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Current Developments in Anaerobic Digestion of Food Waste Coupled with Combined Heat and Power Generation of Electricity

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Abstract. Anaerobic digestion is a series of process which breaks down organic matter into simple chemical components in the absence of oxygen. This process has long been used in treating various organic wastes and has been recognized as a form of energy production. Combine heat and generation of electricity is referred to as simultaneous usable heat and power within a single process. This paper aims to review the current trends in anaerobic digestion and the combined heat and power generation of electricity. The review covers the various stages in anaerobic digestion such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis as well as codigestion of two or more feedstock, enhancement of pretreatment methods, inoculation of substances and temperature variation to reduce process time and enhance biogas production.

Keywords: Anaerobic Digestion, Biogas, Digestate, Co-digestion

1. Introduction

The amount municipal, agricultural and industrial waste being produced is increasing worldwide; therefore it is necessary to develop strategies for effective management of the generated waste [1]. Anaerobic digestion (AD) is one of the oldest means used in the waste treatment for the reduction of solids and pathogens destruction. The commercial use of AD starts in 1895 and the first digestion plant was built at a leper colony in Bombay, India. By the year 1895 AD stretched to England, biogas was trapped from sewage treatment facility and used as a fuel to lighting street lamps in Exeter [2]. The ability of biogas produce by AD to be utilized for electricity generation and other useful energy has steered researches and developing ways to improve gas production from anaerobic digestion [3].

AD has been principally used at larger wastewater treatment facilities treating sewage sludge and biogas production. In 1940 many sewage treatments plants in United State were already able to use anaerobic digestion (AD) and at the same time generate heat and electricity for the AD plant. This mark the beginning of sustainable waste management and pollution control [4]. However, Reference [3] noted that small scales AD were used typically for energy and sanitation purpose, although technical improvement and increasing energy prices have led to diversification of waste treated and large size AD plants.

2. Anaerobic Digestion

Anaerobic digestion (AD) is a series of processes in which microorganisms break down biodegradable material in the absence of oxygen, the end goal of the process is reduction in the waste substrate, organic content and at the same time generate a gaseous fuel called biogas, which can be burned in a boiler to

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produce heat or into a combined heat and power (CHP) engine to produce heat and electricity. The biogas can further be subjected to secondary treatment to produce biomethane. This can be used as a natural gas fed into the national grid in the same way or used as fuel for vehicles [4, 5]. Beside waste minimization and biogas production, AD also produces a by-product called digestate which can be applied to the soil as nutrient supplement. The feedstock usually used in the digesters include sewage sludge, animal manure and slurry, industrial effluent and food wastes, though the potentials of using energy crops as feedstocks is increasing in popularity [5].

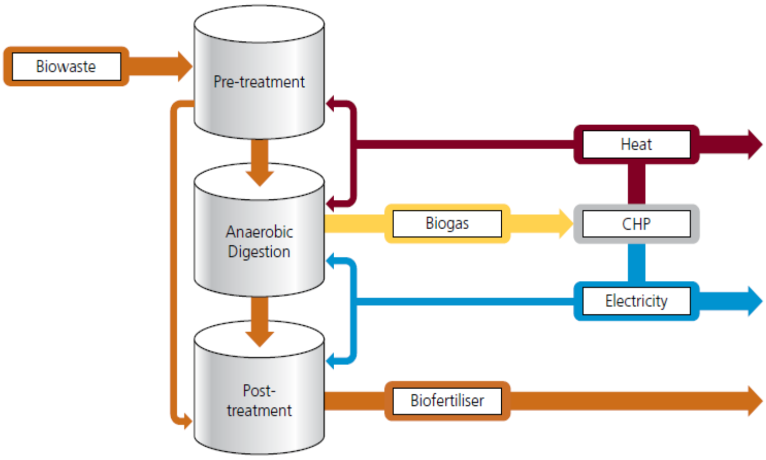

Fig. 1: Overview of an Anaerobic Digestion System [5]

Stages in AD process are divided into: pre-treatment, biological process (the digestion which is further divided into four steps leading to biogas production, the steps are; Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis), gas upgrading and digestate treatment [3].

2.1. Pre-treatment stage

Pre-treatment stage is the first stage as shown in the Fig. 1. Which involves physical processes like screening, shredding and mixing with water for quick fermentation; it can also involve the use heat, mechanical, pressure, ultrasonic irradiation methods [6]. Screening is the process of separation and isolation of all non-digestible materials like plastics, glasses, stones and metallic objects and other harmful chemical products which can introduce pathogens or reactions in the biodigesters [7].

Shredding is aimed at reducing the size of the particles through the use of an industrial shredder calibrated to a certain size depending on the company choice and the type of the biodigesters used; because the particles size in relation to the type digester can determine the achievement of the process [8]. The reduction of particles size provides two benefits to the anaerobic digestion process. Firstly, it decreases the amount of residues produced at the end especially for substrates with high fibre content and it increases the amount of digester gas. Secondly, it decreases the time required for the digestion of substrates with low degradability [7].

2.2. Anaerobic digestion stage

Anaerobic digestion involves interactions between different microorganisms for the breakdown of organic matter in the absence of oxygen [7]. The process or the digester types can be classified into either wet system when it contains (< 10%) total solids or dry system when it contains (< 20%) total solids [9]. The digesters can also be either batch or continuous, batch is when the raw feedstock is loaded in the reactor vessel and the digestate is inoculated in another reactor which is left for decomposition to occur. While continuous digesters are continuously fed with digestate material and then the decomposed material is collected at the bottom of the reactor. The last types of digesters are single step or multi step, single step is a digester in which the digestion process occurs in a single reactor vessel; while a multi-step digester has separate steps for each digestion process [10]. The process is achieved in four stages namely Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis.

2.2.1. Hydrolysis

Hydrolysis is also known as liquefaction, is a process where starch, lignocellulose materials, proteins and fats are broken down and converted to sugars, amino and fatty acids. The aim of this is to facilitate their transport through the cell membrane of the microorganism [11].

The mechanism of the process involves the conversion of insoluble complex organic matter into soluble molecules by the action of fermentative bacteria; proteolytic microbes secretes protease for the conversion of proteins to amino acids, cellulytic microbes secretes celluloses to convert cellulose to glucose while lipolytic microbes secretes lipases for the conversion of lipids into glycerol and fatty acids. This can also be enhanced by addition of chemicals to shorten the time of digestion and boost the methane production [11].

2.2.2. Acidogenesis

Acidogenesis involves the conversion of products formed during the hydrolysis stage; the facultative bacteria convert sugars amino acids, and fatty acid to acetates, hydrogen, carbon dioxide, acetic acids, alcohols and volatile fatty acids. The following equations show how glucose is being converted to different products by the action of the facultative bacteria [11]:

Glucose to acetate $C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$

Glucose to ethanol $C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2$

Glucose to propionic acid $C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O$

2.2.3. Acetogenesis

This stage comes after the acidogenesis stage; it involves the action of acetogenic bacteria otherwise known as acid formers in the conversion of fermentation products into acetate and hydrogen. Examples of acid formers includes S*ytrophomonos wolfei* known for decomposition of butyric acid, S*yntrophobacter wolinii* known for propionic decomposition, others include *Actinomyces, Peptococcus anerobus and lactobacillus and* [7]. The stage can be presented in the following equation below.

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

2.2.4. Methanogenesis

The final stage of the process involves the formation of the methane by the bacteria called methanogens. The methanogens make use of the intermediate products from the acetogenesis stage and then convert them to methane, water and carbon dioxide which are the major constituents of biogas. And the remaining organic materials which the methanogenic bacteria cannot feed on will combine with the residues of dead bacteria and form the solid digestate. Normal pH for Methanogenesis is 6.5 to 8.0, because any slight change in pH can affect the digesters performance because it is pH sensitive [12].

The four stages marked the end of the anaerobic stage and are important in the entire anaerobic process as they affect the performance of the digester. The hydrolysis stage plays a role in controlling the level at which Chemical Oxygen Demand (COD) is converted to methane during the anaerobic digestion of organic solids, while Methanogenesis is a rate limiting stage [12].

2.3. Post treatment stage

The basic products of food waste anaerobic digestion are biogas, and a digestate which can be in form of liquor or fibre. Post treatment stage involves processes of purifying the biogas from toxic or unwanted substances; and the pasteurization which is done kill any pathogens that might be harmful in the final product which depends on the purpose of the product.

2.3.1. Biogas

The biogas produced from the anaerobic digestion of food waste is mainly 60% of methane (CH_4), 40% carbon dioxide (CO_2) and a mixture of other compounds like hydrogen sulphide (H_2S), Hydrogen and Ammonia (NH_3). But the gas should ideally contain about 98% methane, and all other compounds should be removed because high levels of CO_2 reduces the biogas' energy content, H_2S is corrosive and toxic, while NH_3 produces Nitrogen Oxides (NO_X) during combustion of biogas which are also greenhouse gases. However, a mixture of CO_2, H_2S, NH_3 and water can lead to corrosion of pipes [13]. So the post-treatment of biogas involves the removal of the toxic substances and excess water using different techniques as shown in Table 1 so as to get a 98% biogas.

Table 1: Biogas purification and improvement techniques [13]

Biogas compound	**Technique**
Elimination of Water	Demister, Cyclone separator, Condensation, Drying and Adsorption onto silica
Elimination of H_2S	Aerobic biological oxidation, Adding FeCl3 to the digester, Adsorption onto Fe2O3, Absorption (NaOH), Absorption (iron solution), Membrane separation, Biological filters, Activated carbon and Molecular sieves
Elimination of CO_2	Pressure swing Adsorption (PSA), Techniques based on physical absorption, Membrane separation, Techniques based on chemical absorption, Propane adding and Cryogenisation

When the biogas is purified and improved it can be utilized for various purposes which include heat and steam production, fuel oil when upgraded, used in production of chemicals, used in fuel cells as fuel, injection to national gas grid and as a source of energy for generation electricity and cooling (Naja *et al,* 2011) [13].

2.3.2. Digestate

Digestate is the remaining liquid or solid substance which cannot be used or decomposed by the microorganisms during the anaerobic digestion; it is composed of the bacteria that died during digestion and small traces of glasses, plastic and fibre. It is used as a fertilizer to provide soil nutrients to boost food production [14].

2.3.3. Combined heat and power generation of electricity

Combined heat and power (CHP) otherwise known as Cogeneration involves the generation of heat and power from the anaerobic digestion of food waste or other waste streams [15]. Fig. 2 showed a schematic diagram of how heat and power can be generated from biogas, and this happens based on the principle of cogeneration, where the combined heat and power unit burns the biogas in a combustion engine and the resultant pressure will power the generator and subsequently produce heat and electricity, the electricity can be connected to the national grid while the heat is mainly used back to heat the digester contents [16]. CHP power is in form of electricity which can be used on-site or connected to the national grid or power small housing unit; it can also be used mechanically for fans, compressors and pumps [15]. The type of engines used in CHP usually operates at 1,500 revolutions per minute (RPM).

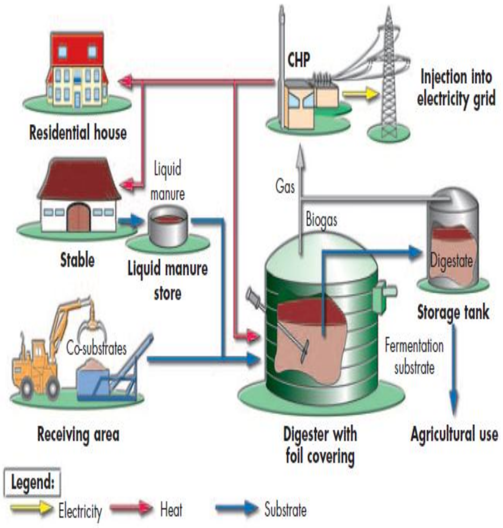

Fig. 2: Conversion of biogas to heat and power [16]

3. Current Trends in Anaerobic Digestion

The current trends in anaerobic digestion which includes combined heat and power generation of electricity are geared towards increasing biogas production through codigestion of two or more feedstock, enhancement of pretreatment methods, inoculation of substances and temperature variation to reduce process time and enhance biogas production. Some trends are explained as follows:

3.1. Co-digestion

Anaerobic co-digestion refers to the instantaneous digestion of two or more feedstock aimed at improving the effectiveness of anaerobic digestion. The importance of co-digestion over a single digestion process includes increment in biogas production, dilution of toxic compounds, and improvement in the buffer capacity, nutrients balance which includes supply of carbon to nitrogen ratio, micro and macro nutrients; and stabilization of pH [17].

Reference [18] evaluated the possibility of increasing methane production through co-digestion of food waste and brown water (faeces without urine). The results indicates an increase in the production of methane from the co-digestion of brown water and food waste than in the digestion of single substrate of brown water or food waste. This is similar to what Reference [19] reported when they carried out an anaerobic co-digestion of food waste and cattle manure aimed at finding out the parameters leading to increase in the biogas production. The study discovered that cattle manure improved the buffer capacity and there was in increased biogas production which was attributed to high biodegradation of lipid and carbon to nitrogen ratio.

3.2. Pretreatment

Pretreatment is an important method in anaerobic digestion which results to a decreased time of digestion due to decrease in the particles' size [6]. A study was carried by [20] in an effort to examine possibility of increase methane production and the efficiency of two physical pretreatment processes which are screwpress and dispergation technologies which employ the use of milling equipments for the treatment of household organic waste. The study finds out a decrease in the nutrients and biodegradable materials from screwpress technology over dispersion technology, which indicates a possible increase in the methane production. However, in an effort to study how waste activated sludge can be used in improving the effectiveness of anaerobic digestion, Reference [21] investigated the effects of chemical, thermal, ultrasonic and thermochemical pretreatment methods on the production of biogas. The study finds a significant increase in the methane production from thermochemical pretreatment compared to other methods as shown in Fig. 3. The study concluded that, thermochemical pretreatment can have impact on the rate limiting step for its increased biogas production.

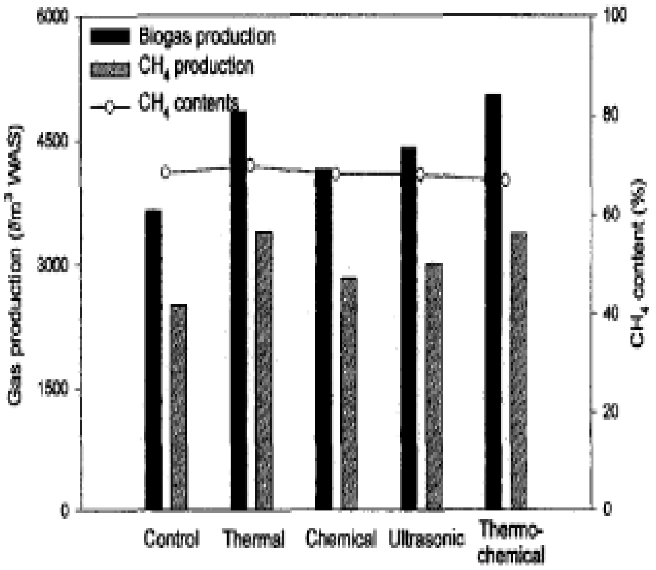

Fig. 3: How pretreatment methods improves biogas production [21]

3.3. Temperature

The activities of microorganisms in the biodigesters and the production of biogas are controlled by many factors temperature included. Lower temperatures during anaerobic digestion can lead to a decrease in the growth of microbial organisms, production of biogas and utilization rates of substrate; it can also lead to lysis or the leakage of intracellular substance and the exhausting of cellular energy. And on the other hand if the temperature is higher it can also reduce the production of biogas as a result of high volatile gases like ammonia which will hinder the action of methanogens [22].

Reference [23] developed a system which consists of hydrolysis, Acidogenesis and Methanogenesis for the digestion of food waste with an aim to check the effect of hydraulic retention time and temperature on the Methanogenesis. They adjusted the temperature from 30 ℃ to 55 ℃ with a retention time of 8 to 12 days.

The study finds out an increase in the production of biogas especially at 45 ℃ and 50 ℃, but there was a decrease in the soluble chemical demand (sCOD) but when digestion was carried below 45 ℃ or above 50 ℃, there will be need for stabilization period. And the study suggested the dependence of methanogenic bacteria on temperature which finally concluded that, thermophilic temperature (<55 ℃) is more effective than mesophilic temperature for biogas production as reported by reference [24] that "thermophilic operations are a reliable and acceptable option for digestion of organic urban wastes".

4. Conclusion

Anaerobic digestion is a current technology which is employed in the treatment of organic municipal solid waste aimed diverting waste sent to the landfills so as to avoid emission of harmful gases that are released into the atmosphere as well as recovering value from waste. The most important products recovered from the anaerobic digestion include biogas which is burnt and converted to heat and power and then used as a source of electricity for homes, industry and even injected to the national gas grid while the digestate is used as a soil conditioner.

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