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Enhanced Anaerobic Digestion of Organic Waste

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Abstract

Anaerobic digestion (AD) of organic municipal solid waste (OMSW) is considered as a key element in sustainable municipal waste management due to its benefits for energy, environment, and economy. This process reduces emission of greenhouse gases, generates renewable natural gas, and produces fertilizers and soil amendments. Due to its advantages over other treatment methods and waste-to-energy technologies, anaerobic digestion has attracted more attention so that numerous research works in this area are performed. In this chapter, an overview of previous studies on anaerobic digestion using OMSW as the feedstock is presented. First, the principals of anaerobic digestion including chemical and biological pathways and microorganisms responsible for different steps of the process are discussed. Factors influencing the efficiency of the process such as temperature, pH, moisture content, retention time, organic loading rate and C/N ratio are also presented in this chapter. Different methods of pretreatment applied to enhance biogas production from anaerobic digestion of municipal solid waste are also discussed.

Keywords: anaerobic digestion, municipal solid waste, renewable resource, waste-to-energy, waste pretreatment, enhancing biogas production

1. Introduction

Municipal solid waste (MSW) management has become a serious environmental issue since the waste generation has rapidly increased with population explosion and economic development. Improper management of MSW can contribute to the degradation of environment quality [1]. For instance, the disposal of municipal solid waste in landfills can cause emission to the atmosphere as well as high nitrogen concentrations in the leachate [2, 3]. However, advancement of technology, establishment of environmental regulations, and emphasis on resource conservation and recovery have greatly reduced the environmental impacts of municipal solid waste management [4]. Emission of greenhouse gases through

municipal solid waste management systems can be reduced by using a series of different treatment and disposal techniques such as sorting, aerobic composting, anaerobic digestion (AD), incineration, and landfill. Mata-Alvarez et al. [5] compared different municipal solid waste management systems including landfill (1.97 tons CO₂/ton MSW), incineration (1.67 CO₂/ton MSW), sorting-composting-landfill (1.61 CO₂/ton MSW), sorting-composting-incineration (1.41 CO₂/ton MSW), and sorting-anaerobic digestion-incineration-landfill (1.19 CO₂/ton MSW). The results showed that anaerobic digestion plays an important role in reducing CO₂ emission from municipal solid waste.

Bioprocessing of organic fraction of municipal solid waste that comprises composting and anaerobic digestion is considered as a viable means of transforming organic wastes into products that can be used safely and beneficially as biofertilizers and soil conditioners [6]. Aerobic treatment has been found to cause large and uncontrolled emission of volatile compounds such as ketones, aldehydes, and ammonia [5]. Additionally, composting is an energy consuming process (around 30–35 kWh/ton waste), while anaerobic digestion is a net energy producing process (100–150 kWh/ton waste) [7].

Energy from waste is seen as one of the most dominant future renewable energy sources, especially since that a continuous power generation from these sources can be guaranteed [8]. The most important property of alternative energy source is their environmental compatibility [9]. Various methods have been applied to convert waste to energy such as combustion, gasification, pyrolysis, fermentation, and anaerobic digestion. Among these methods, anaerobic digestion has attracted more attention because of following advantages: anaerobic digestion can process a variety of biomass materials (sewage sludge, municipal solid waste, agricultural wastes, manure, and industrial wastes); this process can easily treat wet wastes, which are problematic in other methods such as combustion; anaerobic digestion obtains valuable products which are useful for soil fertilization and energy generation; compared to common waste management processes such as incineration, pyrolysis, and gasification, this process causes the least amount of air and solid pollution. The other advantage is the small size of AD plants, which offers less footprint [10–12].

In this chapter, an overview of anaerobic digestion of municipal solid waste including fundamental of anaerobic digestion, microbiology of the process, important operating factors, and the techniques used for enhancing anaerobic digestion of municipal solid waste is presented.

2. Principals of anaerobic digestion

Anaerobic digestion is a series of biological processes in which microorganisms break down biodegradable material in the absence of oxygen. As shown in **Figure 1**, this process occurs in four stages including hydrolysis, acidogenesis, acetogenesis, and methanogenesis.

Hydrolysis, as the first stage of anaerobic digestion, is conversion of insoluble complex organic matter (carbohydrates, proteins, and lipids) into soluble molecules (sugars, amino acids, and long chain fatty acids). Hydrolysis reactions are carried out by extracellular enzymes called

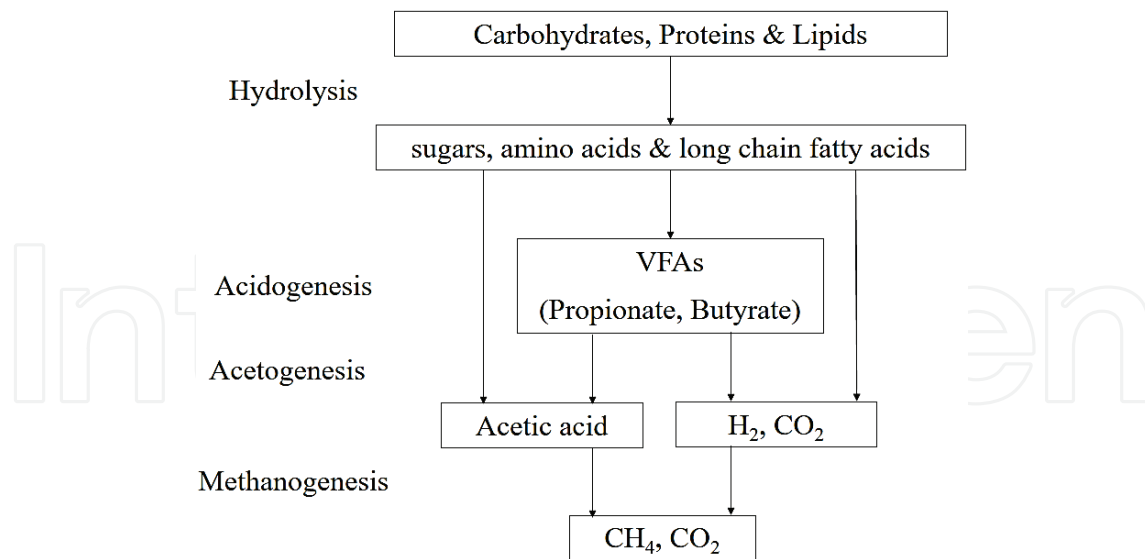


Figure 1. Process flow of the degradation of organic material through anaerobic digestion [16].

hydrolase. These hydrolases can be esterase (enzymes that hydrolyze ester bonds in lipids), glycosidases (enzymes that hydrolyze glycosidic bonds in carbohydrates), and peptidases (enzymes that hydrolyze peptide bonds in proteins) [13]. These enzymes are produced by microorganisms called hydrolytic bacteria. *Clostridium*, *Proteus vulgaris*, *peptococcus*, *bacteroides*, *bacillus*, *vibrio*, *acetivibrio cellulolyticus*, *staphylococcus*, and *micrococcus* have been reported as typical species of hydrolytic bacteria [14]. For example, *Cellulomonas* bacterium produces cellulase enzyme which can degrade polysaccharides into simple sugar; *Bacillus* bacterium converts proteins to amino acids by producing protease enzyme; and lipase enzyme produced by *Mycobacterium*, converts lipids into fatty acids [15]. Hydrolysis was reported [13] as the rate-limiting step in anaerobic digestion process due to the slow depolymerization of the insoluble complex organic matter by hydrolytic bacteria.

In acidogenesis stage, fermentative bacteria convert soluble molecules produced in the hydrolysis stage into volatile fatty acids (propionate, b), lactate, alcohols, and carbon dioxide. There are different fermentation pathways each of which is carried out by different bacterial species. Some genera of bacteria, which carry out fermentation pathways in anaerobic digestion, are as follows: *Saccharomyces* (alcohol fermentation), *Butyribacterium* and *Clostridium* (butyrate fermentation), *Lactobacillus* and *Streptococcus* (lactate fermentation), and *Clostridium* (propionate fermentation). Acetate is also produced in this step by a group of bacteria called acetate-forming fermentative bacteria. *Acetobacterium*, *Clostridium*, *Eubacterium*, and *Sporomusa* are typical species of acetate-forming fermentative bacteria [14, 16].

In the third stage of anaerobic digestion, acetogenic bacteria transform volatile fatty acids (VFAs) and alcohols into acetate, H₂, and CO₂. Different species have been identified as acetogens. *Syntrophobacter wolinii* and *Smithella propionica* are identified bacteria which form acetate by consuming butyrate and propionate, respectively. Some other species such as *Syntrophobacter fumaroxidans*, *Syntrophomonas wolfei*, *Pelotomaculum thermopropionicum*, and *Pelotomaculum schinkii* have been identified as acetogenic bacteria which convert VFAs to

formate, H_2 , and CO_2 . *Clostridium aceticum* is another identified microorganism which produces acetate from H_2 and CO_2 [14].

Methanogenesis is the final stage of anaerobic digestion in which formation of methane gas from acetate and molecular hydrogen occurs. Methanogens play a vital role as the consumer of acetogenesis products due to the fact that accumulation of hydrogen produced in acetogenesis can terminate activity of acetate-forming bacteria [15]. Different species have been identified as methanogenic bacteria including: (i) species which convert acetate to methane and carbon dioxide (acetoclastic methanogenic pathway) such as *Methanothrix soehngenii* and *Methanosaeta concilii*; (ii) species which produce methane from H_2 and CO_2 (hydrogenotrophic methanogenic pathway) such as *Methanobacterium bryantii*, *Methanobacterium thermoautotrophicum*, and *Methanobrevibacter arboriphilus*; and (iii) species which consume formate, hydrogen, and carbon dioxide and produce methane such as *Methanobacterium formicicum*, *Methanobrevibacter smithii*, and *Methanococcus voltae* [14].

3. Important operating factors

The anaerobic digestion of organic material is a complex process, involving a number of different degradation steps. The microorganisms that participate in the process may be specific for each degradation step and thus could have different environmental requirements [17]. Parameters affecting anaerobic digestion include temperature, moisture content, retention time, pH, organic loading rate, and C/N ratio.

3.1. Temperature

Operating temperature is the most important factor determining the performances of anaerobic digestion because it is an essential condition for the survival and growth of the microorganisms [18]. It also determines the values of the main kinetic parameters for the process and, hence, the rate of the microbiological process. There are two range of temperature with maximum anaerobic digestion rate (gas production rates, bacteria growth rate, and substrate degradation rate): thermophilic (50–60°C) and mesophilic (30–40°C) [19].

Mesophilic and thermophilic anaerobic digestion have been widely used for biogas production from various types of waste and the results have shown these processes to have different advantages and disadvantages as listed in **Table 1**.

Results of a comparative study [21] on anaerobic digestion of organic municipal solid waste (OMSW) under mesophilic (35°C) and thermophilic (50°C) conditions showed that microbial activity is favored working at thermophilic range; hence, higher specific growth rate and methane yields were achieved in the thermophilic anaerobic digestion. Thermophilic digesters presented a higher rate of soluble chemical oxygen demand (sCOD) removal and methane production rate compared with mesophilic digesters in a study on anaerobic digestion of food waste [22]. Values reported for microbial activity (maximum specific growth rate) and methane production (specific methane yield) of anaerobic digestion of the organic fraction of municipal solid waste are presented in **Table 2**.

	Advantages	Disadvantages
Thermophilic	Higher loading rate Higher methane production. Higher temperature shortens the required retention time. higher pathogen destruction	Very sensitive to toxins and small environmental changes The process is less stable, as the microbial population is less divers. The system is harder to maintain Additional energy input is required for heating
Mesophilic	Operates with robust microorganisms which tolerate greater changes in the environment. The system is more stable and easier to maintain. Smaller energy expense	Longer retention time Lower biogas production

Table 1. Comparison of thermophilic and mesophilic anaerobic digestion [10, 17, 18, 20].

3.2. Moisture content

Moisture content is one of the most important factors affecting anaerobic digestion. Moisture was reported [10] to aid digestion by (i) controlling cell turgidity; (ii) transporting nutrients, intermediates, products, enzymes and microorganisms; (iii) reacting in hydrolysis of complex organic matters; and (iv) modifying the shape of enzymes and other macromolecules [17]. High

Bacterial group	Mesophilic	Thermophilic		Refs.
	μ_{\max} (d ⁻¹)	CH ₄ production μ_{\max} (d ⁻¹) (m ³ CH ₄ /g VS)	CH ₄ production (m ³ CH ₄ /g VS)	
Acetoclastic methanogens	0.192–0.256	0.0079	0.243–0.410	0.0149 [21]
Hydrolysis	0.024	0.0019		[23]
Acidogens	2.4			
Acetoclastic methanogens	0.1392			
Hydrogenotrophic methanogens	1.39			
Hydrolysis		0.08–0.18	0.016	[24]
Acidogens		0.13–0.16		
Acetoclastic methanogens		0.23–0.28		
Hydrogenotrophic methanogens		0.33–0.40		
Overall		0.118–0.178	0.023 m ³ CH ₄ /g COD	[25]
Acetoclastic methanogens	0.13–0.19	0.0047–0.0079		[26]
All methanogens	0.15–0.26			
Overall		0.58	–	[27]

Table 2. Microbial activity and methane production of mesophilic and thermophilic anaerobic digestion of OMSW.

moisture contents usually facilitate the anaerobic digestion due to the fact that water contents are likely to affect the process performance by dissolving readily degradable organic matter.

Based on the total solids content of the slurry in the digester reactor, anaerobic digestion processes are classified to low solids or wet digestion (less than 10% TS), medium solids or semidry (10–20% TS) and high solids (more than 20% TS). Most of the studies on degradation of organic fraction of municipal solid waste were performed using dry anaerobic digestion process due to the high-solid content of OMSW [21, 24, 27, 28]. However, adding water or codigesting with low-solid wastes such as sewage sludge and manure can increase the moisture content of OMSW and make it suitable for semidry anaerobic digestion process [26, 29].

Lay et al. [30] reported that increasing initial moisture content of mesophilic anaerobic digesters from 90 to 96% increased the methanogenic activity in high-solids sludge digestion. In another study [28], digesters operated at higher initial moisture content obtained higher methane production rate, as well as better dissolved organic carbon (DOC) removal efficiency in mesophilic anaerobic digestion of OMSW. However, it was reported [31] that increasing the moisture content of OMSW decreased methane production rate of anaerobic digesters with periodic cycles of leachate drainage and water addition. The bioreactors operating at 80% moisture content presented a poorer volatile solids (VS) content compared to the ones operating at 70% moisture content due to the fact that water readditions into the bioreactors could contribute to washing out of nutrients and microorganisms.

3.3. Retention time

Retention time is the required time for decomposition of organic matter, which is determined by measuring chemical oxygen demand (COD) or biochemical oxygen demand (BOD) of the influent and the effluent. Longer retention time will result in more degradation of organic matter [18]. Required retention time for complete AD is controlled by the applied technology, process temperature, and waste composition. Mesophilic anaerobic digestion requires retention time of 8–40 days; while less thermophilic AD offers less retention time [32]. Fdez-Güelfo et al. [27] investigated the effect of solids retention time (SRT), from 8 to 40 days, on the dry thermophilic anaerobic digestion of OMSW. They reported that SRT of 15 days obtained the highest VS removal and methane yield.

Reducing retention time reduces the volume required for the reactor and consequently reduces the capital costs of anaerobic digestion. Therefore, different approaches have been suggested [20] for reducing the retention time such as mixing, decreasing solid content, separating stages of anaerobic digestion, and alternating flow pattern and pretreatment.

Proper mixing ensures that bacteria have rapid access to as many digestible surfaces as possible and that environmental characteristics are consistent throughout the digester [20]. Recirculating water and biogas in the chamber to keep material moving has been used as a promising mixing method to enhance anaerobic digestion. Caviato et al. [33] reported that water recirculation improved methane production in a two-phase thermophilic anaerobic process with hydraulic retention time of 3 days. Decreasing solid content can reduce the retention time, because bacteria can more easily access liquid substrate and because the

relevant reactions require water. Additionally, mixing is more complete when the solid content is lower [20]. Retention time can be reduced by separating the stages of the digestion into individual chambers so that the bacterial population in each chamber is optimized for its purpose [20]. Two-phase anaerobic digestion has been used advantageously to treat wastes with high-solid content such as municipal solid waste and reported to be warranted from the kinetic point of view [34].

Using various methods of pretreating waste (discussed later) can also reduce the retention time by increasing digestibility.

3.4. pH

Operating pH is another important factor due to the sensitivity of methanogenic bacteria, their growth as well as methane production to acidic. Biological activities during different stages of anaerobic digestion change the pH level. Production of organic acids during the acetogenesis phase lower the pH down to 5 which is lethal for methanogens and can cause digester failure [18].

High VFA levels could occur due to overloading, poor mixing, nutrient shortage, variation of temperature, and loss of bacteria in the discharge. If there is enough alkalinity available, the acids may be buffered; thus, buffering reagents may be needed. However, buffering can be provided by the reaction of the ammonium ions with bicarbonate ions to form ammonium bicarbonate [10].

In the start-up when fresh waste is introduced, before methanogenesis stage starts, organic acids are formed. This lowers the pH. Therefore, pH control is delicate during the early stages. Addition of buffers such as calcium carbonate or lime to the system in order to increase the pH is necessary [20].

Ward et al. [11] reported that the pH range of 6.8–7.2 is ideal for anaerobic digestion. They also reported that the optimal pH of methanogenesis is around pH 7.0 and the optimum pH of hydrolysis and acidogenesis is between pH 5.5 and 6.5. This is an important reason why some researchers prefer the separation of the hydrolysis/acidification and acetogenesis/methanogenesis processes in two-stage processes. Recirculation of process liquid was also reported to have a beneficial effect on the performance of anaerobic codigestion of OMSW and manure by stabilization of the pH [29].

Zhang et al. [35] investigated the effect of pH, the first stage (hydrolysis and acidogenesis) of anaerobic digestion of kitchen waste adjusting pH values of 5, 7, 9, and 11. They reported that pH adjustment improved both hydrolysis and acidogenesis rates as well as TS removal rate and biogas production during the two-phase anaerobic digestion of kitchen wastes.

3.5. Organic loading rate

Organic loading rate (OLR) is another important parameter to control since the biogas production rate is highly dependent on the loading rate [36]. Basically, for the higher volatile solids, more bacteria is needed for anaerobic digestion. Increasing the OLR increases the population

of acidogenic bacteria which produce acids and multiply rapidly. However, methanogenic bacteria that take longer to increase their populations would not be able to consume the acids at the same pace [20]. Consequently, pH of the system will fall, which can kill methanogenic bacteria and lead to the crash of the system [18].

Dhar et al. [48] investigated the effect of organic loading rate during anaerobic digestion of municipal solid waste using mesophilic reactors with initial loading of 5.1 and 10.4 g/L sCOD. The results showed that the reactor with higher organic loading rate obtained a higher methane yield (168 mL CH₄/gVS_{removed}) as well as higher CODs reduction (84.2%) than the other reactor (methane yield of 101 mL CH₄/gVS_{removed} and 78% CODs reduction). Bouallagui et al. [37] tested anaerobic digestion of fruit and vegetable wastes using three two-phase mesophilic digesters operated with organic loading rates of 3.7, 7.5, and 10.1 g COD/L.d. The results indicated that with the increase in the organic loading rate, the biogas yield increased from 363 to 448 L/kg COD_{input} and COD removal of the total process increased from 79 to 96%.

3.6. Carbon and nitrogen content

As a matter of fact, carbon constitutes the energy source for the microorganisms and nitrogen serves to enhance microbial growth. If the amount of nitrogen is limiting, microbial populations will remain small and it will take longer to decompose the available carbon [38]. Excess nitrogen, on the other hand, inhibits the anaerobic digestion process. Since it has been found that microorganisms utilize carbon 25–30 times faster than nitrogen, a ratio of 20–30:1 was reported as the optimum carbon/nitrogen ratio for anaerobic digestion [11]. Elsewhere, a nutrient ratio of the elements C:N:P:S (carbon:nitrogen:phosphorous:sulfur) at 600:15:5:3 was reported sufficient for methanization [17]. A low C/N ratio, or too much nitrogen, can cause ammonia to accumulate which would lead to pH values above 8.5 [20]. In order to improve the nutrition and C/N ratios, codigestion of different organic mixtures has been employed. C/N ratio and methane yield reported in some of the studies on codigestion of municipal solid waste and other types of organic waste are summarized in **Table 3**.

Sosnowski et al. [39] investigated anaerobic codigestion of sewage sludge (primary sludge and thickened excess activated sludge) and organic fraction of municipal solid wastes (25% total volume). The results showed that addition of the OMSW to the sewage sludge improved the C/N ratio from 9/1 to 14/1 and increased cumulative biogas produced.

Heo et al. [40] studied anaerobic biodegradability of food waste (FW), waste activated sludge (WAS) in a single-stage anaerobic digester operating at 35°C. They reported that as the FW proportion of the mixture increased from 10 to 90%, C/N ratio of the mixtures improved (from 6 to 15), biodegradation of the mixture increased and the methane production increased.

In another study [41], the mesophilic anaerobic codigestion of food waste and cattle manure was tested. The results indicated that the total methane production was enhanced in codigestion, with an optimum food waste (FM) to cattle manure (CM) ratio of 2:1. The C/N ratio and the higher biodegradation of lipids were the main reasons for the biogas production improvement.

AD process	substrates	Dry weight ratio	C/N	Methane yield (LCH ₄ /gVS)	Refs.
Thermophilic batch	OMSW:Sludge	2:1	14.19	0.14	[39]
Two-stage thermophilic-mesophilic	OMSW:Sludge	2:1	14.19	0.18	[39]
Single-stage stage mesophilic	Food waste:Sludge	1:9	5.97	0.186	[40]
		3:7	6.99	0.215	
		1:1	8.9	0.321	
		7:3	11	0.336	
		9:1	14.7	0.346	
Mesophilic batch	Foodwaste:Cattle manure	2:1	15.8	0.388	[41]
Two-phase	OMSW:Cow manure	10:1	20	0.10	[42]
Mesophilic batch	OMSW:Sludge	1:34	17.68	0.15	[43]
		1:19	20.55	0.20	
Singles stage	Food waste:Sludge	1:2.4	7.1	0.303	[44]
		1:0.9	10.2	0.350	
		1:0.4	11.4	0.400	
Mesophilic	OMSW		14.1	0.382	[45]
	OMSW:Vegetable oil	5:1		0.699	
	OMSW:Animal fat	5:1		0.508	
	OMSW:Cellulose	5:1		0.254	
	OMSW:Protein	5:1		0.288	

Table 3. Results of some studies on codigestion of municipal solid waste and other types of waste.

Nitrogen plays an important role in anaerobic digestion due to the fact that in the form of ammonium, nitrogen contributes to the stabilization of the pH value in the reactor. Nitrogen can cause problems in anaerobic digestion because of its metabolic products (ammonia/ammonium) [46]. Ammonium ion may inhibit the methane producing enzymes directly; while ammonia molecule may diffuse into bacterial cells, which causes intracellular pH change by conversion into ammonium and consequently, inhibition of specific enzyme reactions [47]. The NH₃ fraction of total ammonia nitrogen depends on pH and temperature. For three different operating temperatures, the dissociation balance of ammonia and ammonium with change in pH is plotted in **Figure 2**, showing that at high value of pH rapid conversion of ionized

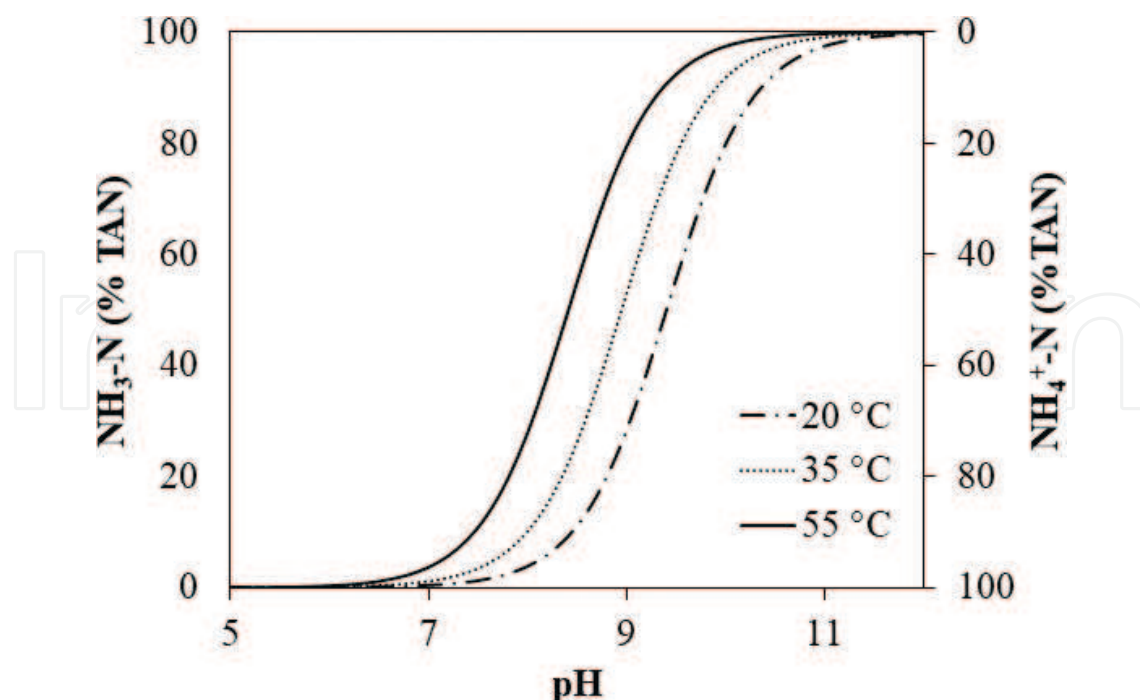


Figure 2. Dissociation balance between ammonia and ammonium at different operating temperatures, adapted from Ref. [46].

ammonia nitrogen (NH_4^+) into free ammonia nitrogen (NH_3) occurs. Increasing amount of NH_3 inhibits the methanogenic microflora and resulted in accumulation of VFAs, which again leads to decrease in pH and thereby declining the concentration of NH_3 . The interaction between NH_3 , VFAs and pH may lead to lower methane yield [46]. Due to the effect of temperature on dissociation of ammonia/ammonium, anaerobic digestion can be more easily inhibited and less stable at thermophilic temperature than at mesophilic temperature [47].

The ammonia-induced inhibition was reported to occur during the anaerobic digestion of organic waste materials rich in proteins. The inhibiting concentrations was found between 30 and 100 mg/L ammonia or 4000 and 6000 mg/L ammonia (at pH value ≤ 7 and temperature $\leq 30^\circ\text{C}$) [46].

Different strategies such as pH and temperature control, acclimation of microflora, and diluting reactor content were suggested in order to prevail over the ammonia inhibition during the anaerobic digestion process [47].

4. Municipal solid waste as the feedstock

Municipal solid waste is the most variable feedstock as the methane yield value depends not only on the sorting method, but also on the location from which the material was sourced and the time of year of collection [11]. Anaerobic digestion became possible because of the introduction of source separation collection of a clean biodegradable fraction, otherwise a presorting step is necessary to remove compounds which are not suitable for anaerobic digestion. However, adding a presorting step significantly increases the treatment costs [8].

Food waste is a significant proportion of organic fraction of residential waste and contains a high moisture content, which can generate leachate and odor. Other contents of OMSW are yard waste and paper products. The characteristics of municipal solid waste used as the feedstock in anaerobic digestion process along with the reactor type, operation condition, VS or COD removal efficiency and methane yield reported by some authors are presented in **Table 4**.

Reactor type	Vol. (L)	T (°C)	Waste characteristics				pH	HRT (d)	OLR gCOD /L.d	VS or COD removal	CH ₄ yield (L/gVS)	Refs.
			TS (g/L)	VS (g/L)	COD (g/L)	TKN (g/L)						
Single stage	2	38	24.7 g/kg	78.6 % TS	21.3	–	6.4–7.5	4	3.85	84% COD _r	0.168	[48]
Two phase	1.5, 5	35	100	88	120	3.8	6.9–7.5	10	1.65	96% COD _r	0.450 (L/gCOD)	[37]
Single stage	4.8	37	184	172	176	3.1	6.5–7.5	19	9.65	64% VS _r	5.3 (L/L _R d)	[49]
		55								65% VS _r	5.6 (L/L _R d)	
Single stage	1	37	29%	77 % TS	–	1.83	–	21	2.36	–	0.382	[45]
Single stage	1	37	1.56%	54.14 % TS	–	3.03 % TS	>6.5	35	–	63% VS _r	0.17	[43]
Two phase	200, 760	55	241 g/kg	203 g/kg	206 g/kg	7.2	4.3, 7.6	6	21 g VS/Ld	–	0.78	[33]
Single phase	3000	55	201.4 g/kg	124.3 g/kg	85.9 g/kg	14 g/kg	7.1–7.7	13.5	9.2 g VS/Ld	–	0.23	[49]
Single phase	4.5	55	0.90 g/g	0.71 g/g	–	–	7.7	15	11.8 g VS/Ld	89% VS _r	1.15 L/L _R d	[27]
Single phase	200	38	67%	75 % TS	1100	11.7	7.2	20	–	43.2% COD _r	0.19	[23]
Single phase	1	35	18.5%	17%	–	3.16%	7.3–7.5	18	8 gVS/Ld	–	0.41	[41]
Two stage	9 dm ³	56	7%	–	–	–	–	8.9	2.76	–	0.3	[39]
	14 dm ³	36						20.9	gVS / dm ³ d			

Table 4. Results of some studies on anaerobic digestion OMSW.

5. Enhancement of anaerobic digestion

In order to enhance biogas production and volatile solids reduction, various pretreatment techniques have been applied. These techniques can be classified as physical pretreatment, chemical pretreatment, biological pretreatment, and thermal pretreatment and combination of these methods such as thermochemical pretreatment.

5.1. Physical pretreatment

Particle size reduction, also known as mechanical pretreatment, is a classic method to increase the efficiency of anaerobic digestion process. This type of treatment improves the biological process by increasing the specific surface available to the microorganisms and leads to more rapid digestion [36]. In addition, the size of the feedstock should not be too large otherwise it would result in the clogging of the digester [5]. Zhang et al. [41] reported that change in the particle size of OMSW did not change the methane yield in the wet anaerobic digestion system. They also reported that the finer materials in the dry digesters caused process failure at high organic loading rates due to the rapid acidification. Advantages of mechanical pretreatment include no odor generation, an easy implementation, better dewaterability of the final anaerobic residue and moderate energy consumption [50]. Nopharatana et al. [23] used hammer-milled MSW with an average particle size of 2 mm and coarsely shredded MSW with an average particle size of 5 cm as feedstock in mesophilic anaerobic digestion. The results showed that reduction of particle size increased the methane yield. However, the author reported that for particle sizes considered, the surface area has no appreciable effect on the kinetics of digestion. Elsewhere [51], methane production rate of mesophilic anaerobic digestion process increased 28% when the mean particle size of food waste was decreased from 0.888 to 0.718 mm by bead milling pretreatment. The authors also reported that excessive size reduction of the substrate decreased methane production due to VFA accumulation.

Rotary drum reactor process was used as a mechanical pretreatment method providing an effective means for separating the organic fraction of municipal solid waste prior to anaerobic digestion [52]. A methane yield of $0.522 \text{ m}^3 \text{ CH}_4/\text{kgVS}$ was achieved from thermophilic anaerobic digestion of municipal solid waste pretreated in a rotary drum reactor for 1 day. However, lower methane yields were reported for the same MSW pretreated with rotary drum for longer retention times; 0.509 and $0.489 \text{ m}^3 \text{ CH}_4/\text{kgVS}$ for 2–3 days retention time was reported, respectively.

Hansen et al. [53] used different pretreatment technologies such as screw press, disc screen and shredder plus magnet prior the anaerobic digestion process. Considering the sorting effect of screw press and disc screen, the screw press was reported to have a larger selective effect than the disc screen by routing more water and easy degradable organic matter and less slowly degradable organic matter. In terms of biogas production, anaerobic digestion of MSW pretreated with the shredder plus magnet yielded a higher amount of methane ($102 \text{ m}^3 \text{ CH}_4/\text{ton waste}$) than those of the two other pretreatment methods ($40\text{--}60 \text{ m}^3 \text{ CH}_4/\text{ton waste}$).

5.2. Chemical pretreatment

Chemical pretreatment methods including acidic pretreatment, alkali pretreatment and ozonation are used to achieve the destruction of the organic compounds and consequently enhance the biogas production and improve the hydrolysis rate [50]. Alkali treatment was reported to be particularly advantageous when using plant materials with high lignin content in anaerobic [11]. Torres et al. [54] investigated the effect of alkali pretreatment on anaerobic digestion of OMSW by lime addition ($\text{Ca}(\text{OH})_2$). The results indicated that the alkaline pretreatment improved anaerobic digestion by increasing the soluble COD (enhancing the COD solubilization). Consequently, the methane yield increase from 0.055 to $0.15 \text{ m}^3 \text{ CH}_4/\text{kgVS}$.

Acid pretreatment was reported to be more desirable for lignocellulose substrates, not only because it breaks down the lignin, but also because the hydrolytic microbes are capable of acclimating to acidic conditions [11]. However, this type of pretreatment has some disadvantages. Strong acidic pretreatment may result in the production of inhibitory by-products such as furfural and hydroxymethylfurfural. Other disadvantages associated with the acid pretreatment include the loss of fermentable sugar due to the increased degradation of complex substrates, high cost of acids and the additional cost for neutralizing the acidic conditions prior to the anaerobic digestion [50].

Ozone is a strong oxidant, decomposes itself into radicals and reacts with organic substrates. As the result, the recalcitrant compounds become more biodegradable and accessible to the anaerobic [50]. Cesaro et al. [55] investigated the effect of ozone pretreatment (at different doses) on mesophilic anaerobic digestion of organic fraction of municipal solid waste. The results indicated that ozonation with a dose of 0.16 gO₃/gTS increased biogas volume by 37%.

Ultrasonic pretreatment is another technique which is commonly used to break down complex polymers in the treatment of sewage sludge. Mechanical shear forces caused by ultrasonic pretreatment as a key factor for sludge disintegration can significantly alter the sludge characteristics in sewage sludge treatment and increase the methane production [11]. Ultrasonic pretreatment of OMSW obtained 16% increase in biogas production of mesophilic anaerobic digestion [55].

5.3. Biological pretreatment

Aerobic and anaerobic methods can be used prior to anaerobic digestion to enhance the biogas production as well as VS reduction. As an anaerobic pretreatment, the first step (hydrolytic-acidogenic) of a two-phase AD process acts as a biological pretreatment method. The advantages of such systems include: (i) increased stability with better pH control; (ii) higher loading rate; (iii) increased specific activity of methanogens resulting in a higher methane yield; (iv) increased VS reduction and (v) high potential for removing pathogens [50]. The addition of microbial strains (such as cellulolytic bacteria and fungi or cell lysate) increases the substrate digestibility [56]. Strains of some bacteria and fungi have also been found to enhance gas production by stimulating the activity of particular enzymes involved in cellulose degradation [36]. Preaeration was found to improve the thermophilic anaerobic digestion of OMSW by reducing the excess easily degradable organic compounds which are the main cause of acidification during the start-up. Charles et al. [57] reported that preaeration of OMSW for 48 hours generated enough biological heat to increase the temperature of bulk OMSW to 60°C which was sufficient self-heating of the bulk OMSW for the start-up of thermophilic anaerobic digestion without the need for an external heat source. Fdez-Güelfo et al. [25] investigated the effect of different biological pretreatments such as using mature compost, sludge and the fungus *Aspergillus awamori* on the anaerobic digestion of OMSW. The results showed that pretreatment with mature compost obtaining the highest increases in DOC (dissolved organic carbon) removal and methane production was the best of all the pretreatments. Sosnowski et al. [39] investigated the anaerobic codigestion of OMSW and sludge in thermophilic batch wise and two-stage quasi-continuous, acidogenic digestion under thermophilic conditions (56.8°C) and mesophilic methane fermentation (36.8°C). They reported

that the separation of acidogenic and methanogenic stages two-stage anaerobic digestion was effective increased the methane yield from 0.14 to 0.18 L CH₄/gVS. Elsewhere [37], phase separation with conventional anaerobic sequencing batch reactors resulted in high process stability, significant biogas productivity and better effluent quality from fruit and vegetable wastes anaerobic digestion.

5.4. Thermal pretreatment

The use of high temperatures can also be used as a pretreatment method. The main effect of thermal pretreatment is the disintegration of cell membranes, thus resulting in solubilization of organic compounds. Thermal pretreatment also leads to pathogen removal, improves dewatering performance and reduces viscosity of the digestate, with subsequent enhancement of digestate handling [50]. Results of a study [58] on the effect of thermal pretreatment of sludge, kitchen waste and fruit/vegetable waste showed that thermal pretreatment at 175°C obtained a doubled methane production rate. While, the thermal pretreatment decreased the methane production by 8 and 12% for kitchen waste and fruit/vegetable waste, respectively. Shahriari et al. [59] used microwave heating at different temperature ranging from 115 to 175°C to enhance anaerobic digestion of OMSW. The biogas production increased 4–7% using 115 and 145°C pretreatment while pretreatment at 175°C decreased the biogas production due to formation of refractory compounds, inhibiting the digestion.

6. Anaerobic digestion for rural communities

Need for fertilizers and soil conditioners in rural areas and also, popularity of biofertilizer compared to chemical products make aerobic/anaerobic composting favorable [60, 61]. Due the aforementioned advantages of anaerobic digestion such as minimizing greenhouse gas emissions, reducing pathogens and sustainable energy production, this method can be considered as the best option for the treatment of organic solid waste in urban as well as rural areas.

In addition to organic fraction of household solid waste generated in rural area, there are other sources including plantation solid waste, residues from animal feed production and livestock manure [62, 63]. This offers the possibility of codigestion which is beneficial for the enhancement of biogas production by adjusting C/N ratio and moisture content mentioned before. Furthermore, different types of “energy crops” (such as maize, grass, and cereals) which have become attractive for biomethanation can be used as cosubstrate in anaerobic digestion and increase the methane yield [63, 64].

Anaerobic digestion in rural communities can be carried out by small-scale or family size biogas plants which utilize animal manure [65, 66]. Rural household biogas was reported to promote agricultural structural adjustment, raise rural incomes, enhance the ecology of rural areas, and improve the quality of both rural life and agricultural products [67]. The other opportunity for anaerobic digestion in rural areas is central anaerobic digestion (CAD)

in which different farms cooperate to feed a single large digestion plant with a variety of cosubstrates. CAD plants have the potential to optimize the biogas production with codigestion and benefit a large community [68].

Small-scale household digesters are mostly built below ground and the produced biogas is mainly used for cooking. They are most commonly used in China and India [66]. Two types of digesters are used for household biogas production: constructed digesters (set up in 1920s) which are made of clay, brick, and concrete and commercial biogas digesters (introduced in 2000) made of glass fiber-reinforced plastics (GRP) [67].

7. Summary

Among the waste treatment technologies, anaerobic digestion can be considered as the best available technique for the treatment of organic fraction of municipal waste treatment technologies. This technology offers benefits for environment, energy, and economy.

This biological process consists of different stages. Through these stages, organic fraction of municipal solid waste is converted to biogas by different pathways in each of which, different species of microorganisms are responsible. Environmental factors such as temperature, moisture content, pH, organic loading rate, and carbon/nitrogen ratio, which influence different stages of the process and consequently the efficiency of the whole system. One of the important factor is C/N ratio of the feedstock which has been suggested to be in the range of 25–30 to obtain the best efficiency. In order to improve the nutrition and C/N ratios, codigestion of OMSW and other organic wastes can be employed.

Availability of different types of waste materials (which can be codigested) in rural areas as well as need for biofertilizer makes anaerobic digestion attractive in these areas. Biogas production can be carried out using household digesters or in a central anaerobic digestion plant which benefits a large community.

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