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Anaerobic co-digestion of sewage sludge with other organic wastes: A comprehensive review focusing on selection criteria, operational conditions, and microbiology

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ABSTRACT

Mono-digestion of sewage sludge (SS) usually suffers from insufficient content of organic matter and low C/N ratio. In order to modify these parameters and enhance the process performance, many organic wastes have been used as co-substrates in conjunction with SS in anaerobic co-digestion (ACoD). In this review paper, the co-substrate selection criteria for ACoD with SS were surveyed. In addition, the effects of all examined co-substrates and operational conditions on process performance in terms of volatile solids (VS) reduction, methane production and microbial community were comprehensively reviewed. Accordingly, the reviewed waste materials were classified into three groups. The first group, including food waste and FOG (fat, oil and grease), can be used as co-substrate with high reliability due to their high organic content, high C/N ratio, negligible amount of toxic compounds, and as well, no evidence of adverse effects on the process in previous reports. The second group includes the wastes with moderate probability of disrupting the process due to low C/N ratio or low organic content, the presence of inhibitory factors, and as well, the observation of their adverse effects in some studies. Industrial waste, slaughterhouse waste, agricultural residue and animal manure can be classified as the second group. The third group, including microalgae, represents the wastes with a high risk of disrupting the process since a considerable number of studies have reported their adverse effects on the process. The issues that should be addressed in future studies include application of paper and cardboard waste in sewage sludge ACoD, sewage sludge ACoD under thermophilic conditions, microbiology of the process, and the dewaterability of the digested sludge resulting from ACoD of sewage sludge.

Abbreviations

SS	sewage sludge
BOD	Biological Oxygen Demand
COD	Chemical Oxygen Demand
C/N	Carbon to Nitrogen Ratio
AD	Anaerobic Digestion
ACoD	Anaerobic Co-Digestion
VS	Volatile Solids
LCFA	long-chain fatty acids
WAS	waste activated sludge
SHW	Slaughterhouse Waste
AM	Animal Manure
ACR	Agricultural and Crop Residue
PCW	paper and cardboard waste
FOG	Fat, Oil and Grease
VFA	Volatile Fatty Acid
FW	Food Wastes
ASRs	Agricultural Solid Residues
VOCs	Volatile Organic Compounds

1. Introduction

The application of improved sewage treatment technology incorporated through rigorous environmental regulations has successfully protected water supply systems from contamination. Sewage sludge (SS) is

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produced as a waste in the wastewater treatment plants and there is a growing concern about its environmental impact due to organic and pathogenic contents [1,2]. SS mainly consists of primary sludge and secondary sludge. Generally, primary sludge contains settleable organic matter, and secondary sludge consists of flocculated bacteria [2–4]. Releasing these two sludge streams directly into the environment without treatment can cause adverse health effects on human, animals, and aquatic ecosystems [1,5]. There are various treatment methods to manage these sludge streams including aerobic digestion, anaerobic digestion (AD), lime stabilization, incineration, and composting among which, AD is the most common process. The AD process reduces sludge volume, inactivates pathogens, reduces chemical and biological oxygen demand (COD and BOD), and converts organic matter to renewable energy [6–8]. As the advantages of AD over aerobic digestion, lower capital investment, lower energy consumption, lower sludge production, and producing methane as a renewable energy source could be mentioned. A combination of the two sludge streams, as the feed entering the digesters, has three substantial problems in practice: 1) the low carbon to nitrogen (C/N) ratio (generally between 6 to 9), 2) The low content of organic matter, and 3) The low biodegradability of organic matter (rate-limited hydrolysis) [6,9]. Besides, the sewage sludge AD is time consuming and highly sensitive to the process conditions such as pH, temperature, C/N ratio, and organic loading rate (OLR). Each of these parameters strongly affects the efficiency of the AD process [10,11]. However due to its satisfactory performance in decreasing sludge volume and converting organic content to renewable energy, AD process is considered as a rational choice among others [12,13].

Co-digestion is a promising approach for solving the mentioned difficulties related to the sewage sludge AD process. The term "co-digestion" refers to the digestion of two or more substrates simultaneously, leading to improved process performance and efficiency [14]. Using appropriate co-substrate improves the feed characteristics and results in synergistic effects, followed by enhancement in specific methane production from the mixture of substrates [15]. Other advantages of co-digestion over mono-digestion include better supply of macro- and microelements, dilution of toxic and inhibitory substances, increase of buffering capacity, reduction of greenhouse gas emission, reduction of process costs, and possibility of using higher loading rates [6,16].

In financial analysis of an anaerobic co-digestion process (ACoD), the costs of transportation to wastewater treatment plant, storage and maintenance, possible pretreatment requirements, management of extra sludge production and sludge dewatering should be considered and carefully investigated [17,18]. Beside financial analysis, considering the technical criteria of selecting co-substrate for ACoD with SS is significantly crucial. Therefore, the most important technical features including methane production content, digester stability, and possible toxicity and disturbances must be considered while selecting a co-substrate [17,18].

Inappropriate selection of co-substrate and its mixing ratio with the SS inhibits the process and makes it unbalanced, leading to reduced performance of the process in terms of methane production and volatile solids reduction (VS reduction). Although many studies investigated the benefits of using different co-substrates in the sewage sludge ACoD process, still, a comprehensive review of all kinds of examined co-substrate sources is missing. Some studies explored a few but not all co-substrates that can be co-digested with SS [19,20].

Another issue that is less discussed in review papers on ACoD of SS with organic wastes is the process microbiology. Microbial community dynamics within the ACoD process will be affected by various factors including the origin of inoculum, operation and environmental conditions, extracellular polymeric substances (EPS), and types of waste streams [21]. Reportedly, the diversity of bacteria and archaea in the mesophilic range (30–38 °C) is higher than in the thermophilic range (50–57 °C). Also, increasing the number of substrates in the reactor causes higher microbial diversity [3,22].

Despite the existence of considerable literature on the sewage sludge ACoD process, many researchers face challenges to evaluate the feasibility of using different co-substrates and to consider different technical criteria. This is mainly due to the lack of a comprehensive literature review that clearly discussed the selection criteria of co-substrate, reviewed all kinds of tested co-substrates, and compared their effects on the performance and microbiology of the process. With the aim of filling the gap in the literature, the present paper has reviewed the ACoD of sewage sludge with all examined organic wastes. For this purpose, the process performance is discussed in terms of VS reduction and methane production for the eight classes of wastes used as co-substrate including: municipal solid food waste (FW), fat, oil and grease (FOG), industrial waste, slaughterhouse waste (SHW), animal manure (AM), agricultural and crop residue (ACR), microalgae, and paper and cardboard waste (PCW). It was also focused on co-substrate selection criteria, the operational conditions of the process (mainly temperature and mixing ratio), and the changes in microbial communities under the effect of co-substrates.

2. Co-substrate selection criteria for sewage sludge ACoD

Co-substrate characteristics and its possible inhibitory effects, along with environmental and operating conditions, are crucial aspects of the ACoD process. Choosing the right co-substrate can improve biogas production and solid reduction while, an inappropriate co-substrate may cause system instability and even lead to system failure. The most important factors that should be considered in selection of a co-substrate are discussed in the following sections.

2.1. Economic factors

The investigated economic factors can be classified into three categories: investment costs, operating costs, and the excess income generated by combusting biogas in a plant. One of the purposes of using ACoD process is to bring about the energy balance in the wastewater treatment plant by providing the energy needed for the treatment units through additional biogas production. Although there might be an economic interest in storing electrical energy from biogas, it should be considered that this stored energy should generate more added value compared to the investment and operating costs [18,23]. Bolozenella et al. (2006) [24] reported that the industrial costs of implementing ACoD facilities for co-digestion of waste activated sludge (WAS) with organic fraction of municipal solid waste (OFMSW) reached 50 Euro/ton MSW without considering the income of selling the produced energy. They reported that considering depreciation, investment costs, and energy recovery, a 3.5 years payback time would be expected [24].

It should also be noted that some co-substrates require special pre-treatment processes, which increase costs and require technical equipment. As estimated by Edelmann et al. [25], the cost of pre-treatment of fruit and vegetables to use in SS co-digestion process was 55 US$/ton and 39 US$/ton for treating half a ton per day and one ton per day, respectively.

The characteristics and composition of the co-substrate affect the required pre-treatment process. In some cases, to enhance homogeneity with SS, the particle size of the co-substrate needs to be reduced, or the impurities (e.g., metal pieces, glass, sand, and stones) need to be removed before use [18,23]. Moreover, various issues such as foam formation (specifically for FOG waste), flotation (for fibrous residues), and accumulation of inorganic materials (gravel and sand) at the bottom of the reactor have been reported to be responsible for increasing maintenance costs. These problems may reduce the active volume of the ACoD reactor or block the system's pipes and valves [26,27]. Consequently, in the co-substrate selection procedure and feasibility study, in addition to the added value of the recovered energy and investment costs, the costs of pre-treatment processes (if required), as well as the operating and maintenance costs and even the co-substrate transportation costs should be considered.

2.2. Technical factors

2.2.1. Process stability

Some of the compounds in the wastes or intermediate components produced during the AD process can inhibit bacterial activity or cause toxicity. Therefore, the type and amount of co-substrate should be carefully determined [18]. For instance, AD of readily biodegradable wastes with high carbohydrate content results in accumulation of volatile fatty acids (VFA) within the reactor, reduces the pH and consequently inhibits the process [28]. In this case, addition of a co-substrate with fewer biodegradable compounds is recommended to balance the process [29].

Furthermore, the high concentration of ammonia released from protein degradation is one of the most important inhibitors of the microbial activity, especially methanogenic activity. Therefore, the protein-rich wastes, such as pig and chicken manure and SHW, may lead to digester instability and failure [30,31]. In addition, the presence of heavy metals and some other toxic substances, which may present in industrial and agricultural wastes, can make the process instable [32, 33]. Accordingly, in choosing a co-substrate for the AD process, care must be taken to ensure it does not contain toxic and inhibitory substances, helps to adjust the C/N ratio, and dilutes the inappropriate substances that may be present in the SS composition.

2.2.2. Nutrients balance

Nutrients imbalance is considered as one of the important drawbacks related to the mono-digestion process. Therefore, the substrate's nutrients content is known as a parameter of high importance in AD process. Carbon and nitrogen are two fundamental nutrients for growth and activity of microorganisms [34]. Carbon is essential as the source of energy needed for cell synthesis and for the formation of new cells, as well [18]. In addition, nitrogen is the limiting material for cell growth as it is a core component of amino acids and nucleic acids for production of proteins and RNA and DNA, respectively [18]. Thus, providing a good balance of carbon and nitrogen within the AD reactor is essential for a successful AD process. A C/N ratio between 20–30 is generally considered optimal for AD [34]. A wider range between 15–45 is also considered as the optimal C/N ratio [35,36]. For example, animal manure has a high nitrogen concentration, which may inhibit the process or make it imbalanced in terms of carbon and nitrogen contents. Municipal solid waste has high amount of degradable and lipid-rich content, which can cause a sharp drop in pH level. High content of N and VFA in SHW also declines the process performance [34,37]. Therefore, co-digestion of wastes should provide a better nutrients balance for the AD process than the mono-digestion.

2.2.3. Dewaterability

Digestate contains high water levels (>95% by weight) and solid particles which carry electrostatic charges, making the dewatering process considerably hard. Therefore, dewatering of digestate requires significant energy and chemical consumption, which involves high costs. The energy required for digestate dewatering accounts for about 25–65% of the total energy costs of a wastewater treatment plant [38]. Different parameters affect the sludge dewatering process such as particle size distribution, organic content, solid concentration, pH, particle surface charge, rheological characteristics, and bound water content [39]. Adding co-substrate to the process can influence the digestate dewaterability [18,40]. Silvestre et al. [40] observed that increasing the organic loading rate from 2.2 to 2.8 kg COD $m^{-3}d^{-1}$ in the co-digestion of SS with grease waste increased the concentration of long-chain fatty acids (LCFA) in effluent and worsened the sludge dewatering characteristics. As reported by Habiba et al. [41], addition of fruit and vegetable wastes to the activated sludge improved the effluent filterability. Zhang et al. [42] reported that adding pig manure to sewage sludge ACoD with a mixing ratio of 2:1 improved the final digestate dewaterability. Nevertheless, adding more than that ratio reduced the dewaterability [42]. Azarmanesh et al. [43] found that sewage sludge ACoD with food waste could improve the digestate dewaterability due to enhancing VS removal. According to Wang et al. [44], waste-activated sludge ACoD with algae resulted in better sludge dewaterability than its mono-digestion because of a lower soluble COD content. Generally, the type and mixing ratio of co-substrate affects the digestate dewaterability. However, there are very few published studies in this regard.

3. Potential co-substrates for sewage sludge anaerobic co-digestion

In this section, all investigated co-substrates for ACoD with SS were reviewed with focus on key features including co-substrate composition, co-substrate inhibitory characteristics, operating conditions, biogas production and VS reduction and the process microbiology. The most important information of the previous studies in the field of ACoD of SS with different co-substrates is summarized in Tables 1-8.

3.1. Municipal solid food waste

3.1.1. Overall process performance

FW has heterogeneous nature with components from various sources, including residential houses, cafeterias, recreational and commercial centers, etc. It has different compositions depending on region, climate, season, and culture [14,45]. Various FW management methods, including use as animal feed, incineration, landfilling, composting and AD, have been used in different regions/countries [46,47]. In underdeveloped countries, food waste is usually dumped in open spaces. In developing countries, about 90% of FW is managed by dumping or landfilling, while only about 6% and 0.6% is handled using composting and AD methods, respectively. Besides, other treatment techniques such as incineration and animal feeding are rarely used in developing countries [46,47]. Finally, in developed countries, AD, landfilling, and composting have been successfully used for FW management [46]. Since 2006, many developed countries in Asia and European countries have extensively used AD for FW treatment [47].

Although landfilling is the most cost-effective and common method, it has several environmental impacts, including groundwater pollution, terrestrial acidification, and land-use area reduction [48]. In addition, FW incineration contributes to 20% of the world's total greenhouse gas emissions [48]. By and large, AD is one of the promising options for FW management due to its high C/N ratio (17–30) [49] and high biodegradable organic content. On the other hand, the low C/N ratio (often between 6 to 9) and low level of the organic content of SS adversely affect the microbial community of the AD process, leading to decreased performance and even process inhibition [50]. For this reason, using food waste as co-substrate in ACoD of sewage sludge brings some benefits such as nutrients balance to the process and reduces the pollution burden on the environment. As some of these benefits, enhanced biogas production and methane yield, accelerated degradation and hydrolysis rate, and dilution of toxic elements can be accounted [11,14,51]. However, high nitrogen content and low digestate dewaterability have been reported as some drawbacks of the ACoD of SS with FW [50].

ACoD of SS with FW is commonly carried out in mesophilic digesters. Such popularity might come from more stable reactions, low energy consumption, better stabilization, and easier operation of mesophilic than thermophilic reactors [52]. Although the addition of FW brings remarkable advantages to the AD process, there is a critical question that how much FW should be added to make the most efficient process? In Table 1, the process conditions as well as the results of the previous studies on ACoD of SS with FW are summarized. Many researchers such as Liu et al. [9] and Cabbai et al. [53] stated that adding 50 w/w% of FW as co-substrate resulted in the highest process performance. Besides,

Table 1
Studies on using FW as co-substrate in sewage sludge ACoD.

	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVS$_{added}$)			VS$_{reduction}$ (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	DS:FW	50:50[a]	35	M (37 °C)	Batch	296.75	–	SMP – 108	–	–	–	[62]
2	SS:FW	67:33 [a]	21	M (35 °C)	Batch	471.1	800	SMP – 22 SBP – 16	81	85.3	5.3	[63]
3	DS:FW	75:25 [a]	30	M (35 °C)	Batch	–	590	SBP – 230	–	–	–	[9]
4	SS:FW	67:33 [a]	25	M (38 °C)	Batch	355	–	SMP – 11		–	–	[50]
5	SS:FW	50:50 [a]	28	M (37 °C)	Semi-Continuous	–	660	SBP – 29	58.4	76.4	30.8	[64]
6	DS:FW	28.6:71.4[a]	20	M (35 °C)	Semi-Continuous	380	–	SMP – 97	32.1	67	108.7	[37]
7	SS:FW	50:50 [a]	40	M	Batch	439	232	SMP – 87.6 SBP – 29	–	–	–	[65]
8	WAS:FW	50:50 [a]	20	M (35 °C)	Semi-Continuous	339	–	–	–	56.3	–	[66]
9	SS:FW	80:20 [a]	20	M (35 °C)	Semi-Continuous	326	–	SMP – 29.3	–	–	–	[67]
10	SS:FW	50:50 [a]	30	M (35 °C)	Batch	365.5	–	SMP – 47	–	–	–	[53]
11	SS:FW	20:80 [a]	12	M (35 °C)	Batch	257	–	SMP – 121.5	–	–	–	[68]
12	SS:FW	20:80 [a]	12	T (55 °C)	Batch	344	–	SMP – 111	–	–	–	[68]
13	SS:FW Pr:WAS	50:50 [a] 50:50 [a]	20	M (35 °C)	Batch	609	867.5	SMP – 71 SBP – 29	51	60	17.65	[43]
14	WAS:FW	67:33 [a] 50:50 [a]	40	M (37 °C)	Batch	233.1 269.6	- -	SMP – 47.25 SMP – 70.31		–		[69]
15	PS:FW	50:50 [a]	20	M (37 °C)	Batch	236.1 (mL/gVS$_{removed}$)	304.9 (mL/gVS$_{removed}$)	SMP – 70.7 SBP – 89.43	11.93	21.13	77.12	[70]
16	WAS: biowaste	–	22	M (37 °C) T (55 °C)	full-scale (2000 m^3)	210 330	350 550	–	–	39.5 47.2	–	[71]
17	SS: OPW	70:30[a]	2	M (35 °C)	semi-continuous	165	–	–	–	76	–	[72]
18	Pr+WAS: FW	80:20[a]	20	M	full-scale (2000 m^3)	–	890 (mL/gVSS$_{added}$)	SBP-128.2	71	81	14.1	[73]

[a] : w/w%, DS: Dewatered Sludge, FW: Food Waste, SS: Sewage Sludge, WAS: Waste Activated Sludge, Pr: Primary Sludge, OPW: Orange Peel Waste, SMP: Specific Methane Production, SBP: Specific Biogas Production, M: Mesophilic, HRT: Hydraulic Retention Time

Koch et al. [50] and some others have reported 25-35 w/w% of FW as the best mixing ratio. Although higher mixing ratios of about 80 w/w% have also been reported to be examined successfully, the ratios between 30-50 w/w% can be used with high reliability as the optimal mixing ratios of FW and SS in ACoD process. Based on data given in Table 1, methane production of ACoD of FW and SS was reported between 165–609 mlCH$_4$/gVS$_{added}$, which is considerably higher than that of SS mono-digestion (114–478 mlCH$_4$/gVS$_{added}$). In addition, VS reduction of SS and FW co-digestion has been reported between 21–85% (Table.1). It should also be noted that using FW over optimal ratios may result in the accumulation of VFAs due to excessive acidification, followed by the reduction of the pH, which may cause process inhibition and failure [9, 54]. Nevertheless, few studies reported that there was no inhibition at mixing ratios higher than the optimum range of 30-50 w/w% [37,55].

3.1.2. *Process microbiology*

The predominant microbial communities in SS mono-digestion are Bacilli (*Alkalibacterium* and *Paenisporosarcina*) and Clostridia (*Alkaliphilus*). In addition, the predominant microbial communities in FW mono-digestion are *phyla Firmicutes, Nitrospirae, Bacteroidetes* and *Chlorobi* [56]. By increasing the organic loading rate in FW mono-digestion, the predominance of *Phylum* will be extended [57,58]. Moreover, the presence of high number of *Bacteroidetes* in food waste AD usually represents a high hydrolytic activity especially in mesophilic condition. *Bacteroidetes* have high ability to ferment sugars into the acetate and propionate which results in high biogas production [58,59]. On the other hand, the predominant microbial types in ACoD of sewage sludge with FW are *Methanospirillaceae, Methanosarcinales, Lactobacillus*, and *Methanosaetaceae* (Table 8). Keucken et al. [57] reported that using 50% FW as co-substrate in ACoD of SS increased the methanogens population, especially *Methanosarcinales*, while the community in the SS mono-digestion reactor remained unaffected [57]. Li et al. [60] observed that by increasing FW mixing ratio up to 80%, the major genera became *Prevotella, Ruminococcus*, and *Clostridium* which play important role in hydrogen and VFAs production. FW usually contain a high amount of protein, leading to ammonia accumulation in AD system. High ammonia concentration in AD process inhibits the methanogens bacteria, which consequently results in accumulation of acetate and propionate. As acetoclastic methanogens bacteria (like Methanosaeta) are much more affected by ammonia than hydrogenotrophic methanogens bacteria (like Methanobacterium and Methanospirillum), the methane production in ACoD of SS with FW switches from acetoclastic to hydrogenotrophic methanogens [61].

3.2. *Fat, oil and grease*

3.2.1. *Overall process performance*

FOG are kinds of lipid-rich waste that usually come from food processing industries, slaughterhouses, dairy wastewaters, resturants and residences [74]. Various problems are caused by FOG in sewers and treatment units among them, clogging, foaming, accumulating in pipes, pump failuring and adsorption of the lipids onto the biomass surface can be considered [75,76]. Therefore, releasing these substances into the sewage collection system is prohibited by strict regulations in many european and north american countries [77]. On the other hand, conventional methods such as landfilling, incineration, composting, and land application are not considered as the proper choices for managing FOG wastes due to aggravating impacts on climate change, high moisture content and leaching problems [78].

High levels of organic compounds, high C/N ratio (up to 90), excellent biodegradability and high potential of methane production (0.7 to 1.43 m^3 CH_4/kgVS) and VS reduction (VS/TS$\geq$90%) makes FOG an attractive co-substrate for the sewage sludge ACoD process [79–81]. Table 2 represents the process conditions as well as the results of studies on AcoD of SS with FOG. According to these reports, the mixing ratios between 20-75 w/w% can be considered appropriate for applying FOG in the ACoD of sewage sludge. This suggests that due to the lower nitrogen content, FOG can be used in the sewage sludge ACoD under relatively higher mixing ratios compared to municipal waste [82]. Generally, the methane production and VS reduction for ACoD of SS and FOG have been reported in ranges of 300-816 ml/gVS_{added} and 26–83%, respectively (Table 2). Nevertheless, using high concentrations of FOG leads to the accumulation of LCFAs, which causes some adverse effects on the anaerobic microbial community, especially methanogens [40, 83]. Girault et al. [84] stated that adding 74 w/w% and 87 w/w% FOG to SS leads to 21.8% and 75.2% reduction of methane production respectively. In addition, Wang et al. [85] and Noutsopoulos et al. [86] reported that adding 83.5 w/w% and 90 w/w% of FOG to sewage sludge AD process resulted in 16.3% and 80% reduction in methane content, respectively.

A considerable number of studies about co-digestion of FOG and SS have been carried out in continuous and semi-continuous systems to simulate the real scale more accuratly [79,87]. Moreover, using FOG waste in the ACoD process was often investegated at mesophilic rather than thermophilic conditions. This can be due to financial aspects, sensitive microorganisms, and poor biomethane yield at high range temperatures [75].

3.2.2. Process microbiology

A wide variety of microorganisms are responsible for the methane production from FOG and LCFAs, and the types of microorganisms strongly depend on the types of substrate and operation [86]. Generally, the most abundant bacteria and archaea of AD of lipid-rich wastewater include Synergistales, Anaerolineales, Actinomycetales, and Nitrospirales belonging to bacteria, and Methanobacteriales and Methanosarcinales belonging to archaea [88]. The products of hydrolyzing lipids are glycerol and LCFAs, which in turn are converted to short-chain fatty acids (SCFAs), acetate, and H_2 [75,89]. The predominant archaea communities in sewage sludge ACoD with FOG are *Methanomicrobium* (hydrogenotrophic methanogens), *Methanosaeta* (acetoclastic

Table 2
Studies on using FOG as co-substrate in sewage sludge ACoD.

	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVS_{added})			$VS_{reduction}$ (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	WAS:FOG	10:90[a]	60	T (55°C)	Batch	491.9	–	SMP – 55.4	–	–	–	[74]
2	WAS:FOG	35:65 [a]	15	T (55°C)	Semi-continuous	421	–	SMP – 88.3	–	–	–	[77]
3	Pr+WAS: GTW	61:39 [a]	15	M (35°C)	BMP	517	–	SMP –131.84	26	35	34.62	[78]
4	SS:GTW	88:12 [a]	20	T (55°C)	Continuous	300	–	SMP – 15	–	–	–	[40]
5	Pr+WAS: FOG	54:46 [a]	20	M (37°C)	First Stage Second Stage	500 610	–	SMP – 47 SMP – 87	–	–	–	[90]
6	WAS+DS: FOG	40:60 [a]	15	M (35°C)	Two CSTR	–	–	SBP – 35	–	–	–	[79]
7	SS: FOG	54:46 [a]	15	M (35°C)	Semi-continuous	641	–	SMP – 66.93	–	59	–	[87]
8	WAS:GTW	25:75 [a]	20	M (37°C)	BMP	816	1217	SMP – 87.81	–	26.4	–	[76]
9	SS:FOG	75:25 [a]	25	M (37°C)	Batch	–	–	–	–	45.7		[95]
10	SS: RGT	32:68 [a]	18.5	M (37°C)	Semi-continuous	620	–	SMP – 66.2	–	73		[96]
11	SS:FOG	40:60 [a]	15	M (37°C)	Semi-continuous	–	700	SMP – 55	–	59	–	[86]
12	Pr+WAS: FOG	77:23 [a]	20	M (37°C)	Batch	369	–	SMP – 48.2	–	52	–	[97]
13	WAS:FOG	36:64 [a]	15	M (37°C)	Semi-continuous	598.4	–	SMP – 137	40	57	42.5	[98]
14	WAS:FOG	80:20 [a]	20	M (37°C)	Semi-continuous	752	–	SMP – 316.67	–	–	–	[85]
15	Pr+WAS: GTW	40:60 [a] 90:10 [a]	13	M (35°C)	Batch Continuous	681 360	–	SMP – 109.54 SMP – 30.43	–	–	–	[99]
16	WAS:GS	60:40 [a]	37	M (36°C)	Batch	483	–	SMP – 77	–	–	–	[84]
		48:52 [a]	27	M (38°C)	CSTR	546	–	SMP – 106.8	29	44	51.7	[84]
17	Pr+WAS: FOG	52:48[a]	35	M (35°C)	Batch	630	–	SMP – 116	36.8	53	44	[100]
18	Ps+WAS: FOG	27.3: 72.7[a]	15	M (35°C)	Batch	244 mL/ $gCOD_{added}$	3814 ml	SMP – 96.8	42.8	83	93.92	[101]
19	WAS+FOG	90.3:9.7[b]	38–58	M	Full-scale (2 × $1900m^3$)	–	–	–	–	–	–	[102]

[a] : w/w%, GTW: Grease Trap Waste, GS: Greasy Sludge, RGT: Restaurant Grease Trap, HT: Hyper Thermophilic, BMP: Biochemical Methane Potential, CSTR: Continuous Stirred-Tank Reactor.

methanogens), *phyla Firmicutes*, and *Euryarchaeota*. Razaviarani & Buchanan [90] reported that by increasing COD loading of FOG to the AD process, the proportion of acetoclastic methanogens (particularly *Methanosaeta*) increased. The improvement in methane production in ACoD of SS with FOG can then be described by the high acetate concentration, which makes the population of *Methanosaeta* more dominant than *Methanosarcina,* as *Methanosaeta* have a faster growth rate in such conditions [91].

However, overloading of FOG decreases the acetoclastic methanogens and increases the hydrogenotrophic communities (*Methanoculleus Bourgensis*), which decreases the reactor performance due to high H_2 partial pressure [92,93]. It should also be noted that in the high range temperature (thermophilic), the genus *Methanosarcina* is predominant in the sewage sludge ACoD with lipid-rich waste [94].

3.3. Industrial waste

3.3.1. Overall process performance

Industrial waste refers to the waste produced from agro-industry, biodiesel fuel production, petrochemical industry and food and beverage industry [98–100,113,114]. It usually contains significant amounts of organic matters and toxic components such as heavy metals, sulfide, halogenated aliphatics, and chlorophenol, which, due to causing severe problems for human, animals and environment, are required to be removed before entering water bodies. Industrial wastewater refers to the waste produced from agro-industry, biodiesel fuel production, petrochemical industry and food and beverage industry [103–105]. Industrial waste can be a good option for AD due to its high content of organic matter. The organic content of industrial wastewater is reported to be 20–4400 times higher than the urban wastewater, with a methane production capacity of 34–572 $mlCH_4/gVS$, depend upon the type of industry [106,107]. In contrast, the amount of nitrogen in industrial waste is low, so they have a high C/N ratio (17.5–49). Therefore, ACoD of industrial waste and SS could have a promising perspective on biogas production and environmental safety [108,109].

Alrawashdeh [109] reported that adding olive mill wastewater to SS up to 10% (v/v) improved the biogas production yield and VS reduction by 35% and 30.1%, respectively. Athanasoulia et al. [110] stated that by adding 2–3% (v/v) of glycerol, the biogas production was improved by 3.8–4.7 times compared with SS mono-digestion. However, the presence of toxic compounds may limit the use of some industrial wastes. In addition, using more than the optimal amount of industrial waste in sewage sludge ACoD process leads to propionic acid accumulation which consequently causes a severe imbalance in the process [100,106,107]. For example, Fountoulakis et al. [112] reported that adding 1–3% (v/v) crude glycerol to sewage sludge could damage the AD system due to overloading. The optimum mixing ratios of glycerol and olive mill wastewater with SS have been reported lower than 5% and between 5%−30% based on their VS values, respectively [105,106,109,110,112,113]. Table 3 represents the process conditions as well as the results of studies on ACoD of SS with industrial waste. According to the table, very different proportions of industrial waste and sewage sludge have been used in the ACoD process and enhancements have been reported for all of them. This shows that the optimal mixing ratio can be very low or very high (0.5–90 v/v%) depending on the type of industry and its waste characteristics.

Many previous studies about co-digestion of industrial waste and SS have carried out using biochemical methane potential (BMP) system. This method was initially used to determine hydraulic retention time, possible inhibitory effects, and biogas production potential [114,115].

Table 3
Studies on using industrial waste as co-substrate in sewage sludge ACoD.

	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVS_{added})			$VS_{reduction}$ (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	SS:OMW	10:90[b]	75	M (35 °C)	BMP	–	420	SBP – 35.4	25.5	55.02	115.8	[109]
2	WAS: OMW	70:30[b]	16.4	M (37 °C)	CSTR	–	1020 ml/g COD_{in}	SBP – 325	–	–	–	[106]
3	SS: OMW SS: CW SS:CG	95:5[b]	24	M (35 °C)	Semi-continuous	–	34.8 l/d 45.9 l/d 185.7 l/d	SBP – 220 SBP – 86 SBP – 350	- - -	38.5 25 39.8	- - -	[105]
4	SS:FJW	8:92[a]	43	M (35 °C)	BMP	–	490	–	–	44.6	–	[51]
5	WAS:PW	50:50[a]	31	M (37 °C)		220	–	SMP – 32	40	45.04	12.6	[104]
6	SS:BS	25:75[a]	40	M (35 °C)	Batch	–	126.67 L	–	–	14.6 –33.6	–	[115]
7	Pr:CG	33:67[a]	32	M (37 °C)	Batch	766	–	SMP – 600	–	–	–	[111]
8	SS: Glyserol	98:2[b]	19.7	M	CSTR	–	780	SBP – 370	–	23.4 –28.7	–	[110]
9	SS:CG	99.5:0.5[b]	30	M	BMP	413	–	SMP – 195	–	20	–	[113]
10	SS:CG	99:1[b]	24	M (35 °C)	Batch, continuous	2353 ml/d		SMP – 110	–	–	–	[112]
11	SS:SWDW	50:50[b]	20	M (35 °C)	Batch	250	–	SBP – 130	–	54	–	[114]
12	SS: Beer	90:10[b]	20	M (35 °C)	semi-continuous (1000 L)	135	–	SMP – 4.65	–	–	–	[122]
13	SS:Wine	90:10[b]	20	M (35 °C)	semi-continuous (1000 L)	80		SMP – (−39.84)*	–	–	–	[122]
14	SS:Soft drink	90:10[b]	20	M (35 °C)	semi-continuous (1000 L)	237		SMP – 5.8	–	–	–	[122]
15	SS:fruit Juice	70:30[b]	20	M (35 °C)	semi-continuous (1000 L)	205		SMP – 0.5	–	–	–	[122]

[a] : w/w%.

[b] : v/v%, OMW: Olive Mill Wastewater, CG: Crude Glycerol, CW: Cheese Whey, PW: Petrochemical Wastewater, BS: Brewery Sludge, SWDW: Sherry Wine Distillery Wastewater, FJW: Fruit Juice Industrial Waste, COD: Chemical Oxygen Demand, CSTR: Continuous Stirred-Tank Reactor.

* : Reduction.

Some continuous and semi-continuous systems were also studied to increase the accuracy of process simulation and to investigate the optimum mixing ratios [105,106].

3.3.2. Process microbiology

The bacterial population is very diverse in agro-industrial and other industrial wastes [116,117]. Most bacterial genes belong to *Bacteroidetes, Firmicutes, and Proteobacteria phyla*, including *Porphyromonadaceae, Bacteroidaceae, Caloramator, Anaerobranca, Petrobacter, and Dechloromonas,* responsible for hydrolysis, acidogenesis, and acetogenesis [118]. *Caloramator, Ureibacillus, Dechloromonas,* and *Petrobacte* are involved in hydrolytic acidogenesis, *Porphyromonadaceae* in the carbohydrates and proteins fermentation, and *Anaerobranca* in VFA degradation [118]. On the other hand, The most predominant archaea population are *Methanosaeta* and *Methanobacterium,* with the higher abundance of *Methanosaeta* than *Methanobacterium* [116,117]. Ripoll et al. [114] stated that adding 50% of sherry-wine distillery wastewater to SS increases the microbial population and archaea populations by 450% and 81.9%, respectively, compared to SS mono-digestion. The presence of many toxic components in industrial wastewater can cause toxicity and inhibition to the microbial community [119,120].

For instance, existing chloroform in the substrate inhibits methanogenic activity, especially acetoclastic methanogens such as *methanosaetaceae*, as they are more sensitive than hydrogenotrophic methanogens like *methanobacteriaceae* and *methanomicrobiaceae* [119]. Huang [121] reported that adding Cd^{2+} and Cu^{2+} to the AD process significantly decreased the predominant archaeal species (e.g., *methanosaeta concilii, methanothrix soehngenii* and *uncultured euryarchaeota*). Generally, the sensitivity of acidogenesis and methanogenesis steps to heavy metals is reported to have the following order: $Cd > Cu > Cr > Zn > Pb > Ni$ and $Cu > Zn > Cr > Cd > Ni > Pb$ [120].

3.4. Slaughterhouse waste

3.4.1. Overall process performance

SHW is the by-product of the meat processing industry and due to the rising demand of the meat, slaughterhouses produce growing amounts of solid organic by-products and waste, every day. SHW usually includes rumen, skin, fats, bones, intestinal content, manure, blood, etc. It has different sources, such as pig, bovine, and poultry [123]. Due to its high organic content and the risk of infectious microbial organisms, SHW is considered a significant threat to the environment and human health. For this reason, strict legislation is laid down on SHW management and disposal and its landfilling is restricted.

Due to high content of organic matter, protein, and lipids in SHW, AD is considered as a promising management alternative for this type of waste, as it provides both material recovery and energy (biogas) production [123,124]. SHW is an attractive co-substrate with the potential of increasing volumetric biogas production in co-digestion with SS [26,125]. In Table 4, the process conditions and the results of previous studies on ACoD of SS with SHW are presented. Salehiyoun et al. [123] reported that adding 40 w/w% of SHW to SS led to producing 735 $mlCH_4/gVS$, about 69% more than the SS mono-digestion. Borowski and Kubacki [125] stated that adding pig SHW up to 50 w/w% to the SS, increased the methane production up to 600 $mlCH_4/gVS$, which was more than twice in comparison to sewage sludge mono-digestion. According to studies, 7.5-50 w/w% can be considered as the appropriate mixing ratio of SHW with sewage sludge for ACoD process [123,125]. However, using SHW over optimal ratio results in the accumulation of ammonia, VFA, and LCFAs which cause impediment to methanogenesis [26,126]. Borowski and Kubacki [125] observed slight inhibition of methanogenesis under elevated mixing ratio of 50:50 w/w% when the loading rate exceeded 4 $kgVS/m^3d$.

Generally, the highest methane production and VS reduction values that have been reported in the literature for ACoD of SS and SHW are 430-736 ml/gVSadded and 36.7–65%, respectively (Table 4). According to the literature, most of the experiments on ACoD of SS and SHW were performed under mesophilic condition and therefore, conducting studies in thermophilic conditions is necessary [123,127].

3.4.2. Process microbiology

The dominant microbial groups in the slaughterhouse waste AD process are *Methanobacteriales, Methanosarcinales*, and *Methanomicrobiales*, and at the family level are *Methanosarcinaceae* and *Methanosaetaceae* [127,128]. *Methanosarcina* has been identified as the predominant methanogens in wastewater with high concentrations of acetate and NH_3 as well as in lipid-enriched wastewater [129,130]. The dominant bacterial population at the phylum level includs *Firmicutes, Bacteroidetes*, and *Proteobacteria* and at the family level are *Clostridiaceae, Erysipelotrichaeae, Sphingobacteriaceae, Porphyromonadaceae*, and *Pseudomonadaceae* [128]. Due to the high nitrogen content of slaughterhouse waste (C/N ratio: 7–10), ammonia accumulation can cause toxicity during anaerobic digestion [120,131]. The ammonia concentrations between 4051–5734 mg NH_3–$NL^{-}1$ will inhibit the acidogens and decrease the methanogens activity by 56.5% in slaughterhouse waste AD process [120]. Besides, a high concentration of LCFAs resulting from the hydrolysis of neutral lipids in SHW, can cause their adsorption onto the microbial cell and inhibit metabolic transport, which leads to sludge flotation and washout and consequently, process failure [119,120]. Low concentration of LCFAs inhibits the acetoclastic and gram-positive microorganisms [120]. Accordingly, high concentrations of ammonia and LCFAs in the ACoD of SHW and SS can be

Table 4
Studies on using slaughterhouse waste as co-substrate in sewage sludge ACoD.

No.	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVSadded)			VSreduction (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	SS:PBS	60:40[a]	28	M (37 °C)	BMP	736.4	–	SMP – 69.4	32.6	36.7	12.58	[123]
2	SS:PBS	60:40[a]	OLR= 1.5 *	M (37 °C)	Continuous	550	–	–	–	64.6	–	[123]
3	SS:PSW	50:50[a]	–	M (35 °C)	semi-continuous	608.6	892.8	SMP – 139.23 SBP – 170.46	50.53	62.16	23.02	[125]
4	SS:CSW: VC	33:33:33[a]	25	T (55 °C)	semi-continuous	560	–	–	–	–	–	[127]
5	SS:SM	92.5:7.5[a]	22.5	M (37.5 °C)	semi-continuous	644.8	–	SMP – 175.67	46.8	64.7	38.24	[26]
6	SS:ABP	87.5:12.5[b]	20		semi-continuous	430	–	–	–	–	–	[132]

[a] : w/w%.

[b] : v/v%, PBS: Pig and Bovine Slaughterhouse, PSW: Pig Slaughterhouse Waste, CSW: Cattle Slaughterhouse Waste, VC: various crops, ABP: Animal By-product Waste.

[*] kgVS/m3.day.

accounted as the most important threats to the process. Therefore, to choose a proper mixing ratio, attention should be paid to these inhibitory effects. Generally, no comprehensive study was found on microbial community in ACoD of SS and SHW, indicating a serious need to perform researches in this regard.

3.5. Agricultural waste and crop residue

3.5.1. Overall process performance

Agricultural solid residues (ASR) are defined as unused plant parts remaining on-farm after harvest or left off-farm after crop processing [133,134]. Corn silage, wheat straw, fruit shells, sugar beet pulp lixiviation, rice straw, and the like are considered ASR. Residues often contain molasses, husks, bagasse, seeds, leaves, stem, straw, stalk, shell, pulp, stubble, peel, roots [135–137]. The accumulation of agricultural residues causes environmental pollution and esthetic concerns, and may adversely affect human and animal health. Therefore, safe treatment and disposal of ASR is required [134,136]. Although several methods such as incineration and landfilling are used for treating and disposing of this type of waste, they tend to increase greenhouse gas emissions.

Since methane production yield of agricultural waste ranges between 214 to 381 ml/gVS, AD can be a promising method to deal with this waste [134,138,139]. However, chemical properties of ASR make them resistant to bio-decomposition by enzymes and microbes. ASR, also called lignocellulosic biomass, mainly contain cellulose (25.5–52.3%), hemicellulose (19–49%) and lignin (5–25%) with small percentage of extractives, protein, and ash [133,140]. The carbohydrate fraction (cellulose and hemicellulose) is more easily degradable and fermentable than lignin. In the hydrolysis step, the cellulase enzyme complex produces glucose by degrading cellulose, and special enzymes break down hemicellulose into a variety of monosaccharides such as glucose, galactose, xylose, arabinose, and mannose [141]. However, lignin is the most recalcitrant to be degraded due to its phenolic and non-phenolic chemically stable arrangement. Moreover, toxicants, such as aromatic intermediates or aldehydes, which are byproducts of lignocellulose and lignin breakdown, as well as the herbicidal compounds used in agriculture, can cause further problems during the process. Consequently, pretreatment before AD is usually required to reduce the structural and compositional barriers of lignocellulosic biomass to enhance biomass biodegradation and biogas production rate [139–145].

Carbohydrates are the predominant components of ASR, having a high C/N ratio (usually 60–90), due to the low levels of nitrogen. Therefore, co-digestion of SS with ASR could improve C/N ratio, increase methane production and VS removal, and decrease the risk of ammonia inhibition [133,135,137]. Zhou et al. [137] reported that by adding 40% (based on COD mass) of corn silage to (waste activated sludge, WAS), the methane production increased by 154% compared to SS mono-digestion. Zhen et al. [143] stated that adding grass to WAS up to 30 w/w% increased the methane production and VS removal by 12.5% and 9.2%, respectively. Table 5 shows the important process conditions and the main results of studies on AcoD of SS with agriculture and crop residue. Given the wide range of C/N ratios in agricultural wastes, choosing the optimal mixing ratio is difficult. According to the literature, depending on the crop type, adding 30-75 w/w% of ASR to the sewage sludge AD process improves the process performance and can be considered as the optimal range of mixing ratio. Nonetheless,

Table 5

Studies on using agricultural and crop residue as co-substrate in sewage sludge ACoD.

	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVS$_{added}$)			VS$_{reduction}$ (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	WAS:CS	55:45[a]	60	M (35 °C)	Semi-continuous	507.6	940	SMP – 125 SBP – 154.1	–	–	–	[137]
2	WAS:CS	64:36 [a]	37	M (35 °C)	Semi-continuous	7.9 ml/gCOD.d	–	SMP – 39	–	–	–	[152]
3	Pr:WS	C/N = 15	29	M (37 °C)	Batch	333.9	–	SMP – 144	50.58	61.68	21.95	[135]
4	Pr: WS+BH	51.6:48.4 [a]	20	M (37 °C)	Batch	481.1	510.55	SMP – 219.88	58.42	73.45	25.73	[144]
5	SS:SE	40:60 [a]	–	M (37 °C)	Batch	176	–	–	–	81	–	[153]
6	SS:SBPL	25:75 [a]	36	M (35 °C)	Batch	520.8	–	SMP – 104	56	57.8	3.21	[145, 151]
7	SS:SHG	60.7:39.3 [a]	20	M (35 °C)	Batch	–	510 (NL/gVS-grass)	–	–	–	–	[154]
8	SS:RS	41 g RS	10	T (55 °C)	Batch	–	813 ml	SBP – 109	–	–	–	[155]
9	SS:RS	62.5:37.5 [a]	80	M (35 °C)	Batch	–	518	SBP – 68.18	37.5	60.1	60.27	[156]
10	SS:RS	62.5:37.5 [a]	80	T (55 °C)	Batch	–	602	SBP – 75	41.3	70.2	69.97	[156]
11	WAS:OP	50:50 [a]	20	M (37 °C)	Batch	210	340	SMP – 31.25 SBP – 36	39.9	45.4	13.78	[157]
12	WAS: Grass	C/N = 17	20	M (35 °C)	Batch	310	–	SMP – 55	–	–	–	[150]
13	WAS:E.d.	70:30 [a]	70	M (35 °C)	Batch	198.32	–	SMP – 12.5	–	13.35	–	[143]
14	SS:WS	50:50 [a]	30	M (36 °C)	Batch	187.01	–	SMP – 52.04	30.64	51.29	67.4	[158]
15	SS:CS	50:50 [a]	–	M (35 °C)	Semi-continuous	157.33	–	SMP – 27.91	30.64	52.39	70.99	[158]
16	WAS:WS	98:02 [a]	80	M (25 °C)	semi-continuous	47 L	–	SMP – 235.71	–	–	–	[159]
17	SS:FVW	77:23 [b]	11	M (35 °C)	Pilot-scale	430	–	–	–	~24	–	[160]

[a] : w/w%.

[b] : v/v% CS: Corn Silage, WS: Wheat Straw, BH: buckwheat husk, SE: Strawberry Extrudate, SHG: Shredded Grass, RS: Rice Straw, OP: Olive Pomace, E.d.: Egeria densa, SBPL: Sugar Beet Pulp Lixiviation, FVW: Fruit and Vegetable Waste.

increasing the agricultural residue more than the optimum mixing ratio leads to the increase of VFAs and the accumulation of ammonia, which inhibits methanogens [135,144]. Based on the previous studies, most of the experiments were performed in the mesophilic temperature range and there is lack of literature in the field of thermophilic ACoD of SS and ASR [145,146].

3.5.2. Process microbiology

Many components of crop residue, namely cellulose, lignocellulose, hemicellulose, and lignin, are highly recalcitrant, requiring specialized microbes and secreted enzymes to break them down during the acidogenesis stage. Hydrolytic bacteria secret Cellulases consist of β-glucosidases, endoglucanases, and exoglucanases to degrade cellulose, and secret Xylanases and α-L-arabinofuranosidases belonging to hemicellulases helping to degrade lignocellulosic materials [147,148]. The bacterial and archaeal community structure at genus level in agricultural waste comprises Ruminococcus sp., Thiomargarita sp., Bacillus sp., Sporobacterium sp., Saccharofermentans sp., Clostridium sp., Oscillibacter sp., Sporobacter sp., Enterobacter sp., and Anaerobacter sp for bacterial and Desulfurococcus sp., Methanosarcina sp. and Methanomassiliicoccus sp., Methanocaldococcus sp., Methanoculleus sp., and Methanospirillum sp for archaeal, respectively [149]. The most predominant archaea sequences in WAS anaerobic co-digestion with crop residues are reported *Methanosaeta, Methanosarcina* and *Methanobacterium* [150]. Adding crop residues to the WAS increases the relative abundance of *Methanobacterium* in the co-digestion process. Dai et al. [150] observed that while the ryegrass is added to WAS under optimum conditions, the total portions of the *phyla Bacteroidetes, Firmicutes, Proteobacteria* and *Spirochaetes* accounted for 85.16% of microbial community. However, in the SS mono-digestion, the mentioned *phyla* groups shared 50.78% of the total community [150]. Montanes et al. [145,151] stated that increasing the mixing ratio of sugar beet pulp lixiviation in sewage sludge ACoD process, leads to an increase in the population of archaea so that the population of hydrogenotrophic become more than acetoclastic methanogens. Therefore, bacterial diversity and relative abundance under co-digestion of ASR with SS was changed compared to SS mono-digestion.

3.6. Animal manure

3.6.1. Overall process performance

AM (also known as livestock manure) are mixtures of animal feces, urine and bedding materials such as straw and rice hulls [161]. AM has a considerable amount of organic matter and nutrients such as nitrogen (N), potassium (K), and phosphorus (P), with a C/N ratio roughly between 6 to 9. Due to high nutrients content, most AM is used in the agricultural land to improve nutrients and physical properties of the soil. However, with the increase in the volume of animal manure, concerns about environmental problems are also intensified. Therefore, the need for addressing problems related to AM such as odor nuisance, greenhouse gas emission, water pollution, and problems related to its disposal, has increased [35,162,163].

Considering the high ammonia concentration of AM and comparing its relatively low C/N ratio to the optimum range of 20–30 for AD process [34], the combination of AM with SS does not seem to help the nutrients balance of the mixture and as well as to improve the C/N ratio [164,165]. Table 6 represents the main process conditions and results of studies on ACoD of SS with AM. Borowski and Weatherley [165] reported that adding 30 w/w% poultry manure to the SS has decreased the specific biogas production from 384 mL/gVS$_{added}$ to 376 mL/gVS$_{added}$ (about 2%). In addition, Bai and Chen [36] reported that by adding 14.3 w/w% pig manure to sewage sludge AD process, the VS removal decreased by about 28%, compared to the SS mono-digestion. However, many positive results have also been reported about the ACoD of AM and SS. For instance, Borowski et al. [166] and Bai and Chen [36], respectively, concluded that by adding 30 w/w% swine manure and 14.3 w/w% pig manure to the SS in ACoD process, the biogas production increased by 40% and 10%, respectively. In addition, Zhang et al. [165] reported that adding 66 w/w% of pig manure to the sewage sludge ACoD process improved the specific methane production by 82.4%.

Many animal manures such as pig manure has been demonstrated to be a great substrate for anaerobic digestion. In contrast, SS is regarded as a material that is not easily biodegradable and has poor biogas production. Therefore, despite the low C/N ratio of AM, its use as co-substrate has enhanced the performance of sewage sludge AD process in most studies [36]. It should also be noted that almost all of the studies on ACoD of SS and AM have been performed in the mesophilic conditions and there is a serious lack of literature in the field of the process performance in thermophilic conditions [145,146].

3.6.2. Process microbiology

The most predominant bacterial phyla in the animal manure AD process are reported as *Firmicutes, Bacteroidetes*, and *Proteobacteria,* and the prevailing archaeal genera are *Methanosaeta, Candidatus Methanoregula* and *Methanomicrobiales* [168,169]. At the genus level, *Petrimonas, Proteiniphilum, Sedim,* and *Ruminofilibacter* are the most abundant bacteria. *Petrimonas* and *Proteiniphilum* are involved in the acidogenesis stage, while *Ruminofilibacters* are responsible for hydrolysis [170].

Due to the high nitrogen content of AM, ammonia accumulation can

Table 6
Studies on using animal manure waste as co-substrate in sewage sludge AcoD.

	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVS$_{added}$)			VS$_{reduction}$ (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	WAS:AS	30:70[b]	32	M (37 °C)	BMP	74.6	–	SMP – 5.8	–	–	–	[171]
2	SS:SM	70:30[a]	30	M (35 °C)	Batch	290	439	SMP – 57.6 SBP – 60	–	45	–	[166]
3	SS:SM	70:30[a]	30	M (35 °C)	Semi-continuous	–	400	SMP – 40	–	32.4	–	[166]
4	DS:PiM	34:66[a]	85	M (37 °C)	Batch	315.8	–	SMP – 82.4	–	55.2	20.5	[167]
5	SS:PM	85.7:14.3[a]	48	M (35 °C)	Batch	200	–	SMP – 10	78.2	56.26	−28	[36]
6	SS:PM	70:30[a]	20	M (35 °C)	Semi-batch	–	176	SBP – (−2)	36.33	49.35	36	[165]
7	DS:CM	30:70[a]	18	M (35 °C)	Semi-continuous	120 ml/g TS	–	SMP – 51.8	–	–	–	[164]
8	SS:SM	50:50[a]	27	M (35 °C)	Batch	447.9	–	SMP – 11	–	–	–	[172]
9	SS: RCM SS:RCM	10: 90[a] 90:10[a]	20	M (35 °C)	Batch	 -	8570 ml 6330 ml	SBP – 154.7 SBP – 88.11	- -	8.8 4.7	- -	[173]

[a] : w/w%.

[b] : v/v%, AS: Aquaculture Sludge, SM: Swine Manure, PM: Poultry Manure, PiM: Pig Manure, CM: Chicken Manure, RCM: raw chicken manure.

cause toxicity during its AD process so that the microbial community is negatively affected [120]. Under ammonia concentrations in the range of 4051–5734 mgNH$_3$–NL^{-1}, the methanogenic population (acetoclastic and hydrogenotrophic methanogens) will lose their activity by 56.5% [120]. Generally, the main drawback of AM as co-substrate is its high risk of ammonia inhibition. Despite this, some previous studies demonstrated the possibility of obtaining stable digestion of manure with ammonia concentrations more than 5000 mg NL^{-1} after an initial adaptation period [120].

Despite the very high importance of the microbial population in the ACoD of AM with SS, no study investigating the subject was found in the literature. This indicates the necessity of conducting research on the microbial community of the mixture of AM and SS in ACoD process.

3.7. *Microalgae*

3.7.1. *Overall process performance*

Microalgae mainly contain carbohydrates (7–69%), proteins (15–84%), and lipids (1–63%) [174,175]. Considering their high content of lipid and volatile matter, microalgae can be an attractive option for co-digestion with SS [176]. However, high amounts of protein results in low C/N ratios of microalgae, with an average of 7.4 [177]. Besides, the presence of hemicellulose compounds in the microalgae cell wall brings high resistance to hydrolysis and anaerobic degradation [176,178].

Table 7 summarizes the process conditions as well as the results of previous studies on ACoD of SS with microalgae. Studies in the literature have reported contradictory results. Some researchers stated that adding microalgae to the sewage sludge AD process has synergistic effects and enhances the process performance in terms of biogas and methane production. Vassalle et al. [179] and Beltran et al. [178] concluded that mixing 30 w/w% and 25 w/w% of microalgae with SS increased the methane production by 25% and 22%, respectively. However, many studies reported that ACoD of SS and microalgae reduces the process performance and efficiency [175,177,180]. According to Goncalves et al. [181] and Olsson et al. [182], adding 20 w/w% and 40 w/w% microalgae as co-substrate decreased specific methane production by 5% and 26% compared to SS mono-digestion. Generally, data given in Table 7 reveals that the specific values of methane production from co-digestion of SS and microalgae can be up to 111% less than that of SS mono-digestion.

Most studies on SS and microalgae ACoD were conducted under mesophilic conditions. In this regard, Caporgno et al. [183] and Olsson et al. [184], who performed their ACoD experiments under thermophilic conditions, reported that synergistic effect was not observed during thermophilic ACoD of SS and microalgae. Olsson et al. (2014) [184] attributed this observation to the high protein content of microalgae (50–60%) resulting in release of more ammonia at higher temperatures. The high ammonia concentration has also accounted as the main inhibitor of the microalgae mono-digestion process as it reduces the proteolytic bacteria's activity [185]. In general, microalgae cannot be considered with high certainty as a suitable co-substrate for ACoD with SS due to their low C/N ratio and the presence of hemicellulosic compounds resistant to hydrolysis and decomposition.

3.7.2. *Process microbiology*

The most predominant bacterial community of microalgae mono-digestion in the major phyla are reported Bacteriodetes, Proteobacteria, Firmicutes, Chloriflexi, WWE1, Actinobacteria, Spirochaetes, Thermotogae, and Synergistetes [186,187]. Inhibitory elements such as ammonia, sulfur, heavy metals, and fatty acids, harm the microbial community during microalgae AD. A high ammonia concentration inhibits some enzyme reactions and decreases the activity of proteolytic bacteria. Moreover, sulfur in the form of sulfate or sulfide can inhibit the microbial community. An excessive amount of calcium and aluminum results in the scaling of bacterial cells and inhibits the growth of methanogens [185].

The most predominant population in ACoD of sewage sludge with microalgae, are reported *Methanosarcinales (Methanosaeta)* for archaea and *Coprothermobacteraota, Thermotogae, Hydrothermae* and *Proteobacteria* for bacteria [188,189]. As stated by Serna-Garcia et al. [188], the hydrolytic and fermentative groups containing *Firmicutes, Bacteroidetes* and *Proteobacteria phyla* with high proteolytic and cellulolytic activities were predominant due to the presence of microalgae in the ACoD reactor [188]. In another study, Serna-Garcia et al. [189] reported that the diversity of microbial community in the ACoD of SS and microalgae was enhanced so that the population of *Chloroflexi, Proteobacteria, Caldiserica, Firmicutes, Cloacimonetes, Bacteroidetes, Thermoto*ga and *Synergistetes phyla* increased. However, *Anaerolineaceae,* which are present in mesophilic anaerobic systems of microalgae and have significant role during saccharolytic fermentation were reduced [189,190].

3.8. *Paper and cardboard*

3.8.1. *Overall process performance*

Paper and cardboard waste (PCW) are produced in the paper mill and

Table 7
Studies on using microalgae as co-substrate in sewage sludge AcoD.

	Substrate	Mixture (%)	HRT (d)	Temp	System	Specific production (mL/gVS$_{added}$)			VS$_{reduction}$ (%)			Reference
						SMP	SBP	Enhancement (%)	Mono	Co	Enhancement (%)	
1	WAS: Chelorella	59:41[a]	45	M (37 °C)	Batch	–	468	SBP – (−3.1)	52	55.5	6.7	[44]
2	SS:MA	70:30[a]	35	M (35 °C)	UASB	211	331	SMP – 25 SBP – 10	–	–	–	[179]
3	Pr+WAS:MA	60:40[a]	50	M (35 °C)	Batch	168	–	SMP – (−19)	–	–	–	[182]
4	SS:MA	50:50[a]	30	M (35 °C)	Batch	327	–	SMP – 9	–	–	–	[191]
5	Pr:MA	90:10[a]	35	M (35 °C)	Semi-continuous	225	–	SMP – (−15)	–	–	–	[180]
6	SS:MA	94:06[a]	20	M (35 °C)	Batch	–	7.4 L	SBP – (−21.5)	39.5	33.8	−14.43	[176]
7	WAS:MA	75:25[a]	30	M (35 °C)	Batch	442	–	SMP – 22	–	–	–	[178]
8	SS:MA	80:20[a]	39	(27 °C)	UASB	200	–	SMP – (−5)	–	63	–	[181]
9	SS:MA	75:25[a]	35	M (33 °C)	Batch	338	394	SMP – (−2.5) SBP – (−15)	–	–	–	[183]
10	SS:MA	75:25[a]	35	T (50 °C)	Batch	219	510	SMP – (−111) SBP – (−10)	–	–	–	[183]
11	SS:MA	63:37[a]	57	M (37 °C)	Batch	408	–	SMP – 23	–	–	–	[184]
12	SS:MA	88:12[a]	57	T (55 °C)	Batch	388	–	SMP – 7	–	–	–	[184]
13	WAS:MA	98.2:1.8[a]	30	M (35 °C)	Batch	225.8	–	SMP – 45.3–69.9	19–30	35	16.7–84.2	[192]

[a] : w/w%, MA: Microalgae.

Table 8
The microbial consortia diversity in ACoD of SS with different co-substrates.

Substrates	Microbial Community	System	HRT (d)	Temp	Reference
SS	*Bacilli (Alkalibacterium and Paenisporosarcina) and Clostridia (Alkaliphilus)*	Batch	21	Mesophilic (37 °C)	[60]
SS + FW	*Methanospirillaceae, Methanosarcinales, Lactobacillus, and Methanosaetaceae*	Continuous	22	Mesophilic (37 °C)	[57]
SS + FW	*Prevotella, Ruminococcus, and Clostridium*	Batch	21	Mesophilic (37 °C)	[60]
SS + FOG	*Methanosaeta, and N09*	Semi-Continuous	15	Mesophilic (37 °C)	[79]
SS + biodiesel waste glycerin	*Methanosaeta and Methanomicrobium*	Two-Stage (CSTR)	20	Mesophilic (37 °C)	[198]
SS + Sherry-wine distillery wastewater	*Acetogens utili, Eubacteria, and Butyrate utilizing acetogens*	Batch	25	Mesophilic (35 °C)	[114]
Activated Sludge + ryegrass	*phyla Bacteroidetes, Firmicutes, Proteobacteria, and Spirochaetes*	Semi-Continuous	20	Mesophilic (35 °C)	[164]
SS + microalgae (Chlorella spp.)	*Methanosarcinales (Methanosaeta), and Coprothermobacteraota, Thermotogae, Hydrothermae, and Proteobacteria*	AnMBR	70	Thermophilic (55 °C)	[188]
SS + microalgae (Scenedesmus and Chlorella)	*Chloroflexi, Proteobacteria, Caldiserica, Firmicutes, Cloacimonetes, Bacteroidetes, Thermotoga and Synergistetes phyla*	Semi-Continuous	100	Mesophilic (35 °C)	[189]

AnMBR: Anaerobic Membrane Bioreactor, CSTR: Continuous Stirred-Tank Reactor.

wood industries, mainly composed of cellulose, lignin, and hemicellulose. Cellulose constitutes a minimum of 50%, while lignin and hemicellulose comprise 10–20% and 1–24% of paper waste, respectively [193,194]. AD of PCW is often restricted in the hydrolysis phase since it mainly contains recalcitrant lignocellulosic materials characterized by fiber length or degree of cellulose polymerization. Lignin and cellulose are also characterized by their hydrophobicity and powerful internal bonding [193,194]. These recalcitrant components reduce the hydrolysis rate, prevent complete hydrolysis, require larger digester for extended solid retention time, decrease process performance and efficiency, deteriorate dewatering properties and increase operation costs [194,195]. Based on the literature, ACoD of PCW with SS has rarely been studied because the AD process does not efficiently degrade lignin [195]. Hagelqvist [195] reported that adding 20 w/w% to 50 w/w% of paper waste to sewage sludge AD process did not significantly decrease methane production. However, Xie et al. [15] stated that adding paper waste to the sewage sludge had a positive synergistic effect and led to higher methane production; therefore at the 1:1 mixing ratio, the specific methane yield and VS removal rate enhanced by 131% and 63.7%, respectively, in comparison with SS mono-digestion. In general, due to the high content of recalcitrant components in PCW and the lack of literature about the ACoD of SS with PCW, further studies are needed in this field in order to be able to make a better judgment about the performance of this process.

3.8.2. *Process microbiology*

The dominant archaeal composition in anaerobic digestion of paper waste and lignocellulosic biomass are reported *Methanosaeta concilii, Methanobacterium, Methanobacteriales* and *Methanomicrobiales* families [21]. In addition, the predominant bacterial community in anaerobic digestion of PCW are *Firmicutes*, including *Ruminococcus sp* and *Clostridium sp* [196]. Due to the high degradation ability of these bacteria, many polysaccharides including cellulose, xylanase, and hemicellulose, can be hydrolyzed [149,197]. For example, Extracellular hydrolytic enzymes including exoglucanases and endoglucanases are produced by *Ruminococcus sp*, for degrading cellulose and hemicellulose to the acetate, formate, ethanol, carbon dioxide and hydrogen, as metabolic products [197]. In addition, *Clostridium sp* as a cellulolytic mesophilic organism, can degrade cellulose to glucose and cellobiose for utilizing as energy and carbon sources [149]. According to the best knowledge of the authors, there are no or very few studies investigating the microbial composition of sewage sludge ACoD with PCW. It seems rational that the dominant microbial population in the PCW mono-digestion process will affect the dominant microbial population in the ACoD of SS with PCW. However, due to the lack of reports, there is a need to conduct more research in this field.

4. Discussion and future perspectives

The results of the previous works on ACoD of SS with different co-substrates are summarized in Table 9. According to the literature review, an appropriate co-substrate for sewage sludge ACoD must have either a high C/N ratio or a high biodegradable organic content to enhance the process performance and increase the methane yield. Each co-substrate should be mixed with the SS based on an appropriate mixing ratio. Adding excess amounts of co-substrates usually results in VFA and ammonia accumulation. Besides, waste containing toxic compounds or recalcitrant substances cannot be easily used as co-substrate. According to these points, the eight reviewed waste materials have been categorized in three classes described below:

The first group- wastes that can be used with high reliability: The first group includes the wastes that can be used as co-substrate with high reliability and low probability of disrupting the process. In most of the researches conducted in relation to the use of these wastes as a co-substrate, significant positive effects on the performance of the ACoD process have been observed and reported. The following wastes belong to the first group:

- Municipal waste (FW): owing to its high C/N ratio, high biodegradable organic content and small amounts of toxic compounds, FW can be considered as an appropriate and reliable co-substrate with the ability to compensate the drawbacks of sewage sludge.
- FOG: with similar characteristics to FW in terms of organic content and toxic compounds, FOG is another promising waste material that can help improving methane production and VS reduction during ACoD with SS. Because of the lower nitrogen content, FOG can be used in the sewage sludge ACoD under relatively higher mixing ratios compared to FW (30-50 w/w% and 20-70 w/w% for FW and FOG, respectively).

The second group- Wastes with moderate probability of disrupting the process: The second group includes the wastes that can be used as co-substrate with moderate probability of disrupting the process. In researches conducted in relation to the use of these wastes as a co-substrate, some adverse effects on the process performance have been observed. For example, although some researchers have reported that using industrial waste, methane production has improved by up to 600%, other researchers have reported a reduction in methane production by up to 39% (Table 9). Therefore, before using these wastes as co-substrate in ACoD of sewage sludge, it is necessary to carefully examine how they affect the process during laboratory studies. The following wastes belong to the second group:

Table 9
Summary of reviews on co-substrates anaerobic co-digestion with sewage sludge.

	FW	FOG	Industrial waste	SHW	ASRs	AM	MA
Mixing ratio (SS: Co-substrate, w/w%)	80:20–20:80	90:10–10:90	50:50–8:92	92.5:7.5–50:50	98:2–25:75	90:10–10:90	98.2:1.8–50:50
Mixing ratio (SS: Co-substrate, v/v%)	–	–	99.5:0.5–10:90	87.5:12.5	77:23	30:70	–
SMP enhancement (%)	11–121.5	15–316.67	(−39.84)–600	69.4–175.67	12.5–219.88	5.8–82.4	(−111)–69.9
SBP enhancement (%)	16–230	–	35.4–370	–	55–154	(−2)–154.7	(−21.5)–10
VS removal enhancement (%)	5.3–108.7	34.62–93.92	12.6–115.8	12.6–38.25	3.21–70.99	(−28)–36	(−14.43)–84.2
High organic content	✓	✓	✓	✓	×	✓	×
High C/N ratio	✓	✓	✓	×	✓	×	×

FW: food waste, FOG: fat oil grease, Industry: agro-industrial by-products and other industries, SHW: slaughterhouse waste, ASRs: agricultural solid residues, AM: animal manure, MA: microalgae.

- Industrial waste: many types of industrial waste have also been reported to be successfuly used as co-substrate for ACoD with SS. However, since the type of industry severely affects the characteristics of industrial waste and its content in terms of the amount and biodegradability of organic matter and the presence of toxic substances, the optimal mixing ratio can be very variable (0.5–90 v/v%) depending on the type of industry.
- Slaughterhouse waste (SHW): SHW characterized by a high content of organic matter, protein and lipids, has shown satisfactory performance as co-substrate for sewage sludge AD process, under mixing ratios between 7.5-50 w/w%. Because of the higher nitrogen content and ammonia accumulation, SHW was used in the sewage sludge ACoD under lower mixing ratios compared to FW and FOG.
- Agricultural solid residues (ASR): ASR are also candidate for use as co-substrate in the ACoD of sewage sludge, due to their high C/N ratio. However, the risk of accumulation of lignin and its breakdown toxic byproducts should be considered while selecting mixing ratio for ASR. Mixing ratios between 30-75 w/w% have been successfully investigated for ACoD of ASR with SS.
- Animal manure (AM): AM has been reported to have a C/N ratio range similar to that of the sewage sludge. Therefore, using AM as co-substrate with the sewage sludge does not modify the C/N ratio of the mixture. For this reason, contradictory results have been reported about the ACoD of SS with AM, although most studies indicate a positive effect of AM on the process.

The third group- Wastes with high probability of disrupting the process: The third group includes the wastes that have a high risk of disrupting the process. Considerable number of studies on the use of these wastes as a co-substrate, have reported adverse effects on the process performance. Therefore, they cannot be recommended for use as co-substrate in ACoD of sewage sludge unless further research shows different results. The following wastes belong to the third group:

- Microalgae: microalgae on the one hand, have a low C/N ratio similar to animal manure, and on the other hand, similar to agricultural residue, have recalcitrant hemicellulose compounds. These characteristics have caused microalgae to be unreliable co-substrates, so that a considerable portion of studies on co-digestion of microalgae and SS show the negative impact of microalgae on the performance of the process.

There are very few reports regarding the application of paper and cardboard waste (PCW) in sewage sludge ACoD. PCW, with similarities to the composition of agricultural waste, contains significant amounts of recalcitrant lignocellulosic compounds. According to this characteristic, it seems that the performance of paper and cardboard waste as a co-substrate would be similar to that of agricultural residue. Nevertheless, due to the lack of studies done in this field, it is not possible to judge accurately.

It is also worth mentioning that most of the previous studies on sewage sludge ACoD have been performed in the mesophilic conditions. Since the microbial community, the degradation pathway of organic material, and consequently the process performance change depending on the temperature range of the AD process, conducting studies on thermophilic ACoD of sewage sludge with different co-substrates is required.

Although it was shown in some researches that adding co-substrates to sewage sludge ACoD improves the microbial community and increases the archaeal population, there is still very little information in this relation. For this reason, much more studies on the changes of the microbial community in the sewage sludge ACoD compared to mono-digestion of SS and co-substrates, under mesophilic and thermophilic conditions, are needed. As well, investigating how far bacterial communities in sewage sludge ACoD can tolerate the possible disturbances such as sharp change in pH or in the organic loading rate and entry of a toxic substance, will be of great value and can fill the research gap of the topic. Besides, the source of inoculum may also be a critical impact factor to the microbial community structures. Therefore, performing studies on the effect of the inoculum source on the microbial community of the sewage sludge ACoD is of high importance.

Another issue that has not been addressed in studies on sewage sludge ACoD process is the dewaterability of the digested sludge. For optimal management, digested sludge is subjected to dewatering process so that it becomes portable and can be used for different uses. Therefore, investigating the dewaterability of the digested sludge resulting from ACoD of sewage sludge is of great importance and necessity from a technical and economic point of view.

5. Conclusions

This work summarized the effect of using eight frequently studied waste materials as co-substrate on the sewage sludge ACoD process. Food waste, FOG, and industrial waste due to having high C/N ratio and high biodegradable organic content, ASR owing to its high C/N ratio, and SHW and AM owing to their high biodegradable organic content can be the appropriate choices for adding to sewage sludge AD process. Although the use of each of these waste materials requires careful consideration and determination of the optimal mixing ratio, more cautions should be taken when using industrial waste, ASR, SHW and AM, due to the presence of toxic or recalcitrant compounds in their compositions. Microalgae, which have a low C/N ratio and high hemicellulose content in their cell wall, lead to high resistance to hydrolysis and can reduce the process efficiency with a relatively high probability. Fewer studies have been done on PCW and since this waste has a high organic content (as a promising factor) on the one hand and contains compounds resistant to decomposition on the other hand, it is not possible to comment with certainty on its performance.

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CRediT authorship contribution statement

R. Azarmanesh: Methodology, Investigation, Writing – original draft. **Milad Zarghami Qaretapeh:** Methodology, Investigation, Writing – original draft. **Maryam Hasani Zonoozi:** Supervision, Writing – review & editing. **H. Ghiasinejad:** Writing – review & editing. **Y. Zhang:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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