Chemica
Volume 3, Nomor 1, Juni 2016, 17-23
ISSN: 2355-8776

Solid-State Anaerobic Digestion of Rice Straw for Biogas Production : A Review

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Abstract

Biogas is one of the alternative fuels to decrease the consumption of fossil fuel. Raw materials for biogas production can be derived from a wide range of organic wastes including lignocellulosic biomass such as rice straw. Lignocellulosic biomass is abundant and renewable. Biogas production can be processed by solid-state anaerobic digestion. Many factors should be considered on SS-AD, including pretreatment of raw material. Therefore, the purpose of this paper is to provide existing knowledge in SS-AD, factors influencing SS-AD, pretreatment of lignocellulosic biomass and identify the preceding researches on the SS-AD.

Keywords: biogas, solid-state anerobic digestion, lignocellulose, rice straw

Introduction

The increase of energy consumption equals to the rise of demand in energy needs, especially for fossil fuels [1]. The amount of oil consumption in the world according to the BP Statical Review of World Energy is 13147.3 million tones in 2015 [2]. On the contrary, global fuel demand increases by around 0.14 million tones per day to attain 15.68 million tones per day in 2035 [3]. In addition, in 2040 the amount of people predicted will reach 9-10 billion that need energy for life [4**]**. Therefore, the renewable energy is needed to overcome the energy crisis. One of the renewable energy is biogas. Biogas produced by renewable sources. Production of biogas has been started in the previous decades, for instance, in India that have produced biogas since 1950s [5]. The demand of biogas also has a positive rank in the global market [6].

Biogas is a suitable alternative energy in the future, which can reduce environmental impacts, e.g. greenhouse effect, carbon dioxide emission and diminish the dependence on fossil fuel. Biogas can be used as a vehicle fuel, electricity and heat generation [7]. Biogas is a non-polluting gas, smokeless, and blue flame [8]. Biogas consist of 60% methane, 40% carbon dioxide, hydrogen sulfide, and trace elements [9]. A variety of organic wastes such as animal dungs, sewage sludge, food wastes, industrial waste water, municipal wastes, including lignocellulosic biomass can be used as raw material of biogas [10,11,12].The plentiful availability of lignocelluloses in the nature makes lignocelluloses gain much interest as feedstock for producing biogas [13]. One of the lignocellulosic biomass, which can be used as a biogas feedstock is rice straw. According to the statistical data, production of rice in Indonesia attained 75.4 million tones in 2015. It was the biggest amount compared with the other agricultural production such as corn, cassava, and peanut [14]. Rice straw consists of 33.4% cellulose, 28.2% hemicellulose and 7.4% lignin [15].

Cellulose and hemicellulose can be converted into biogas [16]. Biogas production consist of pretreatment, hydrolysis and methane production [17]. Biogas production can be generated by either liquid anaerobic digestion (L-AD) or solid-state anaerobic digestion (SS-AD) depending on the total solid content (TS). L-AD is operated on TS content between 0.5 to 15%, while SS-AD operates on the TS content of higher than 15% [18]. Compare to L-AD, SS-AD has some advantages, like smaller reactor volume, less heating, higher volumetric methane, less wastewater generation relatively stable, and lower total energy loss [19, 20]. However, SS-AD also has the disadvantages e.g. long retention time, poor startup performance and the accumulation of volatile fatty acids [21].

Several factors should be considered on SS-AD are feedstock/inoculum (F/I) ratio, the TS content, pH, etc., including pretreatment of feedstock to make biomass converted easily by microbes. Consequently, the aims of this paper is to highlight knowledge about SS-AD, a little brief about steps of biogas formation, and pretreatment methods for lignocellulosic biomass.

Stages of Biogas Formation

Biogas is generated from anaerobic digestion, which involves many different groups of microorganism such as hydrolysing, acidifying, acetogenic and methanogenic bacteria [22]. The general equation of biogas formation is stated in Equation 1 [23].

$$C_cH_hO_oN_nS_s + yH_2O \rightarrow xCH_4 + (c-x)CO_2 + nNH_3 + sH_2S \qquad (1)$$
$$x = 1/8 \cdot (4c + h - 2o - 3n - 2s) \qquad (2)$$
$$y = 1/4 \cdot (4c - h - 2o + 3n + 2s) \qquad (3)$$

Steps of biogas formation comprise of hydrolysis, acidogenesis, acetogenesis and methanogenesis [24]. Sequence of biogas formation can be seen in Figure 1.

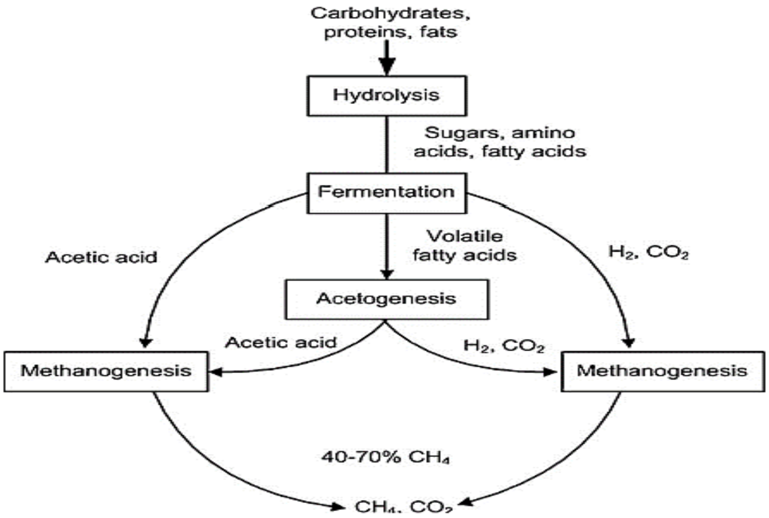

Figure 1. Stages of biogas formation [25]

Hydrolysis

Hydrolysis is the initial step of anaerobic digestion, which decomposes complex organic materials, like carbohydrates, fats and proteins into simple monomers (glucoses, amino acids and long chain fatty acids). This step involves bacteria which secrete extracellular enzyme to help the breaking of complex molecules into simple molecules [26,27]. Some of hydroloysis bacteria i.e. *Peptostreptococcus, Bifidobacterium, Clostridium celerecrescens, Bacteroides ruminicola, Clostridium utyricum, and Clostridium viride* [28, 23].

Fermentation(Acidogenesis)

Acidogenesis step is a process which converts hydrolysis products into hydrogen, short chain fatty acids or volatile fatty acids (propionic acids, butyrate acids, and acetic acids), alcohol and carbon dioxide by acidogenic bacteria [26]. The kinds of acidogenic bacteria are *Enterobacterium, Bacteriodes, Acetobacterium* and *Eubacterium* [28].

Acetogenesis

During this step, acidogenesis products (volatile fatty acids and alcohol) are converted into acetate, hydrogen, and carbon dioxide by *Syntrophomonas* and *Syntrophobacter*, while homoacetogenic microorganisms produce acetic acid from hydrogen and carbon dioxide [26,22]. Several of acidogenesis products such as acetate, hydrogen, and carbon dioxide can be consumed directly by methanogens, whereas volatile fatty acids and alcohol will be converted by acetogenic into acetate [23,29].

Methanogenesis

The last stage of biogas formation is methanogenesis. During this step, methanogens work at anaerobic condition. Methanogens do not degrade all of the substrates. The kind of substrate that can be degraded by methanogens comprises into three groups, namely [23]

CO_2 group : CO_2, $HCOO^-$, CO
Methyl group : CH_3OH, CH_3NH_3, $(CH_3)_2NH_2^+$, $(CH_3)_3NH^+$, CH_3SH, $(CH_3)_2S$
Acetic group : CH_3COO^-

The main substrates which utilized by methanogens to produce methane i.e. carbon dioxide, hydrogen, and acetate. However, the other substrate, for instance, methyl amine and alcohol also can be used to produce methane. Methanogens which produce methane from acetate called as *acetotrophic methanogens* or *acetate-splitting methanogens*, while methanogens which utilize hydrogen and carbon dioxide to produce methane named as *hydrogenotrophs* [28,29].

Composition of Rice Straw

Rice straw is one of the abundant and renewable energy sources in the worldwide due to rice is the staple food for over half of the world's population [30]. Rice straw has 6.59-6.89% of moisture content, 166.29-194.48 kg/m^3 of bulk density, and 71.21-83.2% of porosity [31].

Pretreatment of Rice Straw

Rice straw includes lignocellulosic biomass, which are contained of cellulose, hemicelluloses and lignin. Those components are linked together as a crystallized structure, as a result the degradation of substrate by microorganisms is very hard due their structural complexity [5]. Therefore, pretreatment of rice straw is needed to help microorganisms degrade substrate easily.

1. Mechanical pretreatment
   Mechanical pretreatment can be done by cutting rice straw into smaller sizes. Size reduction can break the cell wall [30]. Furthermore, size reduction reduces the degree of polymerization and increases the specific surface area hence it can enrich the total hydrolysis yield [29].
2. Thermal pretreatment
   Biomass is heated during this pretreatment. Components of biomass will solubilize if the temperature increases above 150-180°C [17]. The thermal pretreament disrupts the chemical bond of the cell wall and membrane [32]. However, thermal pretreatment has negative impacts, i.e. producing phenolic and heterocyclic compounds such as vanilin, vanilin alcohol, furfural and HMF which can be an inhibitory or toxic on methanogens [17].
3. Acid Pretreatment
   Acid pretreatment can be performed by concentrated or diluted acids [33]. The acid pretreatment can be carried out either at high temperature and low acid concentration or at low temperature and high acid concentration [24]. Pretreatment using acid hydrolysis can enhance enzymatic hydrolysis [34]. Acid pretreatment with strong acids can solubilize hemicellulose and lignin [29]. However, acid pretreatment has inhibitor products such as acetic acid, furfural, and 5 hydroxymethylfurfural [33].
4. Alkaline pretreatment
   Alkaline pretreatment can be done by various alkalis, like sodium hydroxide [35]. Alkaline pretreatment results solubilization, redistribution and condensation of lignin and modification in the crystalline structure of cellulose [17]. Nevertheless, this pretreatment can cause production of inhibitors [29].
5. Oxidative pretreatment
   Oxidative pretreatment is carried out by adding an oxidizing compounds, such as hydrogen peroxide or peraacetic acid into the subsrate in order to remove hemicellulose and lignin and increase the accessibility of cellulose [17]. The utilization of oxidative pretreatment has a high risk of inhibitor production [29]. The other disadvantage of oxidative pretreatment is: increasing fraction of carbon dioxide in the biogas [35].
6. Steam Explosion
   During this pretreatment, the susbstrate is heated at high temperature, typically between 160 and 220°C [35]. The aim of this pretreatment is making substrate more accessible to cellulose attack [33]. The negative impact of steam explosion is formation of inhibitor compounds, such as furfural, HMF, and soluble phenolic compounds, which can disrupt the methane production [17].
7. Biological pretreatment
   The Biological pretreatment usually uses microorganism, like brown rot, white rot and soft rot fungi, with white rot are the most effective for biological pretreatment [36]. microorganism can degrade lignin and hemicelluse but in a little fraction of cellulose due to cellulose is more recalcitrant than other components of lignocellulose [24]. The advantages of biological pretreament are able to operate at low temperature without using chemical, low energy requirement and mild operation condition. Nonetheless, the disadvantages of biological pretreatment are slow hydrolysis rate and long residence time [35, 37].

Solid-state Anerobic Digestion

Anaerobic digestion is generally classified into two categories based on the TS content, namely liquid-anaerobic digestion (L-AD) and solid-state anaerobic digestion (SS-AD). L-AD operates on the TS content from 0.5 to 15%, while SS-AD is operated on the TS content of higher than 15% [38]. SS-AD is usually utilized to convert lignocellulosic biomass into biogas. SS-AD has been installed in the Europe since 1990s [39].

SS-AD is an appropriate system for treating lignocellulosic biomass due to the high TS content and low moisture content [40, 11]. Problems in L-AD, like substrate floating and stratification are not found in SS-AD [41]. Biogas production by SS-AD increased 278-357% compared with L-AD [42]. Besides, methane volume generated by SSAD was 2-7 times higher than L-AD [43]. Several researches on SS-AD have been conducted by using a wide range of lignocellulosic biomass, as shown in Table 2.

Table 2. The previous researches of biogas production by SS-AD

No.	Substrate	Methane yield	References
1	Corn stover, expired dog food	304.4 L/kg VS	[44]
2	Spent mushroom substrate and wheat straw	269 L/kg VS	[45]
3	Green waste	524 L/kg VS	[46]
4	Food waste and green waste	272.1 mL/g VS	[42]
5	Switchgrass	116.9 L/kg VS	[43]
6	Wheat straw	66.9 L/kg VS	[11]
7	Hay and soybean processing waste	258 L/kg VS	[38]

Factors Affecting SS-AD

SS-AD must consider several factors for biogas production, as stated below:

1. Temperature
   Generally, there are three temperatures in the anaerobic digestion, i.e. pyschrophilic (10-25°C), mesophilic (25-45°C), and thermophilic (45-65°C) [47]. Lower temperatures during the process will reduce methanogen activity. Methanogen will not be active at temperature between 40 and 50°C [29]. The ideal temperature for methanogens is around 35-37°C in meshophilic digestion. If the temperature drops below the ideal temperature, fermenting microorganisms will be deactivated. As a result, they are not be able to digest all of hydrolysis products. Consequently, the pH system reduced and the process ceased [28]. On the contrary, higher temperatures cause production of volatile gases which can reduce biogas yield [48].

2. pH
   pH is an important parameter in anaerobic digestion influencing the growth of microorganisms [4]. pH requirements for each microorganism are different due to various microorganisms in steps of digestion. The optimal pH for methanogens, i.e. about 6.8-7.6, while the ideal pH for hydrolysis and acidogenesis between 5.5-6.5 [49]. Methanogens growth will reduce at pH values from 6 to 8.5 [29].
   Reduction of pH below the optimum pH causes production of organic acids which can decrease the pH drastically and cease fermentation step [23]. The pH value above 8.5 can inhibit digestion process. The increase of pH values occurred due to ammonia accumulation during degradation of proteins [50]. Methanogens are sensitive to the acid condition and their growth can be inhibited by acidic condition. Therefore, the ideal pH for anaerobic digestion ranges from 5.5 to 8.5 [26]

3. Carbon to Nitrogen (C/N) Ratio
   C/N ratio is denoted as the amount of carbon and nitrogen present in feedstock [24]. An operating C/N ratio for anaerobic digestion ranges between 20 to 30 [4,29,25]. The lower C/N ratio can result, ammonia accumulation and increase the pH value beyond 8.5, whereas the higher C/N ratio can decrease biogas production due to rapid consumption of nitrogen by methanogens [18]. Feedstock with low in C can be mixed by adding materials high in N to get an optimum C/N ratio [4].

4. Total Solids Content (TS)
   The TS content affects the pH value, temperature, and efficiency of microorgansim in the digestion process [29]. TS content in the SS-AD system about 20-30%. A higher TS content can inhibit methanogens activity due to accumulation of organic acids (VFAs) [51]. The TS content higher than 30% decreases methane production about 17% [52].

5. Feedstock and Inoculum
   Substrate (feedstock) converted into methane by microorganisms. The adequate growth of microorganism in anaerobic digestion can be achieved by adding inoculum or nutrient. Microorganisms need an energy source for their activity. The nutrients required for microorganisms, such as carbon, nitrogen, hydrogen, potassium, sulfur, cobalt, copper, iron, nickel, selenium, etc [13].
   Feedstock to inoculum ratio (F/I) affects SS-AD system either batch or continue. The SS-AD system in industrial scale has a very low F/I ratio in order to avoid the failure process and maximize the reaction kinetic [53]. The higher F/I ratio can cause overloading of organic [11]. Overloading of organic material can inhibit methanogens and result the failure of digester due to accumulation of organic acids [38].

Conclusions

Biogas is one of promising renewable energy which can substitute fossil fuels. Solid-state anaerobic digestion is an appropriate method to digest lignocellulosic biomass, such as rice straw into biogas. Since, the recalcitrance of structure of ligocellulose, thus pretreatment is needed to make substrate easily converted by microorganism. The selection of pretreatment must consider several factors, like operational cost, consequences of pretreatment, and effectiveness of pretreatment toward digestion process. Therefore, biogas production by SS-AD must consider the suitable pretreatment method, the paramaters of SS-AD such as temperature, pH, the C/N ratio and the TS content to obtain the optimum biogas yield.

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