Opportunity of Biogas Production from Solid Organic Wastes through Anaerobic Digestion

Sagor Kumar Pramanik[1*], *Fatihah Binti* Suja[1], *Biplob Kumar* Pramanik[2] *and Shahrom Bindi Md* Zain[1]

[1]Department of Civil and Structural Engineering, Faculty of Engineering, Universiti Kebangsaan Malaysia; 43600 UKM Bangi Selangor, Malaysia
[2]School of Engineering and Mathematics Sciences, La Trobe University, Bendigo, VIC-3550, Australia

Abstract. Solid organic wastes create potential risks to environmental pollution and human health due to the uncontrolled discharge of huge quantities of hazardous wastes from numerous sources. Now-a-days, anaerobic digestion (AD) is considered as a verified and effective alternative compared to other techniques for treating solid organic waste. The paper reviewed the biological process and parameters involved in the AD along with the factors could enhance the AD process. Hydrolysis is considered as a rate-limiting phase in the complex AD process. The performance and stability of AD process is highly influenced by various operating parameters like temperature, pH, carbon and nitrogen ratio, retention time, and organic loading rate. Different pre-treatment (e.g. mechanical, chemical and biological) could enhance the AD process and the biogas yield. Co-digestion can also be used to provide suitable nutrient balance inside the digester. Challenges of the anaerobic digestion for biogas production are also discussed.

1 Introduction

The quantity of solid organic waste has enhanced enormously almost all regions of the world because of the higher population growth, which creates many environmental problems [1]. Solid organic waste (SOW) can be defined as the unusable and undesired products in the solid condition which is rejected by people. Various types of SOW are generated almost every day like residential, commercial, institutional, municipal, industrial and agricultural waste. Recently worldwide, the production rate of municipal solid waste (MSW) are nearly 1,300 million tonnes each year, and this quantity is estimated to enhance to around 2200 million tonnes each year by 2025 [1]. Figure 1 displayed the MSW generation per capita of numerous countries around the world. Researchers [2] reported several environment and human health problem which is caused by the improper disposal of large quantity of SOW. Urban air pollution occurs due to the unrestrained burning of solid organic waste and inappropriate incineration. Soli, surface and groundwater pollution are caused by untreated leachate. The decomposition of organic solid wastes in landfills is

[*] Corresponding author: sagorpramanik02@gmail.com

responsible for the emission of greenhouse gases. Hence, it is warranted to manage solid waste properly.

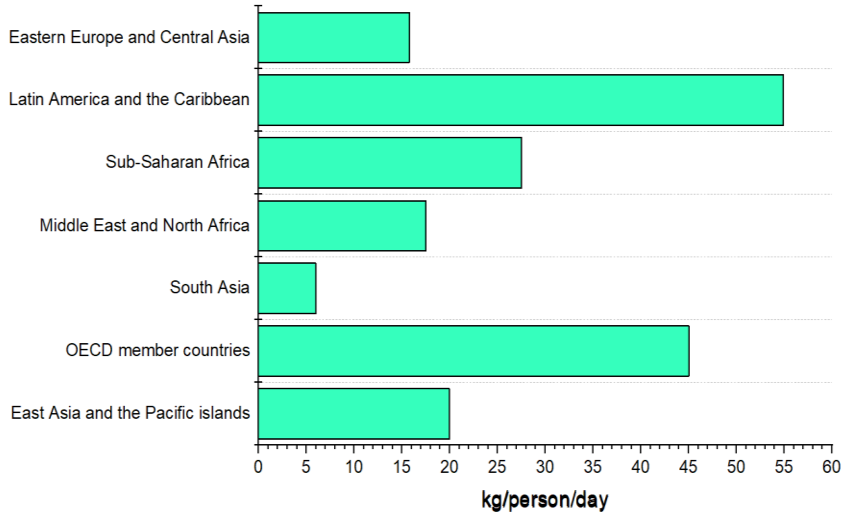

Fig. 1. MSW generation per capita in numerous countries across the world. Source: [1].

Currently, SOW can be treated by using numerous techniques. Among them, anaerobic digestion (AD) considers to be an excellent approach due to its limited environmental impact and high renewable energy recovery. In India and China, the history of the practical application of anaerobic digestion may be found more than 2000 years back which was biodegradation of animal manure [3]. In the year of 1776, Volta discovered that methane is produced from natural anaerobic habitats after that natural biogas was commenced to gather and lighting was the major function. At the end of the 19th century, AD technique was applied for the operation of SOW. The industrialization of AD started at a leper colony in Bombay in 1859 with the first AD system. In England, Biogas was utilized as fuel for street lamps in 1895. Biogas was recuperated at the same time from a sewage treatment plant. The use of AD with the key objective to minimize SOW achieved its fame in the mid of 20th century [3-6].

AD technology offers several benefits as a waste management alternative [7-8]. It helps to reduce not only the greenhouse gas emissions but also the demand for fossil fuels through energy production. It also minimizes soil and water pollution. The residue after AD process can be used as fertilizer. Biogas can be used as a source of heat, electricity, and transportation fuel. However, the drawbacks of AD technology cannot be ignored [7-8]. The possibility of fire and explosions related problem is high in this technique. AD process requires long start-up and retention time. Different corrosive gases and odours might be present in this process. Capital, operation and maintenance costs are relatively high in AD technology.

The objective of this paper is to review the microbiological process and process parameters involved in AD of solid organic waste management. This paper also discusses the opportunities and constraints of adding pre-treatment to augment biogas production and maintain the AD process effectively.

2 Microbiological process involved in AD

Anaerobic digestion is a series of naturally occurring methods without the presence of oxygen, where complex polymers are converted to its soluble chemicals monomers. Biogas can be produced from SOW through four metabolic phases such as hydrolysis, acidogenesis, acetogenesis and methanogenesis. The four phases are displayed in Figure 2 [3, 9, 10, 12].

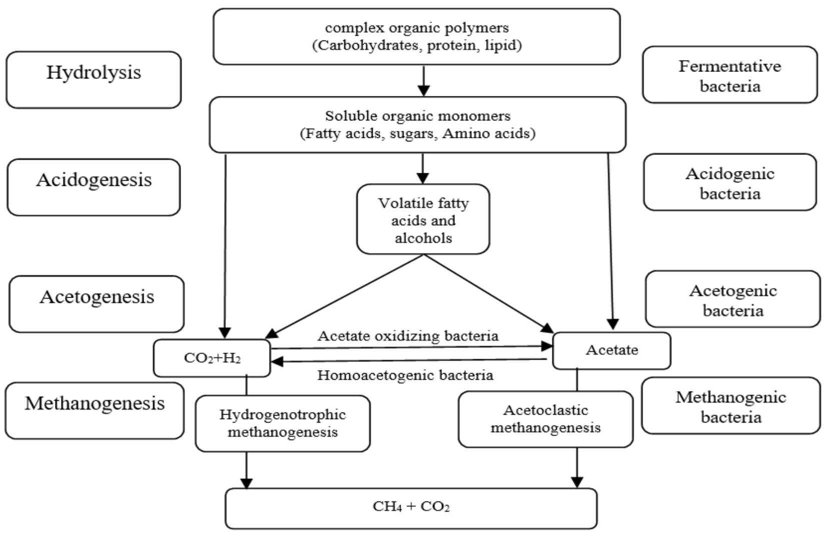

Fig. 2. Primary stages involved in AD process.

2.1 Hydrolysis

Hydrolysis is the first phase in the anaerobic digestion process. Hydrolysis is able to restrict the rate of AD process for high organic content enriched waste (like, food waste, animal manure, and sludge) [7, 10]. In this phase, the complex organic polymers are converted into simple soluble molecules. Proteins, lipids, and carbohydrates are transformed into amino acids, fatty acids, and sugars respectively through this phase. Hydrolysis stage is carried out by different groups of fermentative microorganisms through excreting extracellular enzymes including amylase, cellulose, xylanase, proteolytic, lipage enzymes [4, 9, 11]. The reaction that takes place in hydrolysis is revealed as:

$$2H_2O + C_6H_{10}O_4 \longrightarrow H_2 + C_6H_{12}O_6$$

2.2 Acidogenesis

Acidogenesis is the next phase of AD after hydrolysis which is known as the acid-forming phase. In this process, acidogenic microorganisms convert monomers and dissolved compounds like sugars, amino acids, fatty acids to volatile fatty acids (VFAs) including propionic acid, acetic acid, valeric acid, and butyric acid in company with different gases (such as, CO_2, H_2O, and $H_{2)}$ [9,11]. The growth rate of acidogenesis microorganisms is very fast with a twice time of approximately half an hour [9]. The reaction that takes place in acidogenesis can be written as:

$$C_6H_{12}O_6 \longleftrightarrow 2CH_3CH_2OH + 2CO_2$$
$$C_6H_{12}O_6 + 2H_2 \longleftrightarrow 2CH_3CH_2COOH + 2H_2O$$

2.3 Acetogenesis

Third phase of anaerobic digestion process is acetogenesis that take places place after acidogenesis. During this phase butyric acid, propionic acid, and valeric acid are further degraded by acetogenic bacteria for their development and procedure acetic acid [4, 9]. The enhancement rate of acetogenic microorganisms is gradual with a twice time of one and half to four days [9]. The reaction that takes place in acidogenesis can be written as:

$$CH_3CH_2COOH + 2H_2O \longleftrightarrow CH_3COOH + 3H + CO_2$$

2.4 Methanogenesis

Methanogenesis is the fourth and final phase of AD where methane is produced. In this phase intermediate products of the previous phases are concerted by methanogenic bacteria and produce methane, carbon dioxide and water. Methane can be produced by two pathways: first is the reduction of CO_2 with H_2, and second is CO_2 and CH_4 are produced by acetic acid [4, 7]. Methane generation through acetic acid known as acetoclastic methanogenesis and the methane production through CO_2 reduction known as hydrogenotrophic methanogenesis [9]. The activities of acetoclastic methanogens produce approximately 70% methane, and the growth rate of methanogenic microorganisms is slow with a twice time of two to four days [9]. The reaction that takes place in hydrogenotrophic methanogenesis can be written as:

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$$

The reaction that takes place in acetoclastic methanogens can be written as

$$4CH_3COOH \longrightarrow 4CO_2 + 2H_2$$

3 Parameters involved in AD process

3.1 Temperature

Temperature is the main significant parameters in AD. The rate of AD process particularly hydrolysis and methanogenesis can be determined by temperature. Temperature is generally categorised into three ranges: 10-20°C for psychrophilic, 20-45°C for mesophilic, and 50-65°C for thermophilic [9]. The optimum temperature for mesophilic and thermophilic is 35^0C and 55^0C, respectively [3, 7, 9]. AD process stops when the temperature inside the digester less than 10°C. Therefore, thermophilic and mesophilic temperature ranges are most important in AD process compared to psychrophilic temperature [6]. Past researchers [6] reported that it is significant to keep an optimum functioning temperature in the system, because temperature change affects the AD process. Three kinds of external heat exchangers commonly applied to control the temperature fluctuations in anaerobic digester like spiral exchanger, tubular, and water bath [12]. Because of the suitable range of counter-current flow design and heat transfer coefficients, tubular and spiral exchanger are beneficial compared to water bath.

3.2 pH

The pH of the system is an significant pointer of acid concentration in AD systems and the performance of AD process is influenced by pH [9]. They revealed that bacterial progression can be impeded by the concentration of acid in the digester because methanogenic bacteria are very sensitive to the acid concentration. The ideal pH values for every class of bacteria are not the same. The ideal pH range is 6.5-7.2 and 4.0-8.5 for methanogenic bacteria and fermentative bacteria, respectively [12]. They indicated acetic and propionic acid are formed when pH is 8.0, whereas acetic and butyric acid are the primary product when pH is low. Sodium bicarbonate, ammonium hydroxide, gaseous ammonia, lime, potassium and NaOH can be utilised to maintain the pH level in the digester [6].

3.3 Carbon and nitrogen ration

Carbon and nitrogen ration ratio (C/N) is one of the important factors in the production of biogas and it is represented by the connection among the quantity of carbon and nitrogen present in the SOW [4, 6, 7, 9]. They reported that that bacteria use carbon 20-30 times faster than nitrogen during anaerobic digestion (i.e. C/N ratio between 20 and 30). Methane production can be reduced if the amount of nitrogen is low in the system which results in decrease the number of methanogenic microorganisms. In contrast, the high proportion of nitrogen causes ammonia accumulation which would lead to pH values above 8.5 [4, 6, 7, 9]. Ideal C/N ratio might be possible to maintain in the system by adding different substrates with high and low C/N ratios, like SOW mixed with sludge or manure.

3.4 Retention time

The amount of time that feedstock stays in the digester or it can be defined as time needed for the entire degradation of the SOW is known as retention time (RT) [9]. RT of AD process changes with the type of feedstock composition and the temperature used. RT can be expressed as:

$$RT(d) = \frac{V}{Q}\text{; Where, V= digester volume (m}^3\text{), Q= daily flow(m}^3\text{/d)}$$

There are two types of RT found in AD process like Hydraulic retention time (HRT) and solid retention time (SRT). The liquid sludge remains inside in the AD system is called HRT, whereas SRT is the average time the microorganisms spend in the digester [6, 12]. Shorter HRT not only reduces the size of the digester, but also causes the washout of the gradual increasing bacteria which are essential for the AD system [3]. Zhang et al. [13] observed the effect of reduction in HRT at 38 ^{o}C with a constant OLR of 6.0 gVS $L^{-1}d^{-1}$ on the AD of chicken manure. They reported that the specific biogas production at HRT of 20-45 days (418.7 mL/gVS_{added}) was higher compared to HRT of 5-10 days. HRT of 5-10 days produced an additional washout of bacteria, which reduced by two and half times compared to HRT of 20-52 days. Some researchers [14] reported longer SRT leading to the low methane yield, because of the impaired acidification and increased the discharge of recalcitrant substances. They found that methane production decreased with the increase in SRT.

3.5 Organic loading rate

The feeding quantity of organic material (expressed as VS or COD) which can be utilized by a particular volume of anaerobic digester per unit time is called Organic loading rate (OLR) [3, 9]. It can be displayed as:

$$\text{OLR}(\text{kg/d/m}^3) = \frac{Q \times S}{V}$$

where, Q(kg/d) =daily flow, S (%)=VS concentration, V(m^3) =digester volume

Biogas production is highly affected by OLR, specifically during the digestion takes place in continuous flow mode. Some researchers [15] studied the impact of OLR during AD on recycled paper mill effluent and indicated the digester performance changes with the change in OLRs. System failure and destabilization of the system can be occurred due to the higher OLRs (3.0-2.0 gmCOD $L^{-1}d^{-1}$), which seriously disturbs the digester operation through organic removal.
Reactor displayed a stable function with maximum specific methane production (8.47 L CH_4/day), COD removal (97.69%), and alkalinity (419.2) at OLR of 1.33 gm COD/L/day. However, OLR can be changed due to the change in different parameters like operating condition and anaerobic digester configurations.

4. Parameter associated with the improvement of AD process

4.1 Co-digestion

Co-digestion is one of the significant technique which can be used to improve the methane yield from little production or hard to digest substances. Co-digestion is defined as two or more types of organic waste are mixed and treated simultaneously [16]. There are several benefits of co-digestion like increased the equity of nutrients, synergistic effects of microbes, dilution of harmful substances, enhanced biogas production, developed process permanency and enhanced load of biodegradable substrates [16]. However, there are few disadvantages presence in co-digestion, because of slurry carriage charges and the difficulties rising from the accordance of various strategies of the waste producers [17].

Numerous categories of wastes sources like sludge, organic industrial waste, and animal manure can be utilized as co-substrate for anaerobic co-digestion (Acod) of SOW [3]. Co-digestion of agricultural wastes with animal manures plays significant role to control the carbon and ratio of substrate for anaerobic digestion and this process offers not only to increase biogas production but also can produce fertilizer from its final residue [18]. A summary of Acod practices with different substrate according to the complete operation conditions and methane production is showed in Table 1. Some researchers [19] studied the impact of AD of pig manure (PM) only and co-digestion of PM with grass silage (GS) and revealed that co-digestion of PM with GS delivered some benefits than mono-digestion of PM such as a higher methane content (62%), a higher specific methane yield (251 ml CH_4/g VS_{added}), higher VS (53.9%) and soluble COD (87.8%) removals compared to lower methane content (58%), lower specific methane yield (154 ml CH_4/g VS_{added}), lower VS (41.4%) and soluble COD (81.4%) removals. They observed that co-digestion of PM with GS offered not only minimize free ammonia inhibition (158.3 mg/l) but balance the suitable C/N ratio in the feedstock mixture compared to mono digestion of PM alone.

Table 1. Anaerobic co-digestion studies with different substrates for biogas production.

Reactor Type	Feedstock	Mixing ratio	Temperature (°C)	C/N	OLR g VS/L/d	CH_4 yield mL/g VS	Reference
250 mL conical Flasks (batch)	Chicken manure + apple pulp	2:1	37	18.5	4.8	340	[20]
5 L CSTR (semi Continuous)	Potato waste + cabbage waste	1:1 (VS basis)	37 ± 1	20.5	5	360	[21]
6 L CSTR (semi Continuous)	Cow manure + Salix	53:47	37	23-39	2.6-3.1	235	[22]
SSTR (semi continuous)	Sugar beet byproduct + Pig manure	18.5	37 ± 0.25	18.5	7.4	362.2	[23]
1 L glass batch reactors	pig manure + corn stover and cucumber residues	5:2:3 (w/w)	35	13-16	-	305.4	[24]
16 L continuously stirred digester	chicken manure + poppy straw	4.3:1 (w/w)	36 ± 0.5	15	3.56	360	[25]
2 L glass batch reactors	OFMSW + FVW	1:3 (VS basis)	35	34.7	-	396.6	[26]
1 L glass batch reactors	pig manure + corn stover + cucumber residues	5:2:3 (w/w)	35	14.5	-	305.4	[27]
5 L laboratory scale CSTR	Cattle manure + Whole stillage	15:85	37	-	2.8	310	[28]
1 L batch bottles	Cattle manure + Palm pressed fiber	1 :3	37 ± 1	-	30 g VS/L	346.2	[29]

4.2 Pre-treatment

Hydrolysis rate can be improved through suitable pre-treatment like breaks down the complex structure of organic compounds into simpler molecules, which enhance the biogas production [3]. Pre-treatment techniques have several benefits in AD of organic solid waste. It increases not only the surface properties for higher bacterial interactions but also the hydrolysis rate of the organic solid waste. It helps to perform AD quicker and decrease the harmful composites that may disturb the process. It can enhance the biogas yield and the accessibility of rarely reachable composites. It can assists to process the substrates before using in the AD otherwise organic carbon losses can be occurred through storage/transport [8, 30]. There is numerous pre-treatment technique available to improve the performance of AD process such as mechanical, chemical, and biological pre-treatment.

4.2.1. Mechanical pre-treatment

Mechanical pre-treatment is needed to enhance the definite surface zone, to change the substrate formation, and to minimize cellulose crystallinity. It helps to improve the hydrolysis rate of the substrate. Various kinds of mechanical processes like milling or grinding machines (e.g. ball, two-roll, hammer, colloid, knife, extruder, and vibro mill etc.) can be utilized to improve the biodegradability of biomass or enzymatic hydrolysis [31, 32, 33]. [34] investigated the effects of mechanical pre-treatment with a Hollander beater. To improve the biogas production, it is important not only to decrease the biomass particle size but to enhance the specific surface area of the feedstock. The methane production improved with the reduction of feedstock/inoculum ratio for all beating time. The methane production of 254 ml/g VS was obtained for a feedstock/inoculum ratio of 0.3 and 60 min beating pre-treatment, which was 21% higher compared to unbeaten waste paper.

4.2.2. Chemical pre-treatment

Chemical pre-treatment is one of the most common method which helps to enhance the biogas production. Alkalis and acids are usually utilized to solubilize the lignin and hemicellulose existed in the substrate and preparing them more available for microorganisms, although both lignin and hemicellulose have a complex structure [33]. [35] also reported that alkaline pre-treatment was more useful for the elimination of lignin, however, acid pre-treatment is known to be efficient to solubilize hemicellulose. Alkalis pre-treatment can be performed by sodium, ammonium, calcium and potassium hydroxides [31, 33, 35]. On the contrary, dilute acid or concentrated acid like H_2SO_4, HCl, HNO_3, and acetic acid can be used to perform acid pre-treatment, among them sulphuric acid is the most frequently used [31, 33, 35]. [36] studied the improvement of solid-state AD of corn stover through alkaline pre-treatment. The maximum biogas production of 372.4 L/kg VS was achieved with 5% NaOH pre-treated corn stover, which was 37.0% higher than that of the without pre-treatment. Hydrolysis might not be a rate limiting stage at the time of digestion process, as 5% NaOH pre-treatment removed 31.4% lignin. Lower Biogas production was observed because of higher NaOH concentration (7.5%). This is likely due to the formation of extreme acidic condition which was caused by the accumulation of VFA inhibited the methanogenic microorganisms.

4.2.3. Biological pre-treatment

Biological pre-treatment in different substrate is greatly influenced by three functions such as microorganisms, enzymatic activity, and fungi [35]. Free and easily obtainable sugars can be used by bacteria which is the major carbon source during the biological pre-treatment [30]. Biological pre-treatment needs longer retention time because it is generally slow technique. Biological pre-treatment processes offer several advantages compared to chemical and mechanical pre-treatment like low capital cost, no need to use chemicals, consume minor energy [18, 33]. Hydrolysis rate of maximum biological components is low compared to other pre-treatment process which is the primary disadvantage of biological pre-treatment [32]. The influence of biological pre-treatment on corn straw for improving biogas production was carried out by [37] and reported that methane production of 239 mL_NCH_4 /g/TS was observed at 20 days of pre-treatment, which was 75.57% more than that untreated corn straw. They indicated that the total LCH contents (lignin, cellulose, and hemicellulose) decreased by 5.44-25.10% after the biological pre-treatment. This is due to the synergistic effect of complex bacterial agents.

5 Future research perspectives and recommendation

Anaerobic digestion is an extensively familiar and well developed technology. Rule of thumb is commonly used for evaluating the design and performance of reactor process due to the lack of proper instruments and it is essential to optimize the existing technology [38]. For the development and optimization of anaerobic digestion systems further research is required in several fields like current AD models require to be extended through the addition of bacterial group data; dynamic behaviour of the bacterial groups needs to be identified during AD; further improvement and optimization of pre-treatment techniques are essential to increase the degradability of the substrate; and the advancement and purification of achieved biogas are necessary for more novel applications like vehicle fuel and fuel cells [38]. Nutrient imbalance problem can be avoided by co-digestion of SOW with other waste (like manure, sludge, and agricultural) which offers more appropriate C/N ratio and metal elements concentration for AD [10]. Many perspectives, such as buffering capacity, biogas production rate, and microbiological stability must be controlled, and attempts are necessary to minimize the inhibitory impacts of VFAs, ammonia, hydrogens, and sulphides [39]. Further research is necessary to improve the connections in between biogas production from non-fibre and fibre materials, and nanotechnology could be applied to observe and control the process through chips and sensory system [39].

6 Conclusion

AD has been considered as one of the greatest energy-efficient and environmentally favourable technology for renewable energy production which is able to treat different types of solid organic waste. AD is a complex process where complex organic polymers break down to monomer. The benefits and drawbacks of AD technology have been discussed. There are several parameters that affect the AD process and these parameters need to be optimized for better performance and stability of the AD process. Bacterial growth highly depends on these parameters which affects the biogas production. Co-digestion and pre-treatment techniques basically used to enhance the biogas production rate. The effect of Co-digestion and pre-treatment techniques on different solid organic wastes and how biogas production changes due to the application of these techniques have broadly illustrated in this review. AD of solid organic waste is excellent for the transformation of waste to valuable biogas, and still further research need to be focused on co-digestion and pre-treatment to increase the quantity of methane content in biogas.

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