

FACTORS AFFECTING PRODUCTION OF BIOGAS FROM ORGANIC SOLID WASTE VIA ANAEROBIC DIGESTION PROCESS: A REVIEW

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ABSTRACT

Solid waste can be the source of renewable energy for local use provided that it is subjected to an effective digestion process to produce biogas by utilizing the organic fraction of the solid waste. In Malaysia, rapid development of various industries has generated a significant amount of solid waste which mainly are composed of organic matter. Environmental issues start to arise when these wastes are not properly disposed and manage. Researchers have focused on utilizing these solid waste as feedstock to the anaerobic digester in order to curb with this problem. However, utilizing solid waste into anaerobic digestion is not as easy as it may seem. There are several factors and parameters that need to be taken into account such as but not limited to temperature, pH, organic loading rate (OLR) and retention time. In this review paper, the parameters known to affect the biogas yield from organic solid waste were presented.

Keywords: Biogas; Organic solid waste; anaerobic digestion

INTRODUCTION

Biogas is a combustible mix of gases produced by Anaerobic Digester (AD) or fermentation of biodegradable materials such as but not limited to biomass, manure or sewage, municipal waste, green waste and energy crop [1]. It is stated by Velmurugan *et. al.*, [2] that AD is the biological degradation of a complex microbial ecosystem of organic and occasionally inorganic substrates in the absence of an organic source meanwhile in accordance to Teodorita *et. al.*, [3], AD is a microbiological process of decomposition of organic matter, in which oxygen is absent, a norm to many natural environments and widely applied at present to produce biogas in airproof reactor tanks, commonly named as digester. Biogas contains methane (CH₄) and carbon dioxide (CO₂) with traces of hydrogen sulphide (H₂S) and water vapour.

Anaerobic digestion of these organic waste materials, mainly consists of four main stages which interdependence on one another in such a way the product from one stage is a precursor for the next stages. Each stage involves different types of microorganisms [4]. The first process called Hydrolysis in which the particulate organic materials such as cellulose, hemi-cellulose, pectin, and lignin undergoing hydrolysis by extra cellular enzymes to convert polymers into monomers. Then, the soluble organic matter and the products of hydrolysis are converted into organic acids, alcohols, hydrogen and carbon dioxide by the bacteria of acidogenic. Thirdly, the acetogenic bacteria convert the acidogen products into acetic acid, hydrogen and carbon dioxide. Finally, methanogenic bacteria are accountable for methane production from the aforementioned substances as well as directly from other substrates of which formic acid and methanol are the most important. [4].

In order to ensure the maximum biogas yield, special attention need to be given to certain factors such as, the nature of the substrate, temperature, pH, loading rate, retention time and alkalinity. These factors are known to directly affect the gas production rate and the digestion process efficacy. Besides that, organic material added as inoculums in the fermentative organic substrate [5] and the size of inoculums affected the rate of gas generation [6]. However, it is reported that the yield of biogas is highly dependent on the temperature, OLR, pH and Carbon to Nitrogen (C:N) ratio [7]. According to Liu *et. al.*, [8], a certain amount of inoculums should be added together with the substrate to provide the required microorganisms to start the reactions in a normal start-up of a batch digester. An experiment conducted by Singh *et. al.*, [9] used inoculums that were collected from four different sources such as tannery waste treatment plant, municipal waste treatment, distilleries and sludge of a field scale biogas reactor was added to the cow dung slurry to develop inoculums in a batch reactor. Thus, this review aims to point out some major factors known to directly affect the process efficiency and gas production rate as well as reviewing the result from previous researchers that related to this field of work. The primary substrates used for biogas production is agricultural sector, which accounts as the largest substrate potential to be used as a feedstock in AD [10]. The substrates (feedstock) consist of fresh or ensiled plant material, animal excrements such as manure and slurry, agricultural residues and by-products, wastes from food production industry and the organic fraction of municipal waste such as organic household waste [11].

Over the last few years, the issue of efficient disposal and management of organic solid wastes has become more rigorous due to rapidly increasing population, intensive agriculture and industrialization and rapid urbanization [12]. In Malaysia, solid waste often divided into a number of categories such as organic wastes, paper, plastics and glass. Organic wastes dominated the list by 44.5% in accordance with Noor [13] as illustrated in Fig. 1.

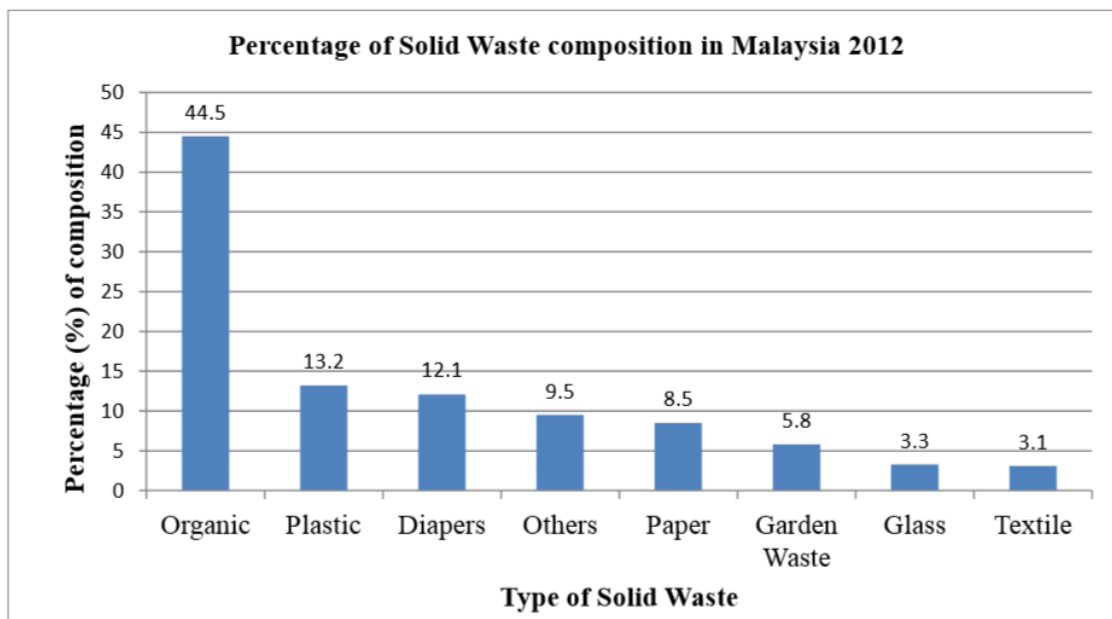


Figure 1: Solid waste composition in Malaysia 2012 [13]

Factor affecting efficiency and biogas yield in anaerobic digestion of organic solid waste.

Temperature

Temperature is one of the critical parameters that often slip from researcher view. Failure to properly control the reaction temperature may lead to decrease in process efficiency and indirectly affect the rate of reaction, the solubility of heavy metals and carbon dioxide as well as buffering. Theoretically, the rate of reaction will increase with the increase of the ambient temperature. Thus, the production of biogas also will increase. There were three temperature ranges in the anaerobic digestion which are: 1) Psychrophilic : 0-15°C, 2) Mesophilic : 15-45 °C, 3) Thermophilic : 45-65 °C [14]. Selection of temperature ranges is made after considering the nature of inoculums to be used. Most conventional digester employed mesophilic temperatures of approximately 35°C in the system. However, thermophilic temperatures ranging from 55°C to 60°C are worth considering as it will gives off more biogas over shorter time [15]. Many literatures highlight the advantages of thermophilic system over mesophilic system. In terms of reaction rates, thermophilic temperatures offer faster reaction rate over shorter time and hence, higher gas yield.

Based on the result obtained by Gou *et. al.*, [16], the performance of co-digestion of waste activated sludge and food waste was better at higher temperature. They highlighted that the gas production rate of the system with thermophilic (55°C) temperature was at 1.6 and 1.3 times higher than the one under mesophilic temperature - 35°C and 45°C respectively.

Furthermore, thermophilic system is undoubtedly able to provide a better sterilization for the end-digestate product as it provides higher degree of destruction to pathogens and weed seeds [17]. In addition to that, thermophilic temperatures are able to keep *Salmonella* and *Mycobacterium paratuberculosis* inactive specifically within 24 h compared to mesophilic temperatures which requires at least few weeks or a month to have the same microorganisms idle [18].

However, some research revealed that the mesophilic temperature range does work nearly as efficient as the thermophilic temperature but only on specific substrate. In a study conducted by Arikan *et. al.*, in treating dairy manure, lower temperature as in 22 and 28 °C does gives off methane about 70% and 87% respectively of the value recorded in a system operated at 35°C. [19].

Other than that, the anaerobic digestion of Buffalo manure under thermophilic (55°C) and mesophilic (37°C) temperature showed that methane concentration was higher in the system with higher temperature [20]. Additionally, the thermophilic reactor can still runs smoothly at pH reached 8.0 whereas the mesophilic reactor gives off biogas with highest methane concentration (65%) at pH 7.0 and any increase in pH decreases the biogas quality.

The solubilization rate was measured based on suspended solid (SS) removal and it has been found that at temperature between 25°C and 45 °C the solubilization rate is considerably high which is between 62.2% and 72.7%. This suggests that microorganism activity was high under these temperature ranges and contributed to the high solubilization rate. In addition, the sudden change from mesophilic to thermophilic or vice versa, and temperature fluctuation imposed to the system will directly affect the process. The biogas production will decline until they have successfully restored the necessary populations for optimum process [21]. Furthermore, even small temperatures changes in the digestion process such as from 35 °C to 30°C or vice versa could significantly reduces the biogas production rate [22].

However, thermophilic system suffers from certain drawbacks that also need to be taken into account. High biogas yield in thermophilic systems has to be balanced against high energy consumption in order to keep the digester at thermophilic temperature [21]. This situation in turn will increased the cost of operation for the anaerobic digester as well as the overall maintenance cost. One has to bear in mind that different methanogenic bacteria posses its own optimal temperature as illustrated in Table 2. Also need to be reminded that not all four process in anaerobic digestion having the same optimal temperature for optimum process. For instance, methanogenesis may work optimally at temperature 37°C but not for hydrolysis, acidogenesis and acetogenesis that has its own desired temperature. For that reason, a multi-stage anaerobic digester might be the interesting alternatives. However, this will not be discussed further in this review.

Table 2: Optimal growth temperature for some methanogenic bacteria [23]

Temperature Range	Genus	Optimal Temperature (°C)
Mesophilic	<i>Methanobacterium</i>	37-45
	<i>Methanobrevibacter</i>	37-40
	<i>Methanocorpusculum</i>	30-40
	<i>Methanogenium</i>	35-40
	<i>Methanoplanus</i>	20-40
	<i>Methanospirillum</i>	30-40
	<i>Methanococcoides</i>	30-35
	<i>Methanohalophilus</i>	35-45
Thermophilic	<i>Methanohalobium</i>	50-55
	<i>Methanosarcina</i>	50-55

Organic loading rate (OLR)

In the AD process, the organic matter to be degraded often refers as Volatile Solid (VS). It is the important parameter that need to be given extra attention before conducting the digestion process. VS represents the amount of degradable solid materials that can be digested [24]. Some researcher measure OLR by amount of VS in the feed while others may refer to the amount of Chemical Oxygen Demand (COD) of the substrate used. OLR directly affects the biogas yield and the overall process efficiency [25]. The amount of organic matter in the process need to be controlled throughout the process such that to avoid organic material overload that may create shock load in the process. Organic matter were first hydrolyzed by rapidly growing microorganism into Volatile Fatty acid (VFA), which are then oxidized by slow growing microorganism [26]. Although VFA is known as the important intermediate compound in the metabolic pathway of methane production, it is important to control the amount of VS fed into the digester such that to prevent VFA accumulation. Overloading of VS may induce the growth of rapidly growing acidifying microorganism at an exponential rate [24]. These acidifying microorganisms are prevailing on the methanogens which may lead to volatile fatty acid accumulation. This situation resulted from the overloading of VS has previously been reported to inhibit bacterial growth and methane formation process [27] and reduces the pH and causes microbial stress [26]. Essentially, the optimum OLR is highly depending on the type of substrate used and the size of the digester used. There are countless amounts of literature available regarding the effect of OLR on the biogas yield as per provided by the past researcher in this area. Table 1 below summarizes the findings on the effect of OLR on the biogas yield.

Table 1: Effect of OLR on biogas yield

Type of Substrate	OLR	Biogas Yield	Source
Municipal solid waste	2.9 kg VS / m ³ .d	0.36 m ³ / kg VS	[1]
Vegetables waste	2.25 kg VS / m ³ .d	0.59 m ³ / k g VS	[2]
Vegetable waste	1.4 kg VS / m ³ .d	33.3 L/d	[24]
	2.0 kg VS / m ³ .d	27.6 L/d	
	2.75 kg VS / m ³ .d	21.3 L/d	
Cow dung	1.7 kg VS / L.d	0.15 L/ kg VS	[27]
Food waste	1.5 g VS /L.d	371 mL/ g VS	[28]
Municipal solid waste	15.2 g/L COD	168.4 mL /g VS	[29]

Based on Table 1, it shows that previous researchers have done an extensive study on the effect of OLR on the biogas yield.

Ilabaya *et. al.*, investigated the biogas production from municipal solid waste and domestic sewage by using the anaerobic digestion process in batch reactor at room temperature. In order to determine the optimum OLR for maximum process efficiency, different OLR of 0.2, 1.0, 2.3, 2.9, 3.5 and 4.3 kg VS / m³.d was employed to the same system. Later, it was found that the optimum OLR is at 2.9 kg VS / m³.d with maximum biogas production of 0.36 m³ / kg VS [1].

On the other hand, a research conducted on anaerobic digestion of mixed vegetables waste (Banana stem, Cabbage and Ladies finger) using fed batch reactor at mesophilic conditions. This system operated with OLR of 2.25 kg VS / m³.d and at the end of the experiment, the biogas yield obtained was 0.59 m³ / kg VS added [2].

A fed-batch pilot scale anaerobic digester treating vegetable waste was studied by Azadeh & Jalal, [24] at mesophilic condition to examine the effect of the change in the OLR on the efficiency of the biogas production. The result showed a maximum amount of biogas production of 33.3 L / d at OLR of 1.4 kg VS / m³.d and this OLR is deduced as the optimum OLR for the process as the reactor showed stable performance with the biogas collected from this operation showed the highest methane percentage (65%).

While in 2012, a group of researchers studied the feasibility of cow dung to be incorporated into anaerobic digestion by using a laboratory scale 10 L bioreactor working in batch and semi- continuous mode at 53°C. The OLR of up to 1.7 kg VS/ L.d was reported feasible for the process as the highest biogas yield recorded was 0.15 L / kg VS added corresponding to the aforementioned OLR [27].

The effect of OLR on AD of food waste has been studied by many researchers. One of the result revealed that under mesophilic condition, the optimal OLR was 1.5 g VS / L. d in which the methane yield of 371 mL/ g VS added [28].

Unlike other researcher that quantify the OLR based on VS, Dhar *et. al.*, measure the OLR based on COD. The efficiency of the system were quantified based on the effective removal of COD. Three different digesters with OLR of 5.1, 10.4 and 15.2 g/L COD were used. The result showed the methane yield were the highest in digester with OLR 15.2 g/L COD where the value recorded is 168.4 mL/g VS.

Hydraulic retention time (HRT)

Retention time can be defined as the theoretical time of the particle or volume of liquid added to a digester and remained in it [30]. Similarly, retention time also defined as the length of time that volatile solid (VS) remain in the reactor [31]. Hydraulic retention time (HRT) refers to the average range that the complex compound retained in the digesters, in contact with the biomass and decomposes into metabolic products such as monosacharides, polysacharides and amino acids [31]. Theoretically, long retention times will lead to low efficiency of the process. In anaerobic conditions, the decomposition of organic substances is slow and this will take some time for digestion to complete. Types of microbial and its temperature range are one of the reasons that will affect the retention time. Thermophilic temperature system in anaerobic digestion will have shorter retention time comparable to mesophilic temperature system. At high temperature, the particles kinetics rate increases so is the reaction rate. Thus, conversion process takes place faster and lessen the retention time. At the same time, shorter retention time subjected the active microbial colony to washout while longer retention time means larger digester volume and increase the operational cost [32]. It is almost critical to determine the suitable HRT for anaerobic digestion process as to ensure a stable condition inside digester. A condition where the number of removed microorganism with the digestate should not be greater than the number those produced by duplication [31].

In designing cost effective digester, HRT is the key factors need to be considered alongside with other parameters mentioned above [31]. Most industries that treating their own waste utilizing conventional ponding system with relatively high retention time about 30 - 45 days in order to ensure the complete digestion of the influent [33]. However, conventional ponding system is not feasible to be applied in a plant that producing biogas for power generation. According to Ahmad *et. al.*, [34], the process retention time can be shortenED to 4 days by employing a high-rate anaerobic digester such as up-flow sludge blanket rector (UASBR). This type of reactor offers several advantages to the process such as low capital cost, high efficiencies and it is not likely to suffer from washout [35]. For digestion of organic wastes, the HRT usually varies from 30 - 50 days depending on the chosen temperature regime. However, for a country with A cooler climate, the process can take up to 100 days [32].

An experiment to study the effect of different HRT on the biogas yield was conducted

by using fruit and vegetable waste as the sole substrate. Researchers vary the HRT to 12, 15 and 20 days as well as varying the feed concentration. For each feed concentration, the highest biogas yield recorded at 0.707 L / g VS added was achieved by the digester operating with HRT of 20 days and feed concentration of 6% [36]

Based on the same fundamentals, the effect of HRT on biogas production of poultry droppings and cassava peels under mesophilic condition was studied by Ezekoye et. al., in 2011 [37]. He deduced that the biogas production increases with the increases of retention time. Cumulative biogas production at the highest during 5 to 15 days of digestion. For the next 20 - 30 days, the rate remains constant and starts declining afterwards.

The co-digestion of frozen seafood wastewater with decanter cake in a CSTR aim to study the influence of retention time of biogas production. The result shows that the biogas production rate was at maximum at 20th day with 1.86 L / d of biogas [38]. From the same research, the Biomethane percentage in biogas generated during 10th day is slightly lower when compared to 20th and 30th day. At the 35th day of digestion, the reaction keeps dormant probably due to cell ceased [38].

Carbon to Nitrogen ratio (C:N)

Organic solid wastes mostly comprised of protein, starch and fat. In anaerobic conditions, nitrogen is an essential nutrient for microorganisms to grow and multiply in number. It is very important to maintain nitrogen concentration throughout the process so that it will not cause disturbance to the process. During hydrolysis, microorganisms responsible for first step biological degradation will deaminate the nitrogenous compound to produce ammonia as the by- product. At this point, improper control of hydrolysis rate will cause ammonia accumulation in the digester which may lead to a condition called ammonia toxicity or ammonia inhibition. Some study stated that ammonia inhibition occurs in the range of 1500 - 3000 mg L⁻¹ of Total Ammonical Nitrogen (TAN) and the pH value over 7.4 [39]. While other literature stated that ammonia with concentrations over 4 g NH₄⁺-N L⁻¹ are known to inhibit the methanogenesis process [40]. Also stated that the free ammonia has been identified to be the main components causing methanogenesis inhibition.

Back in 1986, Sprott *et. al.*, claimed that ammonia may affect methanogenesis by two mechanisms; 1) direct inhibition of methane synthesizing enzyme by ammonium ion, and 2) diffusion of ammonia molecules into the cell wall of microorganism causing change in pH. The second mechanism known to give greater effect to methanogenesis process. It is hypothesized that ammonia molecules are able to diffuse passively into the cell wall of methanogens where some of them will convert to ammonium ion (NH₄⁺). This situation occurred when there are differences in intracellular pH and forces ammonia molecules to absorb proton (H⁺) in the process [41]. Presence of excess ammonia subsequently will cause the digester pH to rise and this situation, if not corrected may lead to digester failure and low product formation.

Based on the study using municipal solid waste (MSW) as substrate in order to

determine the influence of nitrogen in the anaerobic digestion process, the C/N ratio was adjusted to 20, 30, 43.5, 50 and 60. The digester with C/N of 43.5 which is the original ratios of the MSW was observed to produce the highest amount of biogas yield with a value of 1.598 L / kg MSW [42]. Zeeshan *et. al.*, conducted a study focusing on the effect of the C/N ratio in a thermophilic dry anaerobic digester using degradable substrate such as food waste. Two C/N ratio were used which are 27 and 32. At the end of the investigation, the specific methane yield is 327 L / kg VS and 203 L / kg VS respectively [43].

Meanwhile, the digestion of animal excrete with different C/N ratios gives off slightly different result. For digestion with the lowest C/N ratio of 13, the biogas yield was 0.50 m³/ kg VS. The highest C/N ratio used is 24 and the corresponding biogas yield is 0.70 m³/ kg VS [44].

It has been said that the most optimal C/N ratios in a methane generation process were in the range of 20 - 30 [45]. It is also has been stated that the microorganism consumed carbon about 25 to 30 times faster than nitrogen because they uses carbon as the source of energy while nitrogen used for building cell structure [46]. Too high C/N ratios causes nitrogen will be used up first, leaving carbon accumulation which will make the process to slow down. On the other hand, low C/N ratio indicating the amount of nitrogen in the digester is high and carbon is low.

Very soon, carbon is scarce and fermentation will stop leaving nitrogen unutilized. This condition may induce the formation of toxic gas which is ammonia gas [46].

CONCLUSION

It is almost impossible to evaluate the performance of anaerobic digester by one or two parameters only. Each parameter is interconnected with each other. Higher temperature regime undoubtedly increases the reaction rate but requires high operational cost as compared to mesophilic system. As for OLR, determining the optimum OLR requires a lot of trial and error work. Optimum OLR is highly dependent on the type of substrate used in the reaction. As the conventional ponding system requires longer HRT, the development of high rate anaerobic digester reactor aims to lessen the HRT and increases the process efficiency. This parameter also closely related to the type of substrate used in the process. The optimum C:N ratio as suggested by previous researchers are between 20 - 30 and this has been proven effective in countless previous studies. However, one must consider all of the above factors and other factor such as pH, digester configuration and others as stated by past researchers in order to operate a digester with maximum biogas production For instance, rising the digester temperature facilitates in faster reaction and lower retention time. However, this process may suffer from microbial washouts. Operating an anaerobic digester requires a continuous modification process based on current requirements.

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