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An Overview of Biogas Production: Fundamentals, Applications and Future Research

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ABSTRACT

Due to the increase in population, both developed and developing countries are facing mainly issues surrounding the future energy security and a better use of natural resources. Such present and future energy problems can be solved by the use of renewable energy sources. Among several renewable energy sources is a sustainable means of anaerobic digestion (AD) for production of gases. In the past, AD as a source of biogas was used mainly for degradation of waste materials or toxic compounds. However, recently, there has been great interest in producing biogas from energy crops. This paper presents an overview of state-of-the-art and future viewpoints related to the AD process for biogas production.

Keywords: Biogas, Biomass, Anaerobic Digestion, Methane, Renewable Energy
JEL Classifications: Q4, P28

1. INTRODUCTION

Due to the fluctuating cost and the environmental effects of conventional sources (especially crude oil) of energy, there is an emergent interest in the use of renewable energy. As such, the adoption of renewable energy is gradually becoming significant due to the negative effects of greenhouse gas emissions on the environment (Naik et al., 2010; Babatunde et al., 2018, Ighravwe and Babatunde, 2018). Another driver for the use of renewable energy sources is the issue of sustainability. It has been said that the conventional sources have a lifespan and will be totally depleted in future (Ighravwe et al., 2018). The common renewable energy sources that have been explored include solar, wind, hydro, geothermal as well as biomass. It is possible to generate biofuels such as hydrogen, methanol, dimethyl ether, ethanol, synthetic natural gas, etc. In order to fully explore the use of biomass in the generation of energy, several government organisations and researchers have instituted programmes and studies to promote the use of biofuels. For instance, the European Union has a target to make biofuel 10% of its energy share in the transport sector by 2020 (Molino et al., 2018). Furthermore, by 2022, the US is expected to produce about 36 billion gallons of biofuels annually (Molino et al., 2018). Presently, industrial plants are embracing the production of biogas for the generation of energy and on biomethane upgrading for grid injection. The production of biogas is noncomplex and centralised technology with a low level of organic conversion into biogas, (nearly 5–10 wt. %), based on the type of feedstock and the operative conditions (Molino et al., 2013b; Molino et al., 2013a).

Nations with enormous area of fertile cultivable land, a favourable climate as well as water resource can invest in the planting of biomass plants for energy generation. Such agricultural plants include sugarcane, cassava, corn starch etc. For instance, it is possible to produce several types of sugar, and alcohol as well as generate electricity from sugarcane. The agricultural and industrial processing of these plants yields products such as straws, molasses, filter cake, stalks, pulp etc. which can be further exploited to generate electricity. Conversely, there exist significant logistical challenges related to production of biomass feedstock from food products such as cassava and sugarcane. One of such is the challenge of maintaining a balance between the economic, technical, political, social, and environmental factors involved in the biofuel production processes. Thus, decision makers, researchers and other stakeholders have revolved into the conduct of experimental studies as well as mathematical optimisations techniques that can help in attaining the optimum decision that will make biomass more economically appealing and commercially available. One of the end products of this process that has been of major interest of late is the production of biogas. Biogas (considered to be the low carbon fuel sources) offers the best opportunities to the rural communities especially in African countries to meet their energy demand. The use of biogas offers multiple benefits, such as:

- The enhancement of farming in rural communities, which directly enhances the economy of a community through job creation;
- Waste reduction through the use of organic agricultural waste and municipal solid waste (MSW) for energy production;
- The improvement of the environment quality through CO_2 emission reduction (Soccol et al., 2011); and
- The combination of the disposal of organic waste with the formation of valuable energy "methane" by biogas.

The production of biogas is based on a profound technology whose output is principally used for electricity generation and also for the valorization of organic residues (Kougias and Angelidaki, 2018). Biogas is an output of anaerobic digestion (AD), where various microorganisms, breakdown organic matter through different metabolic processes. Tremendous and novel development in biogas production has led to the creation of advanced bioenergy facilities. As such, the biogas facilities are the basis of an economy concept aimed at nutrients recycling, reduction of greenhouse gas emissions and biorefinery purposes. This paper presents an overview of state-of-the-art and future viewpoints related to the AD process for biogas production.

2. BIOGAS PRODUCTION

Biogas is a colourless combustible gas that is produced by the biological breakdown of organic matter; occurring in the absence of oxygen (Umeghalu et al., 2012). The biogas comes from "biogenic materials" (Umeghalu et al., 2012) and it is generated from AD of biodegradable materials such as biomass, cow dung green waste and agricultural residue such as cassava, sugar cane etc. (Ghosh, 2000). Biogas comprises a mixture of different gases, mainly methane (CH_4), carbon dioxide (CO_2), 1–5% other gases, including hydrogen (H_2). The composition of biogas is presented in Table 1 (Umeghalu et al., 2012). The gas is produced by bacteria that occur during the bio-degradation of organic materials under anaerobic conditions (Sutaryo, 2012). Biogas has an elevated methane content (Table 1), which makes it an attractive source of energy. The energy that is released from biogas makes it a suitable fuel in any country for heating and cooking purpose. Biogas can also be used in an anaerobic digester where the energy in the gas is converted into electricity and heat using gas engine (Sorathia et al., 2012).

In as much as the biogas constitutes mainly methane and carbon dioxide, which are greenhouse gases that are harmful to the environment. It is therefore important that it undergoes a burning process before releasing it to the atmosphere. The physical, chemical and biological characteristic of cassava and other potential biomass can influence the biogas composition and yield (Mogami et al., 2006). In general, three key methods are in the thermo-chemical conversion of biomass. The main thermo-chemical conversion processes, the intermediate process and the final energy products resulting from conversion procedure are given in Figure 1.

2.1. AD

The AD is a microbial degradation of organic waste in the absence of oxygen. Organic matter conversion to CO_2 and CH_4 gases occurs next to a sequence of biochemical reactions during an anaerobic process (Bailey and Ollis, 1986). As a result, a breakdown of organics takes place during the digestion, and this is made possible by anaerobic microorganisms. The AD of organic matter follows stages that are organized by different categories of microorganisms. Most biodegradable organic matter are converted to gases while only a small amount (about 10%) is converted to new cell mass through microbial growth (Speece, 1996). Methane produced by AD can be used to run a treatment plant; giving AD an economic advantage over aerobic digestion. Table 2 shows the advantages and disadvantages of an AD taking into consideration costs, start-up time, sludge generation and buffering capacity.

2.2. Stages of Biogas Production using AD

There are four basic stages involved in AD. These four basic stages make up the process of biogas production from various organic materials as it occurs in an anaerobic digester. These four stages are the hydrolysis, acidogenesis, acetogenesis, and methanogenesis as outlined in Figure 2 (Tutuk, 2011). The AD process is characterized by the decomposition of organic matter into methane, carbon dioxide, inorganic nutrients and compost in an anaerobic environment (Arsova, 2011, Ayu and Dyan Aryati, 2010).

2.2.1. Hydrolysis

Hydrolysis in AD is the first step in the process. It is achieved through the solubilization and degradation of biopolymer particulate organic compounds and colloidal wastes into soluble

Table 1: Biogas composition (Prakash et al., 2005, Schnurer and Jarvis, 2010)

Component	Concentration (%)
Methane (CH_4)	55–60
Carbon dioxide (CO_2)	35–40
Hydrogen (H_2)	2–7
Hydrogen sulphide (H_2S)	2
Ammonia (NH_3)	0–0.05
Nitrogen (N)	0–2

Figure 1: The main processes used for the thermo-chemical conversion of biomass (Mckendry, 2002)

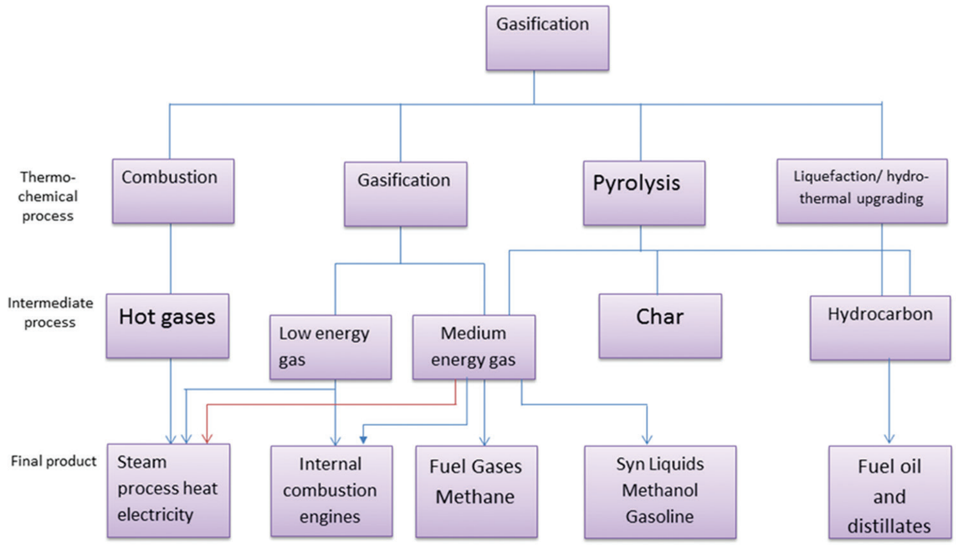


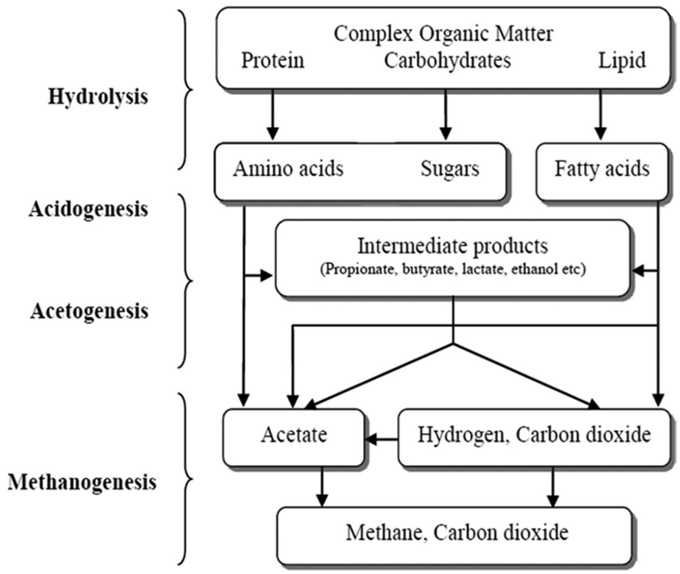
Table 2: Advantages and disadvantages of AD process (Seghezzo et al., 1998, Lettinga et al., 1997, Lettinga, 1995)

Advantages of AD process	Disadvantages of AD process
The operating costs for an anaerobic treatment plant are relatively very low compared to an aerobic treatment plant	Long start-up: the slow growth rate causes as a longer start-up period as compared to aerobic systems
Low-energy consumption and production of biogas for further applications such as the production of electricity; also the system does not require external energy for its operation	High buffer requirements for the pH control: The required pH for AD should be in the range of 6.5–8. Also, chemical addition, mostly in industrial wastewater, may be indispensable for the control of pH with inadequate buffering capacity
The flexibility of an anaerobic system allows the technology to be applied on either a small or a large scale	High sensitivity of microorganisms: Methanogens are sensitive to pH and temperature, it is assumed that they have less resistance toward toxic compounds
Low sludge generation compared to aerobic systems due to a lower yield coefficient	Low pathogen and nutrients removal: Effluents generated from AD are characterized by low removal of pathogens and nutrients. A post-treatment process such as membrane filtration is required to meet the discharge guidelines aiming to protect the environment
The excess sludge is well stabilized thereby resulting to limited environmental impact	The process is more sensitive to the presence of toxic compounds and changes in temperature than aerobic systems
Low nutrient and chemical requirement: This is due to the small biomass production during an anaerobic process; consequently, the nutrients requirement is proportionally less	
Allows for efficient resource recovery, and conservation of non-renewable energy sources	

AD: Anaerobic digestion

monomeric or oligomeric organic compounds (Gerardi, 2003). This process involves the decomposition of complex organic polymeric materials such as carbohydrates, proteins and lipids. These complex organic compounds are hydrolyzed into smaller, water-soluble compounds such as sugars, amino acids, and long chain fatty acids by enzymes produced by the fermentative bacteria (microorganisms) (Eastman and Ferguson, 1981). At the end of the hydrolysis stage, a simple organic compound is produced. These products thereafter undergo absorption and degradation by different facultative and obligate anaerobic bacteria in the acidogenic step, producing short-chain volatile fatty acids (VFA). These combine with alcohols and are converted to acetate, hydrogen and carbon dioxide (Chandra et al., 2012). This phase involves hydrolyzing polysaccharides into monosaccharides, fats into glycerine and fatty acids and proteins into amino acids (Parawira et al., 2004, Lyilade, 2009). The enzymatic catalysis accelerate the hydrolysis process through oxidation of the organic matter via a process called aerobic biological processes (Pisano, 2007). The hydrolysis and aerobic degradation process is a rapid process and the biogas produced is transformed into carbon dioxide (CO_2) from oxygen (Pisano, 2007). When the substrate has been hydrolyzed, it becomes available for cell transportation and the fermentative bacteria can then degrade these substrates during the acidogenesis stage. Optimization of the hydrolysis process is, however, important to prevent inefficient degradation of the macromolecules, which could impact negatively on the rate of digestion or other biological activities, and consequently the biogas yield. It is therefore important to make sure that the culture of microorganisms is actively operational to allow the second process (acidogenesis) to take place. Physicochemical treatments can also be used to promote solubilization of organic matter. However, there should not be air intake in the system, as the presence of air in the biomass will not allow the biomass to perform their duties as anaerobic units.

Figure 2: Biochemical stages of anaerobic digestion/biogas product (Jewitt et al., 2009)



2.2.2. Acidogenesis

The process of acidogenesis transforms the organic acid that is produced during the second stage into acetic acid, acid derivatives, carbon dioxide, and hydrogen. According to (Fang et al., 2010), it is essential that the level of H_2 is low for acidogenic reactions to be favourable thermodynamically. In this stage of the AD process, the products of the hydrolysis stage are further broken down by a variety of obligate and facultative fermentative microorganisms to produce weak acids (mostly organic acids) such as acetic acid, propionic acid, butyric acid (VFAs), lactic acid, alcohols, hydrogen and carbon dioxide (CO_2) (Kalyuzhnyi et al., 2000). The acidogenesis stage involves the production of high concentration of hydrogen by acid-producing bacteria called acidogenic microorganisms and is usually the fastest step in a balanced anaerobic process. Acidogenesis is mainly described by the accumulation of lactate, ethanol, propionate, butyrate, and higher VFAs called electron sink or intermediate products. Acidogenesis is the bacterial response to increased hydrogen concentration in the system to produce acetate by acetogenic microorganisms (Schink, 1997). The degradation of organic matter to generate biogas also depends on the complex interaction of various groups of bacteria, with the two main groups being the acid-producing bacterial (acidogens) and the methane-producing bacteria (methanogens). Therefore, maintaining a symbiotic relationship between the acidogenic and methanogenic bacteria is critical in sustaining the successful operation of any anaerobic digester (White, 2011). This step is critical because it links the fermentation phase with the methane production phase. Thus, more acid is produced to give birth to methanogens elements, which produce methane gas.

2.2.3. Acetogenesis

During the acetogenesis stage, alcohols (ethanol), VFAs with more than two carbon atoms, are converted by acetate-forming bacteria into acetate, with hydrogen and carbon dioxide being the main products (Parawira et al., 2004; Gerardi, 2003). This conversion is a vital process because hydrogen and carbon dioxide are constantly reduced to acetate by homoacetogenic microorganisms (Chandra et al., 2012), thereby reducing the hydrogen accumulation that may affect the functioning of acetogenic bacteria (Weiland, 2010). Low hydrogen partial pressure (10.4 and 10.6 atm) is required for the acetogenic reaction to proceed (Mccarty and Smith, 1986). This is because acetogenic bacteria can survive in a very low hydrogen concentration environment. However, further increase in the concentration of hydrogen partial pressure may result in acetogens losing their ability to produce acetate. In order to ensure that low pressure is maintained all through the acetogenesis stage of the AD process, a mutually symbiotic relationship between the acetogens and the hydrogenotrophic methanogens must occur, so that acetogens produce acetate that can be used as substrate by methanogens (Nges et al., 2012). This step constitutes the final phase for fermentation prior to methanogenesis.

2.2.4. Methanogenesis

Methanogenesis is a critical step in AD. It has a large impact on the AD process (De Vrieze et al., 2012) because approximately 70% of methane used in AD is generated from this stage (Sutaryo, 2012). During this stage, carbon dioxide-reducing and hydrogen-oxidizing methanogens convert hydrogen and carbon dioxide to obtain methane, while acetoclastic methanogens utilize acetate to produce methane (Parawira et al., 2004). Methanogens (Archaea) utilize acetate, hydrogen and CO_2, and to a lesser extent methanol, methylamines and formate, to form methane and CO_2. These end products are the primary substrates for the methanogenic bacteria to produce biogas, which generally consists of 50–75% methane (CH_4), 50–25% CO_2 and trace amounts of nitrogen, hydrogen and hydrogen sulphide. Methanogenesis indicates the extent of biological activities in an anaerobic system and the state of the digestion. The more methane is produced, the more the system is stable and well performing.

2.3. Main Factors Affecting the Biogas Production

The production of biogas is influenced by many factors such as nutrients, pH of feedstock, temperature, flow rate of feed (loading rate) and retention time. These factors may slow or stall the process of biogas production if the values of the factors are not within a certain range (Angelidaki et al., 2009). Some of the factors are presented in this section.

2.3.1. Hydraulic retention time (HRT)

HRT indicates the mean residence time for solids and liquids wastes remaining in a digester (reactor) to contact with the microbial biomass (Khanal, 2008a). In flow-through systems without recycle, such as the CSTRs adopted in Phase II, the HRT and retention time of the microbial biomass or sludge (SRT) are the same. In situations where the influent streams contain high solids concentrations, longer retention times are required to maximize bioenergy production (Khanal, 2008a). The HRT can be understood as the treatment time for a waste that undergoes AD, the higher the HRT the higher the removal efficiency because the biomass has enough time to be in close contact with the waste, therefore removing high amounts of contaminants from the waste being treated.

2.3.2. Nutrients

The inadequate availability of nutrient concentration in energy crops have resulted in problems such as low methane yields, acidification and process instability in crop monodigestion, leading to application of low organic loading rates (OLRs) and long HRTs (Lebuhn et al., 2008; Weiland, 2010). They influence the performance and stability of the AD process (Hinken et al., 2008; Lebuhn et al., 2008; Scherer et al., 2009). The abovementioned setbacks indicate that adequate amounts of both macro- and micronutrients (Bruni et al., 2010) are crucial for continuous performance of the biogas process.

2.3.3. pH of feed stock

The pH value of the material is one of the essential factors. Methanogenic bacteria are sensitive to an acidic condition. This acidic condition could adversely affect the growth of bacteria and the production of methane (Arsova, 2011). Different optimal pH values are reached at different stages of the AD process. These changes occur during biological transformation, which takes place during the different stages of the AD process. The pH level can be below 5 during the production of organic acids, which occurs during the acetogenesis stage (Arsova, 2011). According to Liu et al. (2008), the optimal range of pH for obtaining utmost biogas yield in AD is 6.5–7.5, and this range of pH is relatively wide in the plants. Several factors such as the substrate used and the digestion technique could vary the optimal value of the pH. For this reason, constant pH level is of great importance, and to maintain a constant pH level, equilibrium buffers such as calcium carbonate or lime has to be added into the system. Briefly, pH is a critical indicator in anaerobic process. It provides a clear indication of the performance of the system, including the stability of the digestion. A lower pH is an indication of system failure or low buffering capacity and can inhibit the digestion. High pH can also limit the methanogenesis process. The pH value is dependent on the following factors: VFA concentration, bicarbonate concentration, the alkalinity of the system and the fraction of CO_2 in digester gas. According to Liu et al. (2008), the relationship between the VFA and bicarbonate concentration is crucial to maintain a constant pH value within the system.

2.3.4. Temperature

As reviewed by Davidsson et al. (2008), AD is usually operated within two distinct temperature ranges, with one optimum at 35°C (mesophilic) and the other optimum at 55°C (thermophilic). Though thermophilic digestion may provide some advantages over mesophilic digestion, such as improved reaction rate and pathogen reduction, microorganisms in mesophilic digestion have less demand on nutrients (Takashima et al., 2011) and mesophilic digestion can function like thermophilic digestion (Nges et al., 2012). Temperature indicates the rate of biological reactions. It is a sensitive parameter that has to be monitored regularly, especially when there is a change in weather. The choice of temperature (mesophilic or thermophilic) will depend on the type of expected outcome. However, temperature should be suitable to the type of microorganisms used for waste treatment.

2.3.5. OLR

The amount of substrate (biomass) fed into the unit reactor system is called the OLR and is commonly expressed in terms of chemical oxygen demand kg/m^3•day, volatile solids (VS) of total solids (TS)/L•day or VS/m^3•day. It has been reported that the AD of solid wastes in a single stage may encounter problems if the OLR is increased above the system capabilities and that the hydrogen and the VFAs formed by the acidogenic bacteria are not consumed at the same rate by the methanogens. This is because acidogenic activity and the VFA intermediates produced in the acid forming stages triggers an increase in the acidogenic bacteria at higher OLRs, thereby reducing the growth of the methanogenic population. The increase in OLR and acidogenic activity (production of VFA, CO_2 and H_2) can result in an accumulation of organic acids and a decrease in pH and gas production. This in turn affects the biological activity of methane-producing methanogens as their growth is inhibited below a pH of 6.6, therefore reducing the production of methane, which is the main product of biogas. Therefore, determining the correct OLR for a particular substrate is critical for the optimization of reactor performance and maximizing methane production. The methane yield is generally measured by the amount of gas that can be produced per unit volume of VS contained in the feedstock after exposing it to AD for a sufficient amount of time under a given temperature and specific conditions (Zhang, 2012). The methane yield is also an indication of the biodegradability of the substrate, as feedstock with low VS/TS, such a lignin, are not easily degraded using anaerobic processes. Therefore, the amount of gas produced is also very much substrate dependent.

2.3.6. Retention time

A longer retention time will provide a greater degree of sludge stabilization and allow intimate contact between the biomass and the liquid flow during the treatment process (Keay, 1981).

2.3.7. Mixing

In a conventional anaerobic digester, mixing has been observed to generally increase CH_4 yields and to render the digester more stable (Forday and Greenfield, 1983). Mixing has the effect of bringing a homogeneous environment and an effective use of the entire digester volume. This is achieved by minimizing hydraulic dead zones in the digester and preventing build-up of large pockets of unfavourable environmental conditions (low pH and high VFA). Consequently, the concentration of toxic agents throughout the reactor is diluted. Mixing also assists in the removal of excess CO_2 which has inhibitory effects at partial pressures larger than 0.2 atmospheres (Pulles et al., 2001).

2.3.8. Oxygen

Oxygen is toxic to most anaerobic microorganisms. Its presence in an anaerobic reactor will result in a significant decrease in the digestion rate. However, it is possible that facultative anaerobes metabolize the dissolved oxygen before toxic effects are noticeable (Zinder and Koch, 1984).

2.3.9. VFA

During start-up or when there is organic overloading of the digester, high concentrations of VFA are generally observed. They are usually associated with toxicity and inhibitory effects. Although it is generally understood that VFA inhibition is due to their accumulation and subsequent pH reduction, some VFA are themselves toxic to anaerobic microbes (Mara and Horan, 2003).

2.3.10. Free ammonia

Free ammonia concentrations above 100 mg/l can cause inhibition, although the ionic form, NH^{+}_{4}, will only cause inhibition at much higher concentrations (above 3000 mg/l) (Rittmann and Mccarty, 2012).

3.2. Methods of Biogas Production through AD

It is well known that AD turns organic waste into useful biogas and fertilizer in an anaerobic environment. There are two main methods to produce biogas from AD, namely wet AD (Wet AD) and dry AD (Dry AD). The main difference between these two methods relates to the form of the solid waste. Dry AD handles organic waste as it is by means of simple mechanical sorting and with digestion taking place from waste in its solid form. Wet AD requires that the waste be converted into a homogenous pulp that can be pumped while being processed. Biogas produced during AD is mainly composed of methane and carbon dioxide and is considered as an alternative to traditional energy (Khanal, 2008b). Typically, it contains 60–65% methane, which is flammable. With the technology of biogas utilization improving, it becomes one of the most widely used waste/residues-to-energy technologies (Khanal, 2008a). Traditionally, biogas has been used as fuel to support the process temperatures in anaerobic digesters. Another alternative use is that the gas is burned in an engine generator of combustion to produce electricity in biogas plants. Biogas has also been used as fuel for cooking, lightning and vehicles (Khanal, 2008a).

Biogas production, except for its use as a renewable energy source, has many other benefits. In many countries, farmers must give up their occupations because their land no longer produces enough yield from conventional agricultural production. Biogas production is subsidized in many countries to give an additional income to the farmers. There is an increase in wider unused agricultural areas and farms becoming large-scale industries, which will change the landscape. Biogas production with small-scale farm production could maintain the structure of the landscape. Energy can be generated from the unneeded biomasses, which can save the natural resources. Comparing anaerobic degradation metabolism products to aerobic ones, organic acid and methane contain higher energy than low-energy compounds CO_2 and H_2O, which serve other organisms as nutrients or energy as 20 times as much as the energy lost to air. Biogas plant can also reduce landfill area and protect groundwater quality.

Due to anaerobic processes, organic matters can be reduced to 4%, which reduces landfill area and protects the groundwater. Furthermore, because the reduction of biomass is significant, the reuse of the residue from biogas processes, such as fertilizers, can cut down the expenditure of organic wastes. If co-substrates are used in biogas plants, mineral fertilizers can be replaced by residue. The advantages include cutting down expenditure. Co-substrates can reach the cycle of nutrients and reduce nitrate leaching. Methane and nitrous oxide emissions are reduced when residue and manure are digested instead of being spread on the field or stored. The digested residue produced is less odorous. This process also supports the Kyoto agreement of climatic protection by achieving CO_2-neutral production of energy. It can reduce the fees for the management of wastewater and avoid the connection of sewers, especially in rural areas. Also, a significant reduction in pathogenic germs could be derived from the digested residue after an anaerobic process.

4. TYPES OF BIOMASS AND THEIR POTENTIAL

Biomass is defined as a living organic matter (Fry, 1988). Biomass can be any type of organic matter and it is a source/feedstock. The fuel form obtained after the processing or preparation of this biomass is called biofuel, biogas or bio-solid and the energy output is called bioenergy, which is a measure of the energy capability of the biomass used. An extensive range of biomass is available for the potential sources for CH_4 production as shown in Figure 3.

4.1. Terrestrial Biomass

4.1.1. Biogas from woods and weeds

AD of woody biomass for biogas production has been considered unfeasible without pre-treatment (Nallathambi, 1997) due to its anaerobic biodegradability, which depends on the following factors: low moisture content; relative lignin; cellulose and hemicellulose content; proportion of structural and non-structural carbohydrates; cellulose crystallinity; degree of association between lignin and carbohydrates; particle size; wood-to-bark ratio; and toxic components (Turick et al., 1991). Table 3 shows that hybrid poplar and sycamore with high degradability produced the highest CH_4 yield of 0.32 m^3/kg VS using the BMP assay test, while according to (Tong et al., 1990) eucalyptus, loblolly pine and white fir on poor degradability yielded 0.014, 0.063 and 0.042 m^3/kg VS of CH_4 respectively at mesophilic temperature.

The use of weedy plants as a potential feedstock for biogas production is a recent concept. It is considered a potential biomass for the following reasons (Nallathambi, 1997):

- It has the ability to trap a significant amount of solar energy.

Figure 3: Methane yield from different biomasses (Luna-Delrisco et al., 2011)

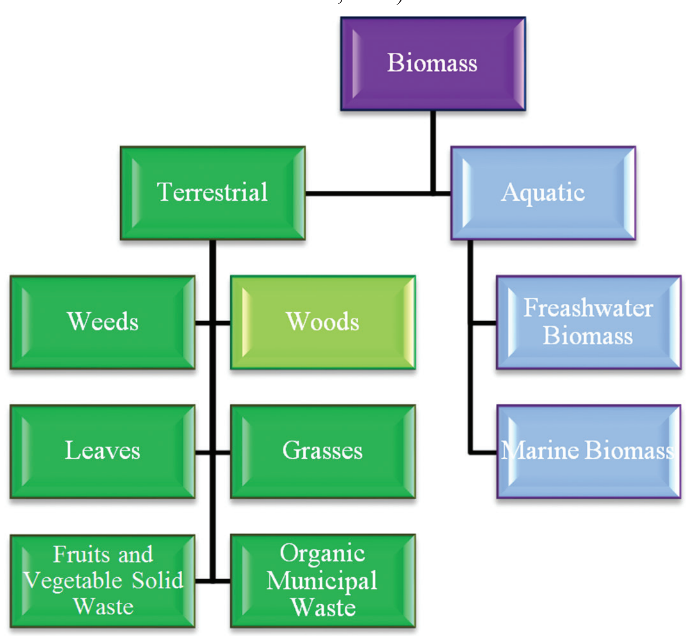


Table 3: Methane yield of woody biomass

Feed stock	Fermenter	Temperature (°C)	Methane yield (m^3/kg VS)	VSr (%)	Reference
Cotton wood	BMP	35	0.220	32.3	(Gunaseelan, 1997)
Hybrid poplar	BMP	35	0.320	53.8	
Sycamore	BMP	35	0.320	56.7	
Loblolly pine	BMP	35	0.063	3.6	
Eucalyptus sp	BMP	35	0.014	1.0	
Black alder	BMP	35	0.240	32.5	
Red alder	BMP	35	0.280	48.4	
White fir	BMP	35	0.042±0.003	NR	(Tong et al., 1990)
Willow	BMP	35	0.140±0.01	NR	(Turick et al., 1991; Chynoweth et al., 1993)
Stem and bark 0.8 mm particle size	BMP	35	0.310±0.01	NR	
Poplar stem and bark	BMP	35	0.290±0.010	NR	
Sweet gum	BMP	35	0.210±0.010	NR	
Poplar wood - 0.003 mm size	BMP	35	0.330	NR	(Chynoweth et al., 1993)

BMP: Biochemical methane potential, VSr: Volatile solid reduction, NR: Not recorded

- Weeds can grow on soils unsuitable for conventional crop production under a wide range of climatic conditions.
- Weeds are not easily affected by pests.
- Weeds grow without inputs and irrigation.
- The use of weeds for biogas production is considered the best strategy of weed management and control.

Table 3 shows some of the weeds studied as a source of $CH_{4,}$ these weeds include Parthenium hysterophorus, Lantana camera, and Ageratum. According to Gunaseelan (1994), the batch co-digestion of cow manure (CM) and Parthenium has shown to increase the production of biogas using Parthenium. AD of Parthenium in CSTR at a temperature of 30°C with a 10-day HRT yielded CH_4 of 0.11 m^3/kg VS while pre-treated Parthenium increased the CH_4 yield by 95% (Table 4). Lantana camera, a weed that grows abundantly on the Himalayan slope, India, treated with NaOH and mixed with CM to feed batch digesters for 37 days at a temperature range of 28–31 °C produced 62% higher CH_4 yield compared to CM alone (Dar and Tandon, 1987; Gunaseelan, 1994). Table 4 shows that Ageratum alone (mono digestion) yielded 0.24 m^3/kg VS added of CH_4 yield in batch digesters at a temperature of 30°C (Kalia and Kanwar, 1990).

4.1.2. Biogas from leaves and grass

According to Chynoweth et al. (1993), methane produced from leafy biomass are generally higher compared to that produced from the stems (Table 5). As reported by Sharma et al. (1988), Ipomoea jistulosa leaves yielded more CH_4 compared to that of the stem. According to (Gunaseelan, 1988), Gliricidia leaves green-leaf manuring found in India when it undergoes AD yielded a CH_4 of 0.18 m^3/kg VS_{added} when co-digested with residue of high manorial value. However, some leaves with the presence of some toxic compound produced low CH_4 due to partial inhibition of the digestion process. One such leaf is Calotropis (Mahamat et al., 1989). Research conducted by Shyam and Sharma (1994) showed that the batch digestion of high solids with mango leaves and CM produced higher biogas yield compared to digestion of CM alone.

Literature shows that grasses such as Napier grass, energy cane (ball milled), Alemangrass-6A, turf grass, wheat straw, paddy straw, millet straw, oats crop, maize crop, corn stover and sorghum exhibited CH_4 yields as high as 0.3 m^3/kg VS added without pre-treatment (Chynoweth et al., 1993). As reported by (Turick et al., 1991), the grass with the highest yield of CH_4 is sweet sorghum. In grass the age of the grass plays an important role as younger grasses produce more methane than the older ones, probably because younger tissues are less lignified (Shiralipour and Smith, 1984).

4.1.3. Biogas from fruit and vegetable solid waste (FVSW) and organic MSW (OMSW)

The organic fraction of MSW has been identified as a diverse material of which the composition differs greatly. Many factors affect the composition of MSW, including regional differences, climate differences, the extent to which recycling is done, the frequency of collection, seasonal change, and cultural practices (Tchobanoglous et al., 1977). The sorting system of MSW is not the only factor that influences the qualities, they are also influenced by various methods used for quantifying the OMSW. According to Mata-Alvarez et al. (1990), mechanical sorting of MSW is present in large amounts of suspended, non-biodegradable solids and small pieces of plastic, wood and paper. OMSW digestion at a mesophilic temperature (35°C) yields a maximum CH_4 ranging from 0.39 to 0.43 m^3/kg VS MSW without paper and wood (Mata-Alvarez et al., 1990) and VS reduction (VSr) ranging from 63 to 69% (Table 6). The methane yield of OMSW ranged from 0.11 to 0.16 m^3 kg-VS and VSr was around 30% due to its high ash value (Mata-Alvarez et al., 1990).

The FVSW wastes are characterized by high percentages of moisture (>80%) and VS (>95%) and have a very high biodegradability percentage. Table 6 shows that the CH_4 yield of FVSW is very high. However, these results are mostly based on laboratory trials. According to Knol et al. (1978), the maximum OLR to obtain a stable digestion of a variety of FVSW ranges from 0.8 to 1.6 kg VS mm^3/d having an HRT of 32 days. According to (Hills and Roberts, 1982), the failure of the digestion of peach waste is due to inadequate alkalinity levels at 3 kg/m^3/d with a 20 days HRT.

Research conducted by Radhika et al. (1983) show that coconut pith (CP) co-digested with CM performed better with a mixture ratio of 3:2 dry weight basis that also showed enhanced biogas production with 80–85% CH_4.

According to a study conducted by Stewart et al. (1984) where the biogas yield from the AD of banana, i.e. damaged fruit and stem, and potato waste was measured (peelings and rejects). The digestion

Table 4: Methane yield from weed biomass

Feed stock	Fermenter	Temperature (°C)	HRT (days)	OLR (kg VS m³/day)	Methane yield (m³/kg VS)	VSr (%)	Reference
Parthenium Hysterophorus (PH)	Semi-continuous	28 – 32	5	4.95	0.034 ± 0.002	25.9	(Gunaseelan, 1994)
PH, untreated, daily Feed			10	2.48	0.117 ± 0.005	42.9	
			20	1.24	0.115 ± 0.001	42.1	
Lantana camera, NaOH Treated + CM (50:50 w/w)	Batch 3l	28-31	NA	NA	0.236	NR	(Dar and Tandon, 1987)
Ageratum, partially decomposed	Batch 3l	29-31	NA	NA	0.241	NR	(Kalia and Kanwar, 1990)

NA: Not available, NR: Not recorded, HRT: Hydraulic retention time, OLR: Organic loading rate, VSr: Volatile solids reduction, VS: Volatile solids

Table 5: Methane yield from grassy biomass (Gunaseelan and Lakshmanaperumalsamy, 1990; Gunaseelan, 1995; Yang and Li, 2014)

Feedstock	Fermenter	Temperature (°C)	Hrthrt (days)	OLR (kg VS m³/day)	Methane yield (m³/kg VS)	VSr (%)	Reference
Penniselum Purpureum (Napier Grass)							
Age: 120 days	BMP	35	NA	NA	0.310	NR	(Gunaseelan, 2007)
180 days					0.260		
Energy cane							
Ball milled	BMP	35	NA	NA	0.320	NR	
Particle size 0.8 mm					0.240		
Particle size 8.0 mm					0.290		
Grass mixture							
Wheat straw							
20 mm size	Batch l litre	35–39	NA	NA	0.255	79	(Ge et al., 2014)
0.5 mm size				0.327		91	
Sugarcane hybrids							
US 72-1288	BMP	35			0.277±0.028	NR	

OLR: Organic loading rate, BMP: Biochemical methane potential, VSr: Volatile solid reduction

Table 6: Performance of MSW at mesophilic temperatures

Subtract	Fermenter	Temperature (°C)	HRT (days)	OLR (kg VS m³/day)	Methane yield (m³/kg VS)	VSr (%)	Reference
MS-OMSW	Laboratory plant	35–40	16–21	10	0.260	NR	
Conc=30–35% TS	0.035 m³			12.1	0.264		(Lemmer and Oechsner, 2002)
	Dranco process				0.260		
Conc=25–35% TS	60 m³	35–40	14–21	15	0.187	NR	
Yard waste	BMP	35	NA	NA	0.209	NR	(Owens and Chynoweth, 1993)
Grass, VS=88.1%TS					0.123		
Leaves, VS=95% TS					0.134		
Branches, VS=93.9%TS					0.140		
Blend, VS=92% TS				NA	0.255		
Paper Waste							
Office, VS=92.7%TS	BMP	35	NA	NA	0.369	NR	(Owens and Chynoweth, 1993)
Printed newspaper VS=97.6% TS					0.100		
Unprinted newspaper, VS=97.9%TS					0.084		
Magazine, VS=78.1%TS					0.203		

VS: Volatile solids, VSr: Volatile solid reduction

was done in a 20 *l* continuous digester at a temperature of 35°C. The greatest CH_4 yields were obtained from the complete digestion of the banana waste, which is almost a complete destruction of the VS. For a HRT of 20 days with OLR 2.5 kg TS/m³/d, the CH_4 yield for banana waste was 0.53 m³/kg VS at 100% VS conversion.

4.1.4. Aquatic biomass

Biogas production from aquatic biomass may be greater compared to the land on the basis of the availability of large areas for growth. Terrestrial biomass production is two-dimensional, while aquatic biomass production is three-dimensional where the "height" is added.

4.1.4.1. Biogas from marine biomass and fresh water biomass

Recent studies on marine biomass involve the bioconversion of marine macroalgae to a potential source for CH_4. This includes the brown algae *Macrocystis pyrifera*, *Sargassum*, *Laminaria* etc. Table 7.

5. FUTURE STUDIES

The global demand for energy is increasing with the steady growth of the world population, economic growth and increased energy

Table 7: Summary of biomass with high methane yield

Biomass	Methane yield (m^3/kg VS)	Reference
OMSW		
HS-OMSW	0.390	(Cecchi et al., 1986)
SC-OMSW	0.403	(Mata-Alvarez et al., 1990)
SS-OMSW	0.399	
Fruit and vegetable solid waste and leaf		
Potato waste	0.426	(Stewart et al., 1984)
Carrot waste	0.417	(Shen et al., 2013)
Banana fruit and stem	0.529	(Murphy et al., 2011)
Tomato processing waste	0.420	(Sarada and Joseph, 1994)
Banana peeling	0.409±0.002	(Izumi et al., 2010)
Grassy biomass		
Sorghum	0.420	(Gunaseelan, 2004)
Corn stover	0.360	(Gunaseelan, 2007)
Paddy straw	0.367	(Mshandete et al., 2006)
Milet straw	0.390	(Mahamat et al., 1989)
Wheat straw	0.383	(Hashimoto, 1986)
Woody biomass		
Iponnoea stem	0.426	(Seppälä et al., 2007)
Poplar wood	0.330	(Gunaseelan, 2004)
Pre-treated vine shoot	0.315	(Odlare, 2005)
Weed biomass		
Lantana treated with NaOH+cow manure	0.236	(Dar and Tandon, 1987)
Partially decomposed Ageratum	0.241	(Kanwar and Guleri, 1995)
Parthenium treated with NaOH	0.236	
Marine biomass		
Ulea and *Chaetomarpha*	0.480	(Hansson, 1981)
Ulea	0.330	(Bohutskyi and Bouwer, 2013)
Maerocystis pyrifera	0.310	(Ogut et al., 2013)
Freshwater biomass		
Pisitia	0.410	(Nipaney and Panholzer, 1987)
Water hyacinth treated with NaOH	0.362	(Chynoweth et al., 1982)

OMSW: Organic municipal solid waste, VS: Volatile solids

usage. Reliance on fossil fuels has also increased over the years and will soon result in the depletion of fossil fuel resource. It is therefore crucial that current research studies explore alternative energy sources that are sustainable and renewable for future generations. The renewable energy generation during AD of biomass has mainly been used for the degradation of biomass or any waste materials or toxic compounds. However, recently there has been increased interest in the production of biogas from carbohydrate rich energy crops by means of AD. Since cassava is enormously grown in Africa, extensive experimental studies into different nomenclature that can give high yield of biogas from cassava can be performed. Some of the research question may include:

- Can cassava single and co-digested with vegetable and fruit waste be a successful and suitable AD feedstock for biomass renewable energy in Africa?
- Can the link between peeled and unpeeled cassava tubers be exploited to evaluate biogas yield from cassava and the effect of the cassava peels on the yield?
- How can cassava as an energy crop be used as a landfill cap in decommissioned landfills in Africa for purpose of biogas energy generation?

Future studies can also be conducted on small scale biogas production technology selection, production scheduling under uncertainty in feedstock supply, farmers perceptions on biomass crops and the impact of biomass plant production on host communities. Furthermore, assessment of small-scale biogas production subsidies in rural communities and employment issues can also be investigated. Investigations into these research gaps will strengthen biogas production management and sustainability in rural communities.

6. CONCLUSION

A review of the AD process and biogas production has been presented in this study. Technologies and processes involved in the production of biogas from AD have proven to be a valuable means for alternative renewable energy generation. Within the anaerobic domain, several important factors (pH, temperature, retention times, and availability of nutrient and OLRs) were identified to exert a high degree of influence on the different steps of the digestion process. In addition, depending on the source of the waste stream, several toxic or inhibitory compounds could be harmful to AD, thereby affecting biogas production and/or methane gas concentration. The evaluation and optimization of the anaerobic process should therefore be considered as an important step towards the realization of optimal biogas production from the AD process.

It would help in obtaining the necessary information on waste components crucial for successful application of AD. Furthermore, continued research on AD to evaluate different types of waste streams and biomass feedstocks as substrates for different digester configurations and the development of processes that would increase the kinetics reaction, to increase the CH_4 yield is essential.

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