Enhancing Biogas Production from Various Biomass Materials Through Pretreatment: A Review

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Abstract

The over-reliance on non-renewable energy forms which are depletable, expensive, emit copious amounts of greenhouse gasses which cause adverse effects to both humans and environment, have braved researchers in the past few decades to find alternative methods to obtain sustainable forms of energy. Utilization of renewable energy sources which are not only sustainable but friendly both for the user and the environment offers the best solution to address these global energy challenges. One such solution is the generation of biogas from the various biomass wastes. Biogas is a renewable energy produced through anaerobic digestion of biodegradable biomass resources. Despite the vast abundance and availability of the biomass wastes, their full utilization has been met with a myriad of challenges. The main drawback being the long hydraulic retention times and the high lignin content in most biomass materials. The objective of this paper is to review the various pretreatment technologies for enhancing biogas production. The pretreatment technologies that were reviewed are mechanical, thermochemical and biological pretreatments. From the review it was found out that pretreatment of biomass materials significantly increases the production of biogas.

Keywords: Biomass, Biogas and Pretreatment

1.0 Introduction

With the increase in the world population there has been a steady rise in the energy use hence making the energy demand a major challenge for the world's leaders. In the developing and the less developed countries most of the energy needs are met using biomass resources. 70% of Kenya's energy demand is contributed by biomass and more than 90% of the rural households depend on it primarily for their energy needs.

The importance of biomass is discernible from the fact that often it is the only easily available and affordable energy source for cooking and heating for the world's poor. The main forms of biomass energy are from wood and agricultural waste. The agricultural waste that are readily available in Kenya include sugarcane bagasse, banana waste, flower waste among others. Utilization of the biomass energy is riddled with other problems like environmental degradation and indoor air pollution for households. This calls for the generation of clean and sustainable forms of energy that do not cause environmental degradation. Therefore, generation of biogas which is a clean source of energy through utilization of biomass from the abundant agricultural wastes can be a solution to these challenges.

The studies done by Nzila et al [1] investigated Kenya's biogas potential as substrate available from crop residues. The study covered cotton, tea, maize, barley and sugarcane, and claimed that without compromising food security these crops residues provide abundant biogas substrate to produce 1,313 million cubic meters of methane annually, equivalent to 73% of Kenya's annual energy demand. These residues could replace or supplement cattle manure in biogas digesters.

Biological processes like fermentation and anaerobic digestion have given rise to the production of biofuels such as biogas and bioethanol. Thus, the most important parameter to consider in the application of anaerobic digestion is the type of feedstock, as almost any organic material can be processed under this process. Feedstock has been defined to include substrates that can be converted to methane by anaerobic digestion [2].

Biomass waste which are rich in lignocellulose are the most favorable renewable organic feedstocks for bioenergy production such as biogas production as they don't compete for arable land that should be used for food production [3]. The problem with using the plants rich in Lignocellulosic content is that there is difficulty in breaking them to simple sugars for methane production. The main challenge in the use of lignocellulose feedstock in the anaerobic digestions is the transformation of the complex polysaccharides into simple sugars which can then be assimilated by a large consortium of micro-organisms [4] This normally inhibits the anaerobic digestion process due to the slow process of breaking down the complex sugars.This therefore calls for the need for pretreatment which is an essential technique that targets the disruption or removal of lignin and hemicellulose present in the biomass making cellulose porous and accessible to the micro-organisms for further digestion to yield energy [4].

2.0 Anaerobic digestion of biomass waste

According to Deng et al., 2021 Anaerobic digestion (AD) is a biological process powered by the metabolism of complex microbial communities primarily consisting of bacteria and archaea with smaller numbers of fungi and protozoa [5]. The microbial community in AD consumes organic matter to produce biogas, a renewable energy source.
Anaerobic digestion is carried out by four stages such as hydrolysis, acidogenesis, acetogenesis and methanogenesis. In these, hydrolysis is the initial and the very important stage which breaks the complex structure into simpler molecules.[6]
Anaerobic digestion has a great future amongst the different renewable energy resources as well as in waste management technologies. However, the low overall bio digestion efficiency of the process and long retention periods (20-30 days) results in low efficiencies. In anaerobic digestion, the hydrolysis process is the rate- restricting step in which soluble organic materials are converted to biogas are generated. Consequently, the biogas yield depends mainly on the biodegradability and hydrolysis rate of the digestion. Biogas production can be improved by pre-treatment of the organic wastes and adding additives to the slurry. During pre-treatment, both solubilisation of particulate matter and biological decomposition of organic long chain polymers to small chain monomers takes place ie. cell-walls of the organic wastes are destroyed and extracellular polymeric substances are digested resulting in the conversion of organic material to a suitable form for easy digestion by acidogenic microorganisms. Additives increase the microbial activity increasing the rate digestion process. [7]
Improving the hydrolysis by pretreatments can increase the biogas yield by increasing the performance of anaerobic digestion. Various pre-treatments can be used to improve the biogas yield such as mechanical, thermal, chemical, biological and combined pretreatments [6]

While producing a clean renewable energy source AD has additional benefits such as waste treatment, bio-fertilizer production, soil carbon sequestration and reducing fugitive methane emissions. A prime example is associated with the agricultural industry, where there is the potential to prevent fugitive methane emissions from open slurry holding tanks, reduce water contamination and produce renewable energy [8]. This in effect will promote a circular economy for the agro-industries where waste from one area is a resource for use in other areas. Table 1. shows the biogas yield from various feedstock type. It should be noted that the liquid cattle manure which is mostly used in producing biogas in most homesteads has the lowest yield of in producing biogas compared to other biogas materials. Hence this calls for the need of incorporating biomass waste in the generation of biogas.

Table 1. Types of organic wastes and their biogas yield [9]

Organic waste	**Total Solid[%]**	**Volatile Solid [%]**	**Biogas yield [$m^3 kg^{-1}$ of VS]**
Municipal organic waste	15-30	80-95	0.5-0.8
Brewery spent grain	20-26	80-95	0.5-1.1
Vegetable wastes	5-20	76-90	0.3-0.4
Grass cuttings (from lawns)	20-37	86-93	0.7-0.8
Grass silage	21-40	87-93	0.6-0.8
Cattle manure (liquid)	6-11	68-85	0.1-0.8

3.0. Pretreatment

The various pretreatment technologies that can be used to enhance biogas yields include, Mechanical, thermal, chemical, biological and combined pretreatments. These Pre-treatments help to solubilize and/or to reduce the size of organic compounds, in order to make them more easily biodegradable [6]

3.1 Mechanical Pretreatment

The mechanical treatment of biomass is one of the important methods used for intensifying the bio-methanation process. The most commonly used mechanical pretreatment methods include milling/grinding, high pressure homogenizer, ultrasonication, mechanical jet, etc [10]

Milling/Grinding

Particle size of the substrate plays a major role in the bio-methanation process. Smaller particle size will increase the substrate utilization because smaller particle size can provide increased microbial activity [11]

By breaking the large structures into shorter chains, the speed and the efficiency of the hydrolysis increases which makes the biodegradability easy [11]. Milling/grinding is used to reduce the particle size of the substrate.

Sharma et al. 1988 [12] evaluated the agricultural and forest residues with five particle sizes (0.088, 0.40, 1.0, 6.0 and 30.0 mm) and found that the maximum quantity of biogas was produced from 0.088- and 0.40-mm particle size.
Also, Fang.S etal 2011[13] noted that reducing the particle size of the feedstocks led to increase in biogas yields. In most cases, after the pretreatment the total hydrolysis yield increased by 5-25% and the digestion time reduced by 23-59%.

Ultrasonication
Ultra-sonication is one of the useful and effective mechanical pretreatment methods to enhance biodegradability of the material [13]. Application of high intensity ultrasound modifies the structure of the material making biodegradability easier compared to untreated samples [13]. Available literature reported that the application of ultrasonic pretreatment in anaerobic digestion of waste activated sludge increases the biogas production and reduces the volatile solids [14]. Wang *et al.* [15] investigated the effect of ultrasonication on waste activated sludge and reported that the methane generation was increased by 64% due to ultrasonic pretreatment.

3.2 Thermal Pretreatment

Thermal pretreatment can be used to treat the biomass prior to the anaerobic digestion process. This promotes splitting of complex organic wastes into simpler and more biodegradable constituents [16]. During the thermal pretreatment, the organic and inorganic compounds in the feedstock are partially solubilized before hydrolysis which reduces digester volume and increases the biogas production [17,]. From literature, it is found that the optimum temperature is 160 to 200°C and the treatment time is 30 to 60 minutes. Temperatures above 250°C should be avoided during pretreatment, because above 250°C unwanted pyrolysis reactions start to take place [18]. Some of the results available in the literature for thermal pretreatment are given in Table 2. Thermal treatment can be done either by steam explosion or by liquid hot water.

Steam explosion
In steam explosion, substrate is contained in a closed vessel and steam with high temperature and pressure is passed directly through it [19]. Hemi-cellulose degradation and lignin transformation are caused by this high temperature which results in the increase of hydrolysis potential of the process [20]. During steam explosion, the pretreatment time is dependent on the moisture content of the biomass. For better solubilization and hydrolysis, the biomass should be subjected to high temperature with less pretreatment time or more pretreatment time with lower temperature [20].

Liquid hot water (LHW)
In this pretreatment technique, steam is replaced by hot water. The hot water easily solubilizes the hemicellulose material and prevents inhibitor formations. The pH level should be maintained between 4 to 7 to minimize the monosaccharides formation and also acts as a catalyst for the hydrolysis of the cellulosic material in the pretreatment process [21].

3.3 Chemical Pretreatment

Chemical pretreatments are used to solubilize the main components of lignocellulosic biomass such as cellulose, hemi- cellulose and lignin. Alkaline and acid pretreatment are some of the main techniques available in chemical pretreatment.

Alkaline retreatment

Alkali pretreatment is the process which involves the removal of lignin and part of hemicellulose using alkaline solutions. [22]. During alkaline pretreatment, various reactions like solvation, saponification, peeling and hydrolytic reactions take place in order [23]. These reactions result in a swollen state of the biomass which enhances the accessibility of bacteria and enzymes [22]. Various alkali agents like KOH, NaOH, Ca(OH)2 and Mg(OH)2 are used in the alkaline pretreatments [7]. The alkaline pretreatment causes swelling of organic/biomass particles, making them more susceptible to enzymatic attack by improving the biodegradability [23].
It should be noted that alkaline pretreatment is the most preferred method because of its low cost on the equipment and operations.

Acid pretreatment

In acid pretreatment, dilute or strong acids like acetic acid, nitric acid, etc are used as agents to treat the biomass chemically. The purpose of acid treatment is to make better the accessibility of cellulose for bacteria/enzymes by solubilizing the hemi-cellulose and removing the lignin [24]. During strong acid pretreatment, the solubilization of hemicellulose and precipitation of solubilized lignin are more pronounced compared to dilute acid pretreatment.

Table 2. Some results of experiments on chemical pretreatments

Feedstock	**AD Condition**	**Treatment Technique**	**Observations**	**Reference**
Plant residues and cattle dung	-	NaOH (1% for 7 days)	The digestion efficiency of the NaOH treated plant residues are almost 31-42% higher than untreated cattle dung with the residues	[25]
Pulp and paper sludge	Batch reactor	NaOH (8 g per 100g of TS)	There was an increase of Methane production by 183.5% of the untreated sludge.	[26]
Oil palm empty fruit bunches	Batch reactor	NaOH (8% for 60 min)	Methane production increased by 85% after NaOH pretreatment.	[27]
Water hyacinth	CSTR (25-36°C)	KOH	Methane composition of biogas increased from 60 to71%.	[28]

3.4. Biological Pretreatment

Biological pretreatment is normally done by a biological agent (microorganisms) with the biomass materials [29]. The micro-organisms usually degrade most of the lignin and hemicellulose but very small part of cellulose. This is because cellulose is more resistant to the biological attack [29]. Various microorganisms such as brown-rot fungi, white-rot fungi, and soft-rot fungi, are commonly used for the degradation of lignin and hemicellulose in the substrate [30]. Brown-rot fungi are mainly used to attack cellulose and the white and soft rot-fungi are used to attack both cellulose and lignin [30]. Some of the results available in the literature for biological pretreatment are given in Table 3.

Table 3. Results on Biological treatment

Feedstock	Conditions in digestor	Pretreatment	Results	Reference
Corn straw	UASB mesophilic anaerobic digester	Yeast and cellulolytic bacteria	Biogas production increased by 33.07% and methane yield increased by 75.57%. Digestion time reduced 34.6%	[31]
Pulp and paper sludge	Batch reactor	Mushroom compost extracts	Methane yield under pretreatment condition was 134.2% of the control.	[32]
Wheat straw	Batch reactor (37°C)	White-rot fungi	Biogas yield from pretreated straw was doubled than the untreated straw.	[33]

4. Conclusion

From the review various pretreatment techniques namely mechanical, thermal, chemical and biological techniques have been developed in order to enhance the production of biogas from biomass during the anaerobic digestion process. A number of researchers have investigated these pretreatment techniques with different biomass feedstocks. From their experiments the results indicated that there is significant increase in biogas yield.

Also, biological techniques by various researchers were also analyzed and it showed a significant enhancement of biogas production.

It is noted that in chemical pretreatment the most preferred method is the use of alkaline and not acidic since it is cheaper.

Given that cattle slurry which has the lowest biogas generation potential compared to other biomass materials is widely used in most households in Kenya, developing countries and other less developed countries. This therefore calls for further research on developing and optimizing cheap pretreatment techniques for pretreating the abundant biomass waste in order to supplement cattle slurry and hence generate more biogas for the households.

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