable experimental conditions in terms of inoculum origin, ISR, and OLR.

Anaerobic co-digestion of livestock residues, for example, manure, together with other organic wastes or energy crops is common practice [37] and has been applied at an industrial scale for quite some years. Co-digestion is more favorable against the single digestion of manure due to its recalcitrant biodegradability potential and inhibitory behavior from high ammonia content. Several studies report that the co-digestion of manure with C-rich wastes improves the C/N ratio and thus the digestibility and methane production capacity of manure [38][39]. To this regard, the co-digestion of manure with primary sludge may present some potential, though it has not been extensively studied. Nansubuga et al. [40] examined the co-digestion of primary sludge with cow manure (CM) or brewery sludge (BS) at ratios of 1:1 and 3:1, as well as the co-digestion of PS with a mix of CM and BS at a ratio of 2:1:1, respectively. Livestock addition to PS did not contribute to biogas production, regardless of the examined mixing ratio. On the contrary, BS addition enhanced considerably the biogas production in all tested conditions, i.e., the biogas production was five times higher than that of single PS digestion at a mixing ratio of 1:1. Interestingly, the biogas produced by the mix of PS with CM and BS at a ratio of PS/CM/BS = 2:1:1 was three times higher than that of single PS. Such biogas yield was comparable to that of PS and BS at a ratio of 3:1, suggesting that livestock was difficult to treat anaerobically, presumably because of poor hydrolysis and decomposition, and thus did not contribute to biogas production. Moreover, Shilton et al. [41] managed to boost up the production of biogas during anaerobic digestion of PS with whey by adding moderate quantities of manure, whereas at the same time, they achieved better control of the alkalinity of the system. The increased process efficiency was obtained at an operational ratio of PS/WH/CM equal to 1:0.8:0.2 on a mass basis.

Table 2. Co-digestion of primary sewage sludge and agricultural wastes.

PS Substrate [1]	Co-Substrate [2]	Inoculum [3]	ISR *	OLR + initial	Tested Concentrations	Mode [4]	Scale [5]	T [6]	Efficiency [7]	Reference	
1.	PS	CSB	ADS	2:1 *w*/*w* VS	-	1.82, 2.55, 3.06 g/g TS^{-}	B	L	TH	+	[42]
						1.82 g/g TS + 0.12 g/g TS/d	C				
2.	PS	WS BH	CM	2:1 *w*/*w* VS	3.0, 6.0, 7.5, 8.0, 10.0, 12.0 g VS/L	PS/WS 1:2 *w*/*w* VS	B	L	M	+++	[23]
					-	PS/WS BH C/N = 10.07, 13.06, 15.01, 20.03, 25.25				+++	
3.	PS	FL GR	ADS + WAS	2:1 *w*/*w* VS	-	PS FL GR C/N = 10, 13, 16, 20, 23	B	L	M	+++	[24]
					0.5 g VS/L/d	PS FL GR C/N = 13	SC				
4.	PS	SBP	ADS	2:1 *w*/*w* VS	-	PS/SBP 7:3, 1:1, 3:7 *w*/*w* VS	B	L	M	++	[26]
5.	PS	SL CS	CM RC	2:1 *w*/*w* VS	-	PS SL CS C/N = 18, 21, 25, 30, 35	B	L	M	+++	[25]
					-	PS SL CS—CM, C/N = 18 PS SL CS—RC, C/N = 20.70	B				
					0.5 g VS/L/d	PS SL CS C/N = 18	SC				
6.	PS	CM BS	UASB	-	0.71 g COD/L/d	PS/CM 3:1, 1:1 *w*/*w*	C	L	M	+	[40]
						PS/BW 3:1, 1:1 *w*/*w*				+++	
						PS/CM:BW 2:1:1 *w*/*w*				+++	

PS Substrate [1]	Co-Substrate [2]	Inoculum [3]	ISR *	OLR + initial	Tested Concentrations	Mode [4]	Scale [5]	T [6]	Efficiency [7]	Reference
7. PS	WH CM	ADS	-	-	PS/WH 4:1 *w/w* PS/WH 1:1 *w/w* + Ca(OH) PS/WH/CM (final) 1:0.8:0.2 *w/w*	SC	L	M	+	[41]

[1] PS substrate, PS: primary sludge. [2] Co-substrate, CSB: corn stover biochar; WS: wheat straw; BH: buckwheat husk; FL: fallen leaves; GR: grass; SBP: sugar beet pulp; SL: sugarcane leaves; CS: Corchorus stalks; CM: cow manure; BS: brewery sludge; WH: whey. [3] Inoculum, ADS: anaerobic digested sludge; CM: cow manure; WAS: waste-activated sludge; RC: rumen content of cattle; UASB: up-flow anaerobic sludge blanket digestion. [4] Mode, B: batch; C: continuous; SC: semi-continuous. [5] Scale, L: lab scale, [6] T: temperature; M: mesophilic; TH: thermophilic. [7] Efficiency, +: 0–40%, ++: 41–80%, +++: >81% enhancement of biomethane production compared to single digestion of primary sludge. * Inoculum-to-substrate ratio: ISR. + Organic loading rate: OLR. Total solids: TS.

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