

Biogas Production Using the Organic Fraction of Municipal Solid Waste as Feedstock

R. Kigozi, A. Aboyade and E. Muzenda*

Abstract— Biogas typically refers to an odourless gas produced by anaerobic digestion (AD) of biomass using microorganisms. It has an approximate composition of 70-50% Methane (a combustible gas), 30-50% Carbon dioxide and other trace gases depending on the nature of the biomass. The idea of using the organic fraction of municipal solid waste (OFMSW) or simply municipal biowaste as feedstock for biogas production represents an environmentally sustainable energy source since it improves solid waste management while simultaneously providing an alternative clean energy source. Among other applications, the gas can be used for heating, cooking and electricity generation. However, notwithstanding, OFMSW as a feedstock for AD comes with its own unique challenges compared to other forms of biomass. This paper therefore reviews the specific opportunities, challenges and techno-economics of using OFMSW as sole feedstock supply for biogas production.

Keywords— Anaerobic Digestion, Biogas, Environmentally Sustainable, Organic Fraction of Municipal Solid Waste

I. INTRODUCTION

ANAEROBIC digestion of biomass for energy production dates back as far as the 10th Century B.C with the earliest available record being around the 19th century. The first anaerobic digester was built in Bombay India in 1859 and the first notable use of biogas in England also dates back to the same year [1]. Over the years, farm based manure has been the most extensively used feedstock for biogas digesters. However other sources have gradually been adopted as alternatives including biowaste, food crops, faecal sludge and municipal sewerage among others [2].

The synthesis of biomass to produce energy is a growing trend worldwide as the quest for clean energy alternatives instead of the traditional fossil fuels intensifies. In this regard, there have been several technologies developed such as the synthesis of bioethanol from Sugar rich energy crops such as corn, the making of biodiesel from vegetable oils and animal fat as well as the production of biogas by anaerobic digestion of biomass among others. However, most of the proposed energy crops also double as food crops, a report by the Food and Agricultural Organisation (FAO) of the United Nations

(2008) indicated that increased use of food crops for bioenergy production in a bid to increase its supply will lead to increased food prices. This in the short run will help agricultural economies to grow significantly but in the long run will lead to food insecurity in developing nations [3]. Therefore, to prevent the risk of increased global food insecurity, alternative types of biomass for bioenergy production should be introduced other than food crops [4]. In this context, other energy crops have been proposed such as *Jatropha* for bioenergy production. But just like food crops, all planted biomass requires resources such as land and water to be able provide a sustainable biomass supply and yet both land and water are also very vital resources for the global energy balance. This therefore disqualifies planted biomass as the best source for bioenergy production [5] [6]. Other than energy crops, bioenergy in the form of biogas can still be produced from biodegradable wastes through AD [7]. It is in this view that the concept of using the organic fraction of municipal solid waste as a feedstock for biogas production becomes a promising potential solution towards the production of alternative environmentally friendly and sustainable energy [5] [6].

World over, urbanisation is on the increase leading to increased waste generation and reduction in available space within urban centres. The waste generated is commonly sorted for recycling and the non-recyclables which are usually the large percentage are taken to landfills. The issue now is the continuously reducing space for landfilling as well as the continuous emissions of landfill gas containing mostly methane which is a potential greenhouse gas [8]. A report by FAO in 2011 showed that at least 33% of the global food supply goes to waste annually totalling to 1.3 billion tonnes of food waste worldwide [9]. If this waste is used for biogas production, it can yield up to 367m³ of biogas per dry tonne at approximate 65% methane with energy content 6.25kWh/m³ yielding 894TWh annually which is about 5% of the world's electricity needs [8]. In 2011, South Africa generated 59 million tons of municipal waste of which 13% was classified as organic waste and another 35% classified as non-recyclable waste [10]:

Biogas produced by anaerobic digestion can be economically manufactured at both small and large scale plants and therefore can be tailored to supply rural and urban gas needs as well as meet regional and nationwide energy demands [2]. The quality of raw biogas can be further upgraded by enriching its methane content up to the natural gas level (75-98%). After methane enrichment and compression, it can be used as a vehicular fuel just like Compressed Natural Gas (CNG). Biogas has lower emission rates than natural gas or any other fossil fuel for that matter hence possesses much less potential for polluting the

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environment compared to fossil fuels as shown in table 1 below [11].

TABLE I

COMPARISON OF GASEOUS EMISSIONS FROM HEAVY VEHICLES [11]

g/kg	CO	HC	NO _x	CO ₂	Particulates
Diesel	0.20	0.40	9.73	1053	0.100
Natural Gas	0.40	0.60	1.10	524	0.022
Biogas	0.08	0.35	5.44	223	0.015

Biogas is now widely used in developing countries as an alternative and renewable source of energy for wide spread range of applications including among others cooking, lighting and heating in households. The digestate from anaerobic digestion is a very useful fertilizer in agriculture. In contemporary times, biogas has been used most extensively on small and large scales in India and China. Currently in Germany and Sweden, biogas technology is in advanced stages and being used as a vehicular fuel and to produce clean electricity in the Mega Watt range [2].

A. Microbiology of Biogas Formation

Biogas forming bacteria is a large group of complex and independent microbe species, most notable of which is the methane-producing bacteria. The process of biogas formation is split into three (3) steps: hydrolysis, acidification, and methane formation as elucidated below; [12].

1. Hydrolysis

At this stage the microorganisms externally enzymolyse organic matter using their extracellular enzymes such as cellulase, amylase, protease and lipase. The bacteria at this stage decompose the long and complex molecular chains of the carbohydrates, proteins and lipids into shorter simpler parts such as monosaccharides, peptides and amino acids [7].

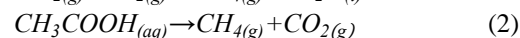
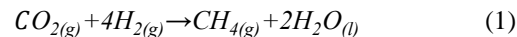
2. Acidification

In the second step, acid-producing bacteria are involved. These are responsible for the conversion of the simple intermediates from step 1 of fermenting bacteria into molecules of acetic acid (CH₃COOH), hydrogen (H₂) and carbon dioxide (CO₂). These bacteria can survive under both anaerobic and aerobic conditions as well as acid conditions. These bacteria utilise the dissolved oxygen or bounded-oxygen in the solution and carbon to produce acetic acid. By doing this, they create an anaerobic condition which is vital for the methane producing microorganisms in the final step of methanogenesis. In addition, they reduce the compounds with a low molecular weight into alcohols, organic acids, amino acids, carbon dioxide, hydrogen sulphides and traces of methane. This process is only possible with energy input, since bacteria alone are not capable of sustaining that type of reaction, hence referred to as endergonic [12].

3. Methane formation

Methane-producing bacteria also known as Methanogens are involved in the third step. These decompose compounds with a low molecular weight such as hydrogen, carbon dioxide and acetic acid created in step two to form methane and carbon dioxide. Methane-producing bacteria are exclusively anaerobic and very sensitive to environmental changes. In

contrast to the acidogenic and acetogenic bacteria, the methanogenic bacteria belong to a group of bacteria with a very heterogeneous morphology and a number of common biochemical and molecular-biological properties that distinguish them from all other bacterial genera. They belong to the genus archaebacter [7]. Chemical reactions during methanogenesis can be summarized as in (1) and (2) below [8];



During biodigestion, the bacteria types involved work symbiotically. The activities and products of one set of bacteria support the other and vice versa. In practical fermentation processes, the metabolic actions of the various bacteria all act in synchronisation. No single bacteria are able to produce fermentation products in isolation. When the acid producing bacteria use up the oxygen to create light compounds, it creates an anaerobic environment for the methanogens as well as compounds of low molecular weight. On the other hand, methane-producing microorganisms use up the intermediates of the acid-producing bacteria from the system thereby eliminating the possibility of creation of toxic conditions for the acid-producing microorganisms [13].

B. Conditions for Anaerobic Digestion

1. Digester Temperature

Temperature inside the digester has a major effect on the biogas production process. There are various temperature ranges during which anaerobic fermentation can take place [14];

- Psychrophilic (< 30°C)
- Mesophilic (30 – 40° C)
- Thermophilic (50 – 60° C)

However, anaerobes are most active in the mesophilic and thermophilic temperature ranges [2]. The methanogens are inactive in extreme high and low temperatures. The optimum temperature is 35° C. When the ambient temperature goes down to below 10° C, gas production virtually stops. Satisfactory gas production takes place in the mesophilic range, between 25° to 30° C. Proper insulation of digester helps to increase gas production in cold climates or high altitudes [15] [16].

2. Concentration of feedstock

The solids concentration in the influent to the biodigester affects the rate of fermentation. The amount of fermentable material of the feed in a unit volume of slurry is defined as solids concentration. The mobility of the methanogens within the substrate is gradually impaired by increasing solids content, and the biogas yield may suffer as a result. Ordinarily 6-9% solids concentration is best suited. In an experiment reportedly conducted in China, the optimum concentration of solids was considered to be 6% in summer but between 10 and 20% in winter and spring. When temperatures are low and materials take longer to decompose; it is better to have a higher total solids concentration, although this might result into impeded flows through the digesters [2].

3. Loading rate

Loading rate is the amount of raw materials fed per unit volume of digester capacity per Day. Gas production is also highly dependent on the loading rate. Studies have shown that methane yield increased with a reduction in the loading rate. If the loading rate is too high, there will be more substrate than the bacteria can decompose. If the digester is being overloaded, the gas production will rise up initially and then fall after a while when inhibition occurs. Inhibition is caused because methanogens multiply more slowly than the acid forming bacteria and the gas inhibits the methanogens from producing methane and thus the gas production will be inhibited [16].

4. Feed materials composition and nutrients

Anaerobic digestion processes are able to utilize a large number of organic materials as feedstock, including animal manure, human waste, crop residues and other wastes. Although, in order to grow, bacteria need more than a supply of organic substances as a source of carbon and nutrients, they also require certain mineral nutrients. In addition to carbon, oxygen and hydrogen, the generation of biomass requires an adequate supply of nitrogen, sulphur, phosphorus, potassium, calcium, magnesium etc. Agricultural residues and wastes usually contain adequate amounts of these elements [2].

5. Hydraulic retention time (HRT)

Retention time (also known as hydraulic detention time) is the average time spent by the input slurry inside the digester before it comes out. In countries with colder climates; the HRT may go up to 100 days as compared to warmer climates where the values lie between 30-50 days. Shorter retention time is likely to face the risk of washout of bacterial population while longer retention time requires large volume of the digester and hence more capital. There is a linear relationship between retention time and the digester temperature up to 35° C, the higher the temperature, the lower the retention time and the reverse is true [16].

6. pH value

The methane-producing bacteria live best under neutral to slightly alkaline conditions. The pH in a biogas digester is directly dependent on the retention time. In the initial stages of fermentation, large amounts of organic acids are produced by acid forming bacteria; this in turn leads to the pH inside the digester falling to values below 5. This inhibits or even stops the digestion process. Methanogenic bacteria are very sensitive to pH and do not thrive below pH 6.5. Later on, as the digestion process continues, concentration of ammonium increases due to digestion of nitrogen which can increase the pH value to above 8. Once the process of fermentation has stabilized under anaerobic conditions, the pH will normally take on a value of between 7 and 8.5 [16].

7. Carbon-Nitrogen ratio

The ideal Carbon/Nitrogen (C/N) ratio for anaerobic biodigestion is between 20:1 and 30:1. Methanogenic bacteria use Nitrogen to meet their protein requirements. Therefore in cases of high C/N ratios higher than the optimum ranges, the Nitrogen will be depleted rapidly by the bacteria and will no longer react on the left over carbon remaining in the material

thereby reducing the gas production. For cases of lower rations than the desired range, the excess Nitrogen will result into Ammonia (a strong base) formation hence raising the working PH over the desired 8.5 inhibiting the microbes and ultimately dropping gas production rates [2].

8. Toxicity

Mineral ions, heavy metals and the detergents are some of the toxic substances that inhibit the normal metabolism of methanogens in the digester. Small quantities of mineral ions (e.g. sodium, potassium, magnesium, ammonium and sulphur) also stimulate the growth of bacteria, while a heavy concentration of these ions will have a toxic effect. Detergents including soap, antibiotics and organic solvents among others inhibit the activities of the methane producing bacteria and addition of these substances into the digester should be avoided. Therefore the source of water for mixing the feedstock should be taken into consideration [16].

9. Agitation

Stirring of the digester contents needs to be done to ensure intimate contact between the microorganisms and substrate which ultimately results in improved digestion process. Agitation of the digester contents can be carried out in a number of ways, for instance daily feeding of the digester instead of periodical gives the desired mixing effect [2].

10. Air-tightness

Biological activities of anaerobic microorganisms including their development, breeding as well as metabolism do not require oxygen to take place. They are indeed very sensitive to the presence of oxygen. The breakdown of organic materials if any in the presence of oxygen will yield carbon dioxide instead of the desired output methane whereas in airless conditions methane is produced.

In addition, if the digester is not sealed to ensure the absence of air. The action of the microorganisms and the production of biogas will be inhibited and some will escape. It is therefore crucial that the biogas digester be air and watertight [2].

11. Moisture content

The microorganisms' excretive and other essential metabolic processes require water to take place hence the feedstock should have optimum moisture content for performance of the bacteria. The optimum value of moisture content should be about 90% of the total volume of feedstock.

Excess water in the feedstock leads to a fall in the rate of production per unit volume of feedstock and on the other hand, inadequate water leads to an accumulation of acetic acids which inhibit the digestion process and hence production. Furthermore, a thick scum will form on the surface of the substrate. This scum may prevent effective mixing of the charge in the digester [2].

II. SUBSTRATE QUALITY FOR ANAEROBIC DIGESTION

The quality and quantity of organic matter available for use in a biogas plant constitutes the basic factor of biogas generation. The volumetric yield of biogas per kilogram (kg) varies from one substrate to another depending on the composition as well as nature of the substrate. In addition, the

percentage of methane obtained from the resultant biogas also varies independently according to type of biomass material [7]. The yield of biogas in litres per kg of various materials is summarized in Table 2 alongside the percentage of methane production per raw material.

TABLE II
BIOGAS PRODUCTION POTENTIAL FROM DIFFERENT WASTES [17]

Raw Material	Biogas Production Litres/kg	Methane Content In Biogas (%)
Cattle Dung	40	60
Green leaves	100	65
Food Waste	160	62
Bamboo Dust	53	71.5
Fruit Waste	91	49.2
Bagasse	330	56.9
Dry Leaves	118	59.2

A. Key Substrate Parameters for Anaerobic Digestion

For efficient biogas production, a clear understanding of the nature of the input substrate has to be made because the properties of the substrate have a direct bearing on the resultant volume of the biodigester, the quantity/quality of output biogas and hence the project cost. Among the substrate parameters that should be ascertained are: Total Solids (TS), Total Volatile Solids (TVS), Substrate Dryness, Chemical Oxygen Demand and organic loading rate. These have been summarised as below [18];

1. Total Solids (TS)

This is the total amount of solid matter present in a given substrate. The Total solids' content of a substrate is obtained by weighing the residue or dry material left after drying it for 48 hours at 105°C. The mass obtained is the raw estimation of both the organic and inorganic content of the substrate [8].

2. Total Volatile Solids (TVS)

Volatile solids (VS) also referred to as the organic fraction of the total solids represent the digestible portion of the total solids normally expressed as a percentage. It is determined by heating the TS to 550°C for 24 hours. The balance of the process is the inorganic fraction of the TS [19].

3. Chemical Oxygen Demand (COD)

This parameter is the indicator on the oxygen equivalent of organic material in a substrate. It gives a precise estimation of the organic (degradable) material content of a given substrate sample [8]. COD is determined by adding a strong chemical oxidizing agent to the substrate in an acidic medium [20].

4. Organic Loading Rate (OLR)

Organic loading rate (OLR) represents the amount of organic material that is added to the biodigester within a given amount of time usually expressed volume per day. The OLR gives an indication on the amount of volatile solids to be fed into the digester each day thereby becoming a key parameter in the sizing of the plant [18].

$$OLR = \frac{Q \times S}{V} \quad (3)$$

Where:

OLR: Organic Loading Rate (kg substrate/ m³/ day),

Q: Flow rate of input (m³/day)

S: Concentration of VS in the input (kg/m³)

V: Reactor Volume (m³)

From (3) above, the size of the reactor can be calculated by a modified version of the OLR equation as [8]:

$$V = \frac{Q \times S}{OLR} \quad (4)$$

Usually the OLR of a given system is pre-determined basing on several factors among with are the pumpability of the substrate and its composition among others. Therefore, OLR governs the design and dictates the value for the HRT [8].

B. Substrate Pre-treatment

This refers to all the processes that the feedstock undergoes prior to use in anaerobic digestion. These processes range from physical ones like sorting and particle size reduction to chemical processes like alkali treatment and metal addition among others [19]. The pre-treatment of feedstock can yield higher biogas production rates and volatile solids reduction [21]. The main effects that pre-treatments have on various substrates are particle-size reduction, biodegradability enhancement, formation of refractory compounds and loss of organic material [22]. The various performance enhancers are as elaborated below;

1. Seeding

Seeding is a way of kick-starting a newly commissioned biogas plant by feeding it with previously digested material from another established plant. Alternatively, materials such as ruminant manure are often used to seed a new reactor, so as to reduce the plant start-up time. The method aims to introduce inoculum into the system [15].

2. Particle size

The particle sizes of the substrate directly affect digestion as it has direct indications on the available surface area for hydrolysing enzymes especially with plant fibre. Methane yield and fibre degradation have been found to improve with decreasing particle sizes within the feedstock from 100mm to 2mm [23].

3. Alkali treatment

Treatment of biodigester feedstock with alkali solution has been found to improve biogas production and reduce cellulose production especially when using plant material. The degradation rate of paper waste was also found to increase by adding Sodium hydroxide (NaOH) [22] [24]. However, alkali solutions often lead to saponification reactions in continuous plants. These reactions tend to yield generate compounds leading to tremendous drops in acetate and glucose degradation rates [25].

4. Thermal/thermochemical pre-treatment

Pre-heating of substrate before anaerobic digestion has proved to improve methane production as well as volatile solids reduction. Studies have also showed that pre-heating of substrate that has been treated with chemical additives (thermo-chemical) even gives better results [26]. Thermochemical pre-treatment of chicken manure with Sodium hydroxide or Sulphuric acid at 100°C has been found

to increase both the biodegradability of the substrate and the methane yield [27].

5. Ultrasonic pre-treatment

Commonly used in sewage sludge treatment, the feedstock is treated using ultra sonic sound waves. Generally the method has been found to improve biogas production from anaerobic digestion. The mechanical shear forces caused by ultrasonic cavitation are the key factor for sludge dis- integration, and collapse of cavitation bubbles which significantly alter the feedstock characteristics [21].

6. Metals

Addition of certain metals to the feed material has been found to increase biogas production. Anaerobic co-digestion of cattle manure with potato waste was improved in terms of biogas production by the addition of heavy metals at 2.5 mg/l rather than 5mg/l, with the greatest increase from Cd²⁺ followed by Ni²⁺ then Zn²⁺ [28].

III. MUNICIPAL BIOWASTE AS FEEDSTOCK FOR BIOGAS PRODUCTION

A. Composition of Municipal Solid Waste (MSW)

Municipal solid waste or "General Waste" as defined by the National Environmental Management (NEM) Waste Act, 2008 (Act No. 59 of 2008) of South Africa is that waste that does not pose an immediate hazard or threat to health or to the environment, and includes; domestic waste, building and demolition waste, business waste; and inert waste. It includes predominantly household waste (domestic waste) with the occasional addition of commercial wastes collected by a municipality within a given area. They are in either solid or semi-solid form. There are five broad categories of MSW [29];

- Biodegradable waste: food and kitchen waste, green waste,
- Recyclable material: paper, glass, bottles, cans, metals, certain plastics, etc.
- Inert waste: construction and demolition waste, dirt, rocks, debris.
- Composite wastes: waste clothing, Tetra Packs (polystyrene), waste plastics such as toys.
- Domestic hazardous waste & toxic waste: medication, paints, chemicals, light bulbs, fluorescent tubes, spray cans, fertilizer and pesticide containers, batteries, shoe polish.

Therefore the organic fraction of municipal solid waste is made up of food and kitchen waste as well as green waste [29]. 48% of the 59 million tonnes of MSW collected in South Africa in 2011 was OFMSW [10].

B. Qualities of OFMSW as a Substrate for Anaerobic Digestion

1. TS

OFMSW is a predominantly solid substrate with a TS content of 30% as well as relatively large particle sizes [30]. It is of heterogeneous nature with a complex composition which usually makes estimates or measurements for its composition quite difficult [8].

2. VS

OFMSW has a high range of volatile solids ranging between 90-95% of TS and 28-29% of wet weight [31].

3. Optimum Organic Loading Rates (OLR)

OFMSW gives optimum anaerobic biodigester performance at organic loading rates between 5-10kgVS/m³ [32] [33].

4. PH

Due to a high volatile fatty acids contents from food waste (the predominant composition), OFMSW tends to be acidic yielding overall PH levels lower than the desired 7 [34].

5. Biogas yield

Values from literature indicate that depending on the source of the OFMSW, the substrate can yield approximately anywhere between 300 to 500m³ of biogas per tonne of volatile solids of 65% methane [8]. The average biogas production from OFMSW is 367m³/tVS [30]. Table 3 below shows the various biogas yields as quoted from different sources.

TABLE III
EXPERIMENTAL BIOGAS YIELDS FOR OFMSW

Source	Biogas yield m ³ /tVS
Discarded Food	355 [8]
Food waste	367 [30]
OFMSW	310-490 [8]
OFMSW	300-400 [32]
OFMSW	390 [35]
Food Waste	472 [31]

The average methane content of biogas obtained from OFMSW as primary feedstock is 65% [32]

C. Benefits of Using OFMSW as a Substrate for Biogas Production

1. Availability at low or no cost

Compared to energy crops that require extra costs to be grown and availed, OFMSW is readily available in abundance and is an inexhaustible substrate which requires minimal input to be ready as a raw material for biogas production. In most cases it will be availed at no extra cost since the anaerobic digestion can be incorporated into the existing waste management systems in which OFMSW is normally discarded to landfills as a useless component [6].

2. A tool for environmental conservation

The use of OFMSW for biogas production as discussed in the previous sections is a window of opportunity that helps to solve the current growing problems of solid waste management (SWM) in urban settings that are relying majorly on landfilling of the OFMSW that leads to methane gas emissions to the atmosphere. In addition, the anaerobic digestion process produces useful energy in the form of biogas heat that can be used as a substitute to the traditional fossil fuels for heating, cooking as well as electricity generation. Fossil fuels are rich in carbon emissions and any clean energy alternative is of indubitable value to environmental conservation [30] [34].

3. High TS and VS values

As discussed in the previous section, OFMSW has high TS and VS values compared to other wastes like farm manure and

municipal sewerage. As opposed to farm manure, fresh OFMSW has not undergone any prior digestion processes therefore still has high energy content hence high concentration of digestibles also herein referred to as the volatile solids. This fact implies that OFMSW produces more biogas per unit weight than most wastes making it a more economical option for biogas production [8]. Below is a figure showing a comparative analysis of biogas yields from various substrates;

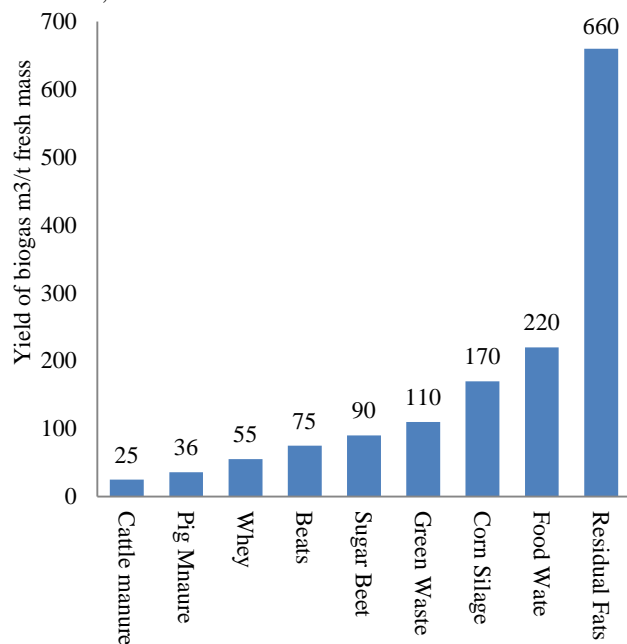


Fig. 1 represents biogas yields of various substrates in m³/tonne VS [8]

The high biogas yield per unit weight of substrate also means that for a target production rate of biogas, a smaller digester will be required than for the case of other substrates like farm manures hence a reduced overall cost of AD [36].

4. Good quality of biogas

The quality of biogas is measured by the methane (the combustible gas) content of the biogas which ranges between 50-70% [17]. At an average of 65% composition of methane [32], the biogas produced from the biodigestion of OFMSW is high grade compared to most substrates such as cattle dung at 60% [17] as shown in table II.

D. Limitations of Using OFMSW as a Substrate for Anaerobic Digestion

1. Heterogeneous Nature of OFMSW

As noted in the earlier sections, the efficiency of an anaerobic digestion process primarily depends on the composition and nature of the feedstock [7]. Unlike most substrates, OFMSW is a very complex type whose composition is highly unpredictable [8]. OFMSW can contain a wide spectrum of components from basic food waste, garden waste (leaves and stalks), paper and residual inorganics also referred to as contaminants like metals, glass, dust, stones and plastics among others varying according to season and location [37]. To be able to obtain a quality feedstock for

anaerobic digestion from OFMSW a thorough sorting procedure has to be designed and set up which can be anything from source sorting to the integration of hydro-mechanical equipment like trommel screens, hydropulpers and hydrocyclons among others [38]. The sorting involved in OFMSW is a costly and time consuming input that escalates the costs of the overall process which would otherwise be avoided if less complex substrates like farm manure or sewerage sludge were used. The mechanical sorting equipment increase the initial capital costs, overall system power demand as well as the plant operation and maintenance cost [37]. Arsova (2010) conducted studies on five AD plants of OFMSW three in Spain and two in Canada all using somewhat varied sorting criteria. The economic analyses of these revealed that the high capital and maintenance costs of the AD facilities coupled with limited revenue from the biogas and compost products, the gate fee to be paid by the citizens or local government, had to be in the order of \$100-150 per ton of waste delivered at the plant. Considering the average landfill gate fees at the time in U.S. of USD 42 per ton, the AD facilities had to be subsidised for economic feasibility [38].

2. Large particle sizes

Generally, OFMSW has large particle sizes unlike the more fluid substrates like farm manures and municipal sewerage. This makes pumpability and agitation of the substrate difficult and reduces the surface area for microbial activity making the system inefficient [8]. However particle size reduction of OFMSW can be achieved by incorporating shredders and grinders prior to feeding the biodigester which increases the project costs. The direct costs aside, any additional equipment onto the AD system have power requirements too [19]. Nathan Curry (2010) designed and implemented an AD system at Concordia University downtown Montreal, Quebec Canada. For system efficiency, the system had to incorporate a mechanical pre-treatment assembly comprising of a grinder, mixer and a biofilter. These combined had a power demand of up to 943.6kWh/year and would cost the project an extra USD 30,310 [8].

3. Acidity

OFMSW substrates are characterised by low pH level below the optimum 7 due to high concentration of volatile fatty acids from oily and meaty food wastes [34]. This can however be counter balanced by pre-treatment of the substrate with a controlled amount of alkali solutions like Sodium hydroxide to raise the initial pH of the substrate above 7 [24].

A study carried out on anaerobic digestion of OFMSW by Stenstrom et al (1981) revealed that the digestion was very sensitive and the digesters would easily be overloaded and produced high volatile acids concentration. However, it was demonstrated that digester failure could be avoided by pH control using Sodium carbonate and by temporarily reducing loading rate. In extreme cases, feeding digested sludge was necessary to insure prompt recovery [39].

4. Complexity of urban settings

An efficient biogas generation system is usually one in which the substrate, the biodigester and user are all located in

the same place to minimise costs. However, for most urban areas where OFMSW is generated, the space available is minimal and permanent utilities have already been set up making incorporation of biogas digesters quite difficult as opposed to rural settings [38] [8]. On the case of Curry (2010), the AD system was set up in the middle of downtown Montreal and therefore special attention had to be given to standing gas and fire points, and building codes as well as health and safety regulations. These introduced extra costs of set up with items such as relocation of old ventilation systems, gas safety and digestate management which cost the project an extra USD 60,000 [8].

E. Economics of Anaerobic Digestion of OFMSW

New technologies cannot be presented as solutions or implemented without a proper understanding of their costs against benefits. The major point of concern is always the pay-back time as no one wishes to invest into no-profitable ventures [8]. Biogas Technology has mostly been disseminated by non-profit organisations (such as SNV, FAO, GTZ) or government institutions because over the years economic analyses have revealed that the high initial investment costs as well as operation and maintenance costs limit its feasibility as an investment unless subsidies are provided to the investor. Biogas projects are usually characterised by long breakeven periods and yet the direct commercial benefits are usually small given the competition from existing energy sources like fossil fuels which also discourages investors. One of the ways to make biogas plants profitable is by complimenting revenues from gas production with sales on the digestate as a fertilizer as well as claiming carbon credits [40]. The other way that can improve the economic feasibility of AD technology is by increasing the scales of production. At larger scales, the costs of production essentially go down. Evaluations on AD plants of OFMSW in Europe indicated that if a plant with a capacity of 100,000 tonnes per year has a treatment cost of less than €30 per tonne, another plant with a capacity of only 20,000 tonnes per year would have a treatment cost of around €60 per tonne. [37]. Due to the heterogeneous nature of OFMSW, AD systems utilising OFMSW as their primary substrate usually cost more than when other homogeneous substrates are used such as farm manures due to the extra costs usually involved in substrate pre-treatment so as to improve its properties for efficient AD system performance such as grinding for particle size reduction, sorting for contaminants removal and alkali pre-treatments for pH control among others [33] [37].

IV. OBSERVATIONS AND RECOMMENDATIONS

From various researches, it is clear that technically the production of biogas from the anaerobic digestion of the organic fraction of municipal solid waste is a potential solution to environmental conservation, sustainability and provision of alternative clean energy. OFMSW as a substrate for production of biogas from AD is very efficient especially due to its ability to give higher biogas yields of good quality

per unit weight than most available substrates and its abundance as well as availability at low costs.

However, there are some draw-backs on the use of OFMSW as a substrate for production of biogas such as its heterogeneous nature that calls for extra sorting of the substrate, big particle sizes that are harder to work with in AD and its high acidity due to high concentration of fatty acids that inhibit methanogenesis. All these can be solved via several developed pre-treatment techniques such as sorting, alkali additions, grinding among many at an additional cost to the project. These factors in mind, the use OFMSW in anaerobic digestion becomes a costly venture compared to most of the other available substrates like farm manures that will not require pre-treatments such as sorting.

Therefore, more research is recommended on techno-economic pre-treatment innovations that can improve the properties of OFMSW for anaerobic digestion such as low-cost systematic sorting at source to ensure good quality feedstock, treatments that can improve pH and reduce particle sizes simultaneously. In addition, central governments should aim to subsidise AD technology to improve its economic viability as an investment. City planners can also start integrating biodigesters in the urban setting as a waste management strategy and a useful clean energy source.

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