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Anaerobic Conversion of Biodegradable Municipal Solid Waste to Biogas: A Review

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Abstract
Huge quantity of Municipal Solid Waste (MSW) is generated daily. This waste comprises a biodegradable portion which can be converted into biogas (bioenergy) by anaerobic digestion (AD). This study reviews MSW and its management, AD feedstock and their characteristics, factors affecting biogas production in a biodigester and anaerobic co-digestion of Organic Fraction of MSW (OFMSW) with other substrates. Municipal solid waste is managed through waste diversion (reduction, reuse, recycling and recovery) and waste disposal (controlled incineration, landfilling and controlled dumping). AD feedstock includes agricultural waste/residues, animal wastes, energy crops, food waste, forestry crops and residues, organic industrial waste and wastewater, weeds, aquatic algae, sewage and OFMSW. The essential factors that influence the production of biogas are temperature, pH, mixing rate, carbon/nitrogen ratio, organic loading rate, micro and macro-nutrient availability, retention time, nature of the feedstock and digester type. Anaerobic co-digestion of OFMSW with other substrates results in improved AD process stability, enhanced biogas productivity, maximization of the capacity of available feedstock for anaerobic digestion. It is also a cost-effective and improved technique to optimize anaerobic digestion process via the increase in nutrients and bacterial variety in substrates. The generation rate and composition of MSW, as well as the characteristics of OFMSW feedstock for anaerobic digestion, are required for the design of a full-scale biodigester for municipal use. The information provided in this review is invaluable to researchers, governments, industries and other stakeholders interested in anaerobic conversion of biodegradable solids to bioenergy.

Keywords: Municipal solid waste, anaerobic digestion, biogas, biodegradable, biodigester, bioenergy.

Introduction
Human activities generate wastes which pose health and environmental challenges, so waste management is a necessity in every community. Waste is any substance or object which the holder discards or intends or is required to discard (European Commission, 2008). Waste may be in solid, liquid or gaseous form. Solid wastes are refuse materials that are not liquid waste, hazardous waste or atmospheric emissions (Bailie *et al*., 1997). Biodegradable wastes or biowastes are those wastes that are organic in nature and can be decomposed by microorganisms, they include organic fraction of municipal solid waste (OFMSW), animal waste (e.g. dung/manure), forestry and agricultural residues, food wastes and sewage sludge (Khan *et al*., 2017).

Anaerobic digestion (AD) can be used to recover the energy potential of biowastes; it is a biological process of breaking down organic matter by microorganisms in the absence of oxygen (Sawatdeenarunat *et al*., 2015; Zhang 2016). AD of biodegradable material produces biogas, a gas consisting mainly of methane, which can be utilized to generate heat and electricity (Edelmann *et al*., 2000; Sonesson *et al*., 2000; Hamzawi *et al*., 1999; Kythreotou *et al*., 2014). AD can be harnessed in a bioreactor named digester to convert biodegradable waste into biogas (Nkoa, 2013; Edelmann *et al*., 2000; Sonesson *et al*., 2000; Hamzawi *et al*., 1999). In addition to biogas (a form of bioenergy), AD generates liquid and solid fertilizers which are superior to manure and compost in terms of nutrient availability, and could increase the organic fraction of soil and provide essential nutrients to plants (Nkoa, 2013; Edelmann *et al*., 2000; Sonesson *et al*., 2000; Hamzawi *et al*., 1999).

The decomposition of organic wastes produces methane, a greenhouse gas (IPCC, 2007). When this degradation takes place in landfills or in the open, the methane generated is liberated directly into the atmosphere where it contributes to global warming (IPCC, 2006). It has been estimated that as much as 12% of the total global methane emission is contributed by sanitary landfills (EPA, 2006). However, when these organic wastes are converted to biogas in a biodigester, the subsequent combustion of methane in biogas does not make a net contribution to greenhouse effect because the carbon dioxide released is the amount that was absorbed from the atmosphere by the plant from which the biowaste (and consequently the biogas) came from. Hence the conversion of biowaste to biogas in a biodigester mitigates global warming in addition to the generation of useful energy and biofertilizer. Besides the generation of bioenergy and biofertilizer, the microbial degradation of OFMSW in a digester helps to reduce the unpleasant stench produced by the decomposition of organic matter in landfills.

Municipal Solid Waste and Its Management

Municipal solid waste (MSW) has been defined as all waste collected by private and public authorizes from domestic, commercial and some industrial (non-hazardous) sources (Igoni *et al*., 2008). MSW largely composed of solids or semi-solids that are considered useless or unwanted (Bailie *et al*., 1997; Byrne, 1997; Igoni *et al*., 2008; den Boer, 2010; Kiely, 1998; Ogwueleka, 2009). MSW includes waste from households, commerce and trade, office building, institutions (schools, hospitals etc.) and small businesses, yard and garden, street sweepings, content of litter container and market waste but excludes wastes from municipal sewage networks and treatment and municipal construction and demolition (Ogwueleka, 2009; den Boer 2010; Jamasb and Nepal, 2010; OECD, 2019).

Municipal solid waste management (MSWM) is the collection, transfer, treatment, recycling, resource recovery and disposal of solid waste in urban areas, including the supervision of such operations taking into account parameters such as public health, economics and the environment (Ogwueleka, 2009). The major goal of MSWM is to protect man and the environment (Brunner and Rechberger, 2014). MSW is a non-fluid type of waste which makes its handling and management relatively difficult, compared to the types of waste that can flow from one location to the other, or even vaporize (Ogunbiyi, 2001).

The components of MSW usually include paper and cardboard, plastics, metal, glass (including pottery and china), food waste, disposable diapers, rubber and leather, garden and park waste, wood, textiles, ash, dirt, dust, soil, electrical and electronic waste (Tchobanoglous *et al*., 1993; IPCC, 2007; Jha *et al*., 2008; Harris 2012). MSW composition is influenced by culture, economic development, climate, energy sources and geographical location (Tchobanoglous *et al*., 1993). The biodegradable portion of MSW are referred to as the organic fraction of municipal solid waste (OFMSW), this mainly consists of paper, textile, food, garden and wood wastes (Tchobanoglous *et al*., 1993; Hartmann and Ahring, 2006; Jha *et al*., 2008; Hoornweg and Bhada-Tata, 2012).

Solid waste management processes may be classified into waste diversion and waste disposal; waste diversion activities include waste reduction, reuse, recycling and recovery (aerobic composting and anaerobic digestion) while waste disposal activities involve controlled incineration (with energy recovery), landfilling and controlled dumping (Jamasb and Nepal, 2010; Hoornweg and Bhada-Tata, 2012). Energy can also be recovered from waste by gasification and pyrolysis (Weiland, 2010). Waste collected in Africa is almost exclusively dumped or sent to landfills (Hoornweg and Bhada-Tata, 2012). In Nigeria MSW are usually disposed on dump sites or by open burning (Ogwueleka, 2009; Solomon, 2009); it is common to see waste dumped indiscriminately in several places which consequently leads to blockage of waterways and drains (resulting in flooding), offensive odour, obstruction of traffic flow, atmospheric pollution, environmental degradation and the consequent detrimental effects on public health (Igoni *et al*., 2008; Ogwueleka, 2009; Hoornweg and Bhada-Tata, 2012).

The population of Nigeria was 55.6 million in 1963, 89 million in 1991 and 140 million in 2006 census (National Population Commission, 1991; Federal Republic of Nigeria, 2006; Population Council, 2007), this implies a high rate of waste generation in the country (Tan *et al*., 2015). The enormous organic fraction of the municipal waste generated by this large population can be converted to biogas and biofertilizer by anaerobic digestion in a biodigester, as an environmentally benign and sustainable alternative energy source (Pognani *et al*., 2009). Most importantly, the use of OFMSW in anaerobic digestion as a waste management method minimizes land and air pollution.

The composition and rate of generation of solid waste vary in different socio-economic groups due to many social and environmental factors such as education, occupation, number of family members and family income (Khan *et al*., 2016). Hence, the generation rate and composition of waste are important parameters required to plan and design an effective waste management system for any given region (Gidarakos *et al*., 2006; Gomez *et al*., 2008). In addition to the generation rate and composition of MSW, the characteristics of OFMSW feedstock for anaerobic digestion are required for the design of a biodigester (Talia, 2018).

Anaerobic Digestion

Anaerobic digestion (AD) is a biological process of breaking down organic matter (also known as substrates) by microorganisms in the absence of oxygen (Sawatdeenarunat *et al*., 2015; Zhang *et al*., 2016). It is a complex and multistep microbial process carried out by bacteria and archaea whereby the bacteria decompose complex substrates into volatile fatty acid (VFA), carbon dioxide (CO_2) and hydrogen (H_2), while archaea produce methane (Ren *et al*., 2017).

AD involves four principal steps namely hydrolysis, acidogenesis, acetogenesis and methanogenesis (Valijanian *et al*., 2018). The large macromolecules of organic matter which comprise carbohydrate polymers (e.g. cellulose and starch), fat and protein are broken down by hydrolysis to sugars, long chain fatty acids and amino acids, respectively, which are soluble organic molecules. The hydrolysis products are fermented to produce volatile fatty acids (mainly lactic, propionic, butyric, and valeric acid) during acidogenesis. Bacteria then consume these fermentation products in the acetogenesis steps to produce acetic acid, carbon dioxide and hydrogen. In the final step, methanogenic organisms consume acetate, hydrogen and some of the carbon dioxide to produce methane. Figure 1 illustrates the anaerobic digestion process steps. The anaerobic digestion of organic matter produces biogas, a form of energy which can be used for heating and electricity generation, and a digestate, which can be used as a biofertilizer for soil conditioning (Curry and Pillay, 2012). Thus anaerobic digestion is a process that can treat organic waste such as OFMSW, generate clean renewable energy and recycle nutrients.

The presence of ammonia, hydrogen sulfide and volatile fatty acids (VFAs) can inhibit methanogenesis in anaerobic digestion; however, the inhibitory effects can be mitigated by gas stripping, adsorption, microaeration and chemical oxidation processes (Markou, 2015; Serna-Maza, Heaven and Banks, 2015; Diaz *et al*., 2015; Bozym *et al*., 2015).

Volatile fatty acids (VFAs) consists of organic acids such as acetic, butyric, propionic and valeric acids (Haugen, 2014), they are produced during hydrolysis and acidogenesis stages and consumed as substrates during the acetogenesis and methanogenesis stages of anaerobic digestion process to generate methane. The concentration of VFAs in a digester is a suitable indicator of the stability of the process and can be monitored to evaluate process stability. VFAs hinder AD process if its accumulation occurs beyond certain limit (over 1500 – 2000 mg/L) (Falk, 2012; Labatut and Gooch, 2012). VFAs accumulation may be due to abrupt changes in process condition such as substrate composition, inhibitors overload and/or temperature instability; the main cause is the fast biodegradation of organic macromolecules like proteins, fats, and carbohydrates in food and agro-industrial waste (Jain *et al*., 2015). VFAs accumulation, particularly propionic acid may significantly lower pH and subsequently inhibit methanogenesis (Jain *et al*., 2015; Drosg, 2013).

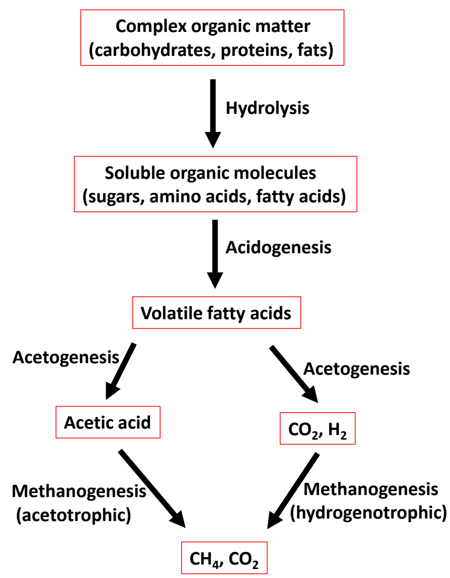

Figure 1: Anaerobic digestion process steps

Biogas

Biogas, the gas produced when organic matter of animal or plant ferments in an oxygen-free environment (anaerobic condition), occurs naturally in swamps, lake sediments and landfills containing organic waste. It is a mixture of gases which comprises about 55-65 % methane, 35 – 45% carbon dioxide, 0 – 1% hydrogen sulphide, 0 – 1% nitrogen, 0 – 1% hydrogen, 0 – 3% carbon monoxide, 0 – 2% oxygen and traces of ammonia and water vapour (Zhang, 1999; Kalia *et al*., 2000; Keefe, 2000). It is a clean, colourless, odourless and highly flammable gas which has a calorific value of 4500–5000 kcal/m^3 when its methane content ranges from 60 to 70% (Madu and Sodeinde, 2001; Igoni *et al*., 2008).

Biogas can be produced in a biological reactor (bioreactor) named biodigester or simply digester in which organic materials are broken down by bacteria and archaea. The biogas yield and composition vary for different substrates, biological consortia and anaerobic digester condition. Biogas can be used directly as a fuel for heating (cooking, etc.) without the removal of carbon dioxide, or converted to electricity. Internal combustion engines or turbines connected to power generators are required to convert biogas to electricity. The utilization of biogas as vehicle fuel requires that the biogas be upgraded to methane by removal of carbon dioxide; the upgraded methane consists of 95 – 97% methane and 1 – 3% carbon dioxide (Dareioti *et al*., 2009). The removal of hydrogen sulphide is also necessary as biogas used in steam boilers and internal combustion engines for electricity generation must not contain H_2S in quantity above 200 ppm.

Anaerobic Digestion Feedstocks and their Characteristics

A wide range of organic material can be used as anaerobic digestion feedstock. Digester feedstock are referred to as substrate, they include agricultural waste/residues (e.g. leaves, roots, seeds, stalks and seed shells), animal wastes (dung/manure and rumen), energy crops, food waste, forestry crops and residues, organic industrial (e.g. food industry) waste and wastewater, weeds, aquatic algae, sewage and organic fraction of municipal solid waste (Khan *et al*., 2017). The organic fraction of municipal solid waste includes kitchen wastes (consisting mainly of scrap foods), paper and cardboards, textile, food, garden and wood waste (Tchobanoglous *et al*., 1993; Hartmann and Ahring, 2006; Jha *et al*., 2008; Hoornweg and Bhada-Tata, 2012).

Animal manure and organic sludge of aerobic wastewater treatment processes are among the most widely used feedstock for anaerobic digestion (Chaiprasert, 2011; Horváth *et al*., 2016). AD can convert dry as well as wet feedstock; a wet digestion process uses a pumpable aqueous slurry containing 15% (w/w) dry solids as feedstock while dry feedstock are sufficiently dry to be stackable (Valijanian *et al*., 2018). Feedstocks of plant origin which contain lignin, cellulose and hemicellulose are referred to as lignocellulosic feedstocks while those which do not have these components are non-lignocellulosic e.g. animal wastes. Anaerobic digestion feedstock may be composed of sugars, starch and fats which are high energy compounds and lignocellulosic materials which are recalcitrant. Feedstock composition majorly determines its decomposition and biogas potential. Lignocellusolic feedstocks have slow hydrolysis rate and require longer treatment or high retention time and so larger reactor volumes are needed for their anaerobic digestion compared to non-lignocellusolic which are readily hydrolysable or soluble substrates. Large amounts of high-energy substrates such as fats may also disrupt anaerobic digestion especially methanogenesis.

Lignocellulosic materials, being substrates that are recalcitrant to anaerobic digestion, are usually pre-treated to enhance biogas production (Zhang *et al*., 2016). Substrate pre-treatment can be done chemically, physically or biologically. Physical pre-treatments include mechanical (high shear mixing, ball-milling grinding and sandpaper/mesh grating- (Ruffino *et al*., 2015; Lindner *et al*., 2015; Tsapekos *et al*., 2015) and thermal disruptions (Zhang *et al*., 2016).

The biogas potential of OFMSW depends on the biodegradability of the waste which is a function of the proteins, lipids and carbohydrates available in the waste, in addition to the composition of lignin, hemicellulose and cellulose fractions (Hartmann and Ahring, 2006). Owing to the different proportion of these components in the OFMSW collected from one region to the other, the biodegradability differs considerably; also, the characteristics of MSW is a function of the waste collection system and sorting of MSW influences the quality of the OFMSW available (Hartmann and Ahring, 2006). Hence, it is necessary to characterize OFMSW, as AD feedstock, by determining the physicochemical properties including total solids, volatile solids, moisture content, biochemical methane potential and carbon to nitrogen ratio.

Total Solids and Volatile Solids

Total solids (TS) refer to the overall amount of solids available in a feedstock which include both organic and inorganic constituents while volatile solids (VS) is the organic matter of the feedstock without considering the inorganic salts and ash. The degradation degree of a particular substrate could be determined by comparing the VS values of the digester's influent and effluent (Wolf, 2013). Information on VS contents in the substrates is important for determining the methane yield.

Moisture Content

Water is required by the bacteria involved in anaerobic digestion and metabolic processes for optimal production of biogas (Igoni *et al*., 2008). The recommended moisture content for optimum performance is 90% (Abbasi *et al*., 2012).

Biochemical Methane Potential

Biochemical Methane Potential (BMP) is used to determine biogas yield and is usually expressed in m^3 of biogas per tonne of fresh or dry biomass. It is used as a relative measure of the strength of sample per g of VS (mL biogas/kg of VS or m^3 biogas / tonne of VS); it shows the relative richness of a substance for production of biogas.

BMP is an indication of the anaerobic biodegradability and optimum methane potential of an organic material as well as the biodegradation rate on a laboratory scale. To determine the BMP of a feedstock, a known amount of the feedstock sample is added to a small volume of digester sludge, then incubated for 30 days at 35 ºC under mixing. The gas that is evolved is measured. A large number of samples is required to achieve a reasonable accurate assessment because low sample size reduce accuracy of BMP measurement resulting in high variability. The type of inoculum used can also cause variability in BMP analysis (Quintero *et al*., 2012). Owing to the variability of all substrates, both VS and TS as well as BMP analysis are required to accurately quantify the total available biogas from a given material for anaerobic digestion. For instance in manure, differences in operational parameters such as breeds, diets and management practices can cause a high variability in BMP values (Labatut *et al*., 2011). Thus the individual analysis of a given anaerobic feedstock for biogas production is highly essential. Wang *et al*. (2015) have proposed a substrate concentration ">10 g VS/L" for BMP tests to avoid underestimation of methane productivity.

C/N ratio

The carbon/nitrogen (C/N) ratio is the relative proportion of carbon and nitrogen in an organic matter. It is a major factor that affects the production of biogas from a particular substrate and an important parameter in estimating nutrient deficiency and ammonia inhibition (Hartmann and Ahring, 2006).

Factors that affect Biogas Production from OFMSW in a Biodigester

There are important factors that influence anaerobic digestion of organic matter, they affect the performance of a digester and consequently the production of biogas. These factors are temperature, pH, mixing rate, carbon/nitrogen ratio, toxicity, dilution, organic loading rate, micro and macro-nutrient availability, retention time (hydraulic and solids) and digester type (Abbasi *et al*., 2012; Matheri *et al*., 2017; Tabatabaei *et al*., 2018). In addition, the nature (structure and characteristics) of the feedstock significantly affect the digester performance, thus feedstock pre-treatment e.g. size reduction impacts the aerobic digestion.

Total solids, Volatile solids and Concentration of Feedstock

Information on VS contents in the substrates is important for determining the methane yield. TS values exceeding 15 % can lead to stirring problems in conventional continuously stirred tank reactors (CSTRs) while the VS/TS trend in the digester provide information on when to anticipate an eventual problematic ash accumulation. The concentration of feedstock or substrate which is defined in terms of solids concentration is the measure of biodegradable materials in unit volume slurry; the feedstock concentration determines the digestion rate (Igoni *et al*., 2008).

Carbon/Nitrogen (C/N) Ratio

The carbon/nitrogen (C/N) ratio is the relative proportion of carbon and nitrogen in an organic matter. Carbon is a source of energy for the microorganisms while nitrogen forms ammonia gas in the digester (Matheri *et al*., 2017). Nitrogen is liberated and accumulates in form of ammonia in the digester if the C/N ratio is too low, this increases the pH of materials in the digester which produces a toxic effect on methanogens when it exceeds 8.5. However, if the C/N ratio is too high, nitrogen is consumed rapidly by the methanogens to meet their protein need, so it is no longer available to react with leftover carbon in the material which consequently reduces biogas production. The optimum C/N ratio for anaerobic digestion is 20 – 30. Duck, chicken, goat, pig, sheep cow dung have a C/N ratio of 8, 10, 12, 18, 19 and 24, respectively; water hyacinth, municipal solid waste, maize straw, rice straw and wheat straw have C/N ratio of 25, 40, 43, 60, 70 and 90, respectively while human excreta has a C/N ratio of 8 (Kigozi *et al*., 2014). Plant materials have high carbon so their C/N ratio is high (e.g. rice straw has C/N ratio of 70) compared to animal waste e.g. cow dung which has an average C/N ratio of 24 (Kigozi *et al*., 2014). Hence, materials of low C/N ratio can be mixed with those of high C/N ratio to maintain the C/N level of materials in the digester at optimum level (Kigozi *et al*., 2014; Matheri *et al*., 2017).

Dilution

Anaerobic digestion feedstock may require water addition to obtain a slurry of appropriate solid component depending on the digestion system (Igoni et al., 2008; Talia, 2018); a slurry that is too thick may be difficult to stir which may impede gas flow to upper part of digester while solid particles may settle down in digester if the slurry is too thin.

pH

A pH of 6 – 7 is required of input mixture into the digester for optimum biogas production (Wang *et al*., 2014; Wellinger *et al*., 2013), while the pH of materials in the digester is usually 7.2 – 8.2 when biogas production is stable. Anaerobic microorganisms cannot grow under high acidic conditions, leading to low methane yield or digester failure (Matheri *et al*., 2017). A reduction in pH, usually due to the production of organic acids, can be controlled with the addition of lime.

Temperature

Anaerobic digestion can take place in three different temperature ranges: <10, 20 – 40 and 50 – 65 ^{o}C which are called psychrophilic, mesophilic and thermophilic conditions, respectively; each condition has a consortia of microorganisms which functions optimally within the temperature range and cannot survive outside it (Mshandete, 2004; Matheri *et al*., 2017). The most suitable thermophilic and mesophilic temperatures are 55 and 35 ^{o}C, respectively. AD operated in thermophilic condition requires extra energy input and is more difficult to control but more efficient than mesophilic process. However, large scale digesters are generally operated in mesophilic mode (Matheri *et al*., 2017).

Organic Loading Rate (OLR)

Organic loading rate (OLR) is the quantity of biodegradable material fed to an anaerobic digester within a given period usually presented as capacity per day (Ward *et al*., 2008; Drosg, 2013; Schnurer and Jarvis 2010); more specifically, it is the quantity of VS fed per working volume of a digester per day and is expressed as kg VS/m^3 digester/d (Esteves, 2013).

The OLR represents the biological conversion capacity of a digester, it is an important operational control parameter especially when the digester is operated in continuous mode. The digester runs efficiently at low OLR but high OLR can lead to system failure due to overloading (Linke and Schelle, 2000). Knowledge of the biodegradable material content such as dry and volatile solids are essential to optimize the organic loading rate of an anaerobic digester (Kigozi *et al*., 2014).

The OLR gives useful information for the design and operation of an anaerobic process, the knowledge of OLR also shows how effectively a digester volume is being used (Adebayo *et al*., 2015). The volumetric OLR is related to the retention time through the active biomass concentration in the digester and is used to characterize the loading on anaerobic treatment systems (Adebayo *et al*., 2015). The organic loading rate is inversely proportional to methane production (Matheri *et al*., 2017); if the substrate in a digester increases more than the bacteria, the bacterial may not be able to decompose the substrate due to an accumulation of undigested biodegradable material such as fatty acids. The accumulation of fatty acids creates an acid environment which decreases the pH and makes the digestion process unstable (Kigozi *et al*., 2014).

Retention Time and Food-to-Microorganism (F/M) Ratio
Retention time is the duration that microorganisms (solids) and organic matter (substrates) must remain together in a digester to achieve the desired extent of degradation. The hydraulic retention time (HRT) is the time an organic matter spends from the instant it is fed to the digester to its exit while solid retention time (SRT) is the duration for which active microorganisms reside in the digester. Retention time depends on substrate composition, temperature, digestion system classification as well as the processes (Matheri *et al*., 2017). The shorter the HRT required to achieve the desired extent of degradation, the more efficient the reactor. Food-to-microorganism (F/M) ratio is the ratio of the amount of substrate to the quantity of bacteria available to consume that substrate. It is the controlling factor in all biological treatment processes. A low F/M ratio is needed to ensure that a greater percentage of the substrate is converted to biogas, so it is required to keep the SRT high even though the HRT should be kept low to achieve high digester efficiency. In CSTR and low-rate digesters, HRT is the same as SRT, the solids/microbes and substrates have the same residence times in the digester. To operate a digester within a targeted retention time, it should be supplied with a sufficient number of microorganisms (Kigozi *et al*., 2014).

Toxicity
The growth of microbes in the digester require small amounts of minerals e.g. calcium, potassium, sodium, magnesium, sulphur and ammonium and heavy metals e.g. copper, nickel, cobalt, lead, chromium and zinc (Davison and Zhang, 1994; Temminghoff *et al*., 2000; Yang *et al*., 2016) however, higher quantities have a toxic effect on the microorganisms while organic solvents, antibiotics and detergents also inhibit the growth of microbes in the digester (Haak *et al*., 2016; Feng *et al*., 2010).

Pre-treatment of Feedstock
Feedstock pre-treatment can be mechanical, thermal, chemical or biological pre-treatment; pre-treatment is necessary to increase the efficiency of anaerobic digestion and production of biogas (Wang *et al*., 2012). Mechanical pre-treatment involves the reduction of the particle size of the substrate to increase its specific surface area that is available for bacteria to act upon thus making it easier for the bacteria to decompose the substrate and prevent digester clogging; the merit is the reduction of digester volume required for anaerobic digestion without adversely affecting the rate of biogas production. Thermal pre-treatment involves heating the feedstock at 220 ºC for a given pressure and then cooling it to a lower temperature before it is fed to a digester; it is also known as liquid hot water treatment. This pre-treatment has the merits of pathogen removal, improved dewatering performance and better digestate handling due to reduction of digestate viscosity. The effect of thermal pre-treatment depends on the biodegradable substrate, mesophilic and thermophilic conditions, however, it can result in loss of volatile organics and lower biomethane production from an easily biodegradable material. Chemical pre-treatment involves the use of alkalis or strong acids to treat substrates; alkali pre-treatment is used to raise the alkalinity in order to adjust the pH while acid pre-treatment or oxidative method is used to enhance digestibility and hydrolysis rate of lignocellulosic materials. Biological pre-treatment is employed in pre-acidification and multi-stage fermentation in which the first two stages (hydrolysis and acidogenesis) of AD are separated from the remaining two stages of acetogenesis and methanogenesis. In a first digester, pre-acidification occurs and pH is 4 - 6 inhibiting

methane production while maximizing hydrolytic enzyme efficiency resulting in the formation of hydrogen (Ryckebosch *et al*., 2011; Wang *et al*., 2012).

Agitation

Agitation or mixing of the materials in the digester is required to ensure fluid homogeneity; this would prevent pronounced temperature gradients within the digester, obviate the formation of scum and combine materials fed to the digester with microbes, and so ensure the stability of the anaerobic digestion process (Kigozi *et al*., 2014). The content of the digester determines the level of mixing that is required; if the stirring is slow, it could lead to inadequate mixing while very rapid mixing can disrupt the microbe community in the digester.

Types of Biodigester

The floating dome, fixed dome and ballon digesters are low rate, high hydraulic retention time (HRT) "semi-batch" anaerobic reactors which typically have a HRT of 40 – 50 days; they are popular in developing countries (especially India and China) and are primarily employed for biogas production from animal dung usually cattle dung by rural farmers and dwellers (Abbasi *et al*., 2012). The digestion rates in these reactors are very slow because there are no provisions for proper mixing of the slurry and retaining of microbes within the digester. MSW have not been successfully used in these low rate reactors due to digester clogging problem (Yadvika *et al*. 2004; Bouallagui *et al*., 2005; Abbasi and Abbasi, 2010).

The covered lagoon digester is a less expensive traditional anaerobic pond covered with an impermeable cover that traps the biogas produced by manure digestion; this digester requires large land area, it is most suitable for liquid manure containing less than 2% solids and plagued by poor process control (Abbasi *et al*., 2012).

There are also the anaerobic sequencing batch reactor, continuous stirred tank reactor and anaerobic plug-flow reactor, based on conventional types of chemical engineering reactor (Abbasi *et al*., 2012; Talia, 2018; Valijanian *et al*., 2018). The anaerobic sequencing batch reactor is loaded one time at the fill stage and all digestate formed during digestion is recirculated until the end of the cycle; it is the most suitable for very dilute manure of <1% TS (Abbasi *et al*, 2012; Talia, 2018). In the CSTR and plug flow digesters, the substrate is fed constantly into the reactor and digestate withdrawn continually. They can handle a wide range of substrates including manure, industrial waste, energy crops and OFMSW (Abbasi *et al*, 2012; Talia, 2018). The CSTR has a mixing system which ensures a high efficiency of digestion of volatile solids compared with other reactors, it can also be operated at different temperatures and OLRs, however, the investment costs for the CSTR is higher than that of the other reactors (Talia, 2018).

In addition to these, other reactors have been designed to enhance the retention of active microbial sludge, increase the rate of substrate conversion and reduce hydraulic retention time in the anaerobic digester, these are referred to as sludge retention reactors (Valijanian *et al*., 2018). They include the anaerobic contact reactor (Capela *et al*., 2009; Şentürk *et al*., 2010; Şentürk *et al*., 2013), up-flow anaerobic sludge blanket reactor (Mao *et al*., 2015; Reungsang *et al*., 2016; Jiang *et al*., 2014), expanded granular sludge blanket reactor (Mao *et a*l., 2015), up-flow anaerobic solid-state reactor (Mumme *et al*., 2010; Pohl *et al*., 2013), anaerobic baffled reactor (Mao *et al*., 2015), internal circulation reactor (Tauseef *et al*., 2013; Mao *et al*., 2015; Wang *et al*., 2017), anaerobic fluidized bed reactor (Zhang *et al*., 2008), anaerobic membrane reactors (Skouteris *et al*., 2012; Visvanathan and Abeynayaka, 2012; Ozgun *et al*., 2013; Horváth *et al*., 2016) and anaerobic biofilm reactors (Karadag *et al*., 2015).

Anaerobic Co-digestion of OFMSW with other Substrates

The organic fraction of municipal solid waste have been singly converted to biogas in biodigesters by anaerobic digestion (Hartmann and Ahring, 2005; Hartmann and Ahring, 2006; Macias-Corral *et al*., 2008; Karagiannidis and Perkoulidis, 2009). Anaerobic co-digestion is the simultaneous digestion of a mixture of different substrates/feedstock in a digester. Co-digestion is used to balance the C/N ratio of digester feedstock for instance cattle manure may be co-digested with plant biomass (Zhang *et al*., 2016). This process has the merits of usage of large number of different substrates, synergistic effect of microorganisms, high process stability, enhanced biogas yield, high nutrient recycling and odour reduction (Marañón *et al*., 2012; Zhang *et al*., 2014; Langeveld *et al*., 2016).

OFMSW is characterized by heterogeneous nature, high C/N ratio, large particle size and high solids content, they are macro and micro-nutrients deficient and may contain toxic and slowly biodegradable lignocellulosic materials; these issues have led to challenging process control, poor biogas yields and digester failure which have limited the anaerobic digestion of OFMSW (Hartmann *et al*., 2002). Also, the food waste in OFMSW is highly biodegradable and undergoes rapid hydrolysis which leads to the accumulation of volatile fatty acids and ammonia in the digester causing process inhibition which affects digester stability and eventually leads to process failure (Banks *et al*., 2012; Nagao *et al*., 2012; Zhang *et al*., 2013; Ren, 2017). The stability of an anaerobic digestion process and its ability to handle a largely diverse heterogeneous feedstock essentially determine its commercial feasibility (Kayhanian, 1999).

Hence, recent research focus is on the co-digestion of OFMSW with other substrates in biodigesters e.g. sewage sludge (Sosnowski *et al*., 2003; Silvestre *et al*., 2015; Abudi *et al*. (2016); Grosser *et al*., 2017); manure (Hartmann and Ahring, 2005; Capela *et al*., 2008; Macias-Corral *et al*., 2008; Matheri *et al*. (2017)), fruit and vegetable waste (Pavi *et al*. (2017) and agricultural residue (Negi *et al*., 2018). The co-digestion of OFMSW with a co-substrate may stabilize AD process conditions such as C/N ratio, macro and micronutrients, pH, total solids, inhibitors/toxic compounds and so increase biogas production (Matheri *et al*., 2017; Guven *et al*., 2017; Pavi *et al*., 2017; Matheri *et al*., 2017; Negi *et al*., 2018).

The merits of co-digesting OFMSW and other substrates include enhanced productivity, improved process stability and performance, maximization of the capacity of available feedstock for anaerobic digestion and better handling of mixed waste as slurry; OFMSW is also a cost effective and improved technique to optimize anaerobic digestion process via increase in nutrients and bacterial variety in substrate (Capela *et al*., 2008; Zhang *et al*., 2013; Belle *et al*., 2015; Matheri *et al*., 2017). Other benefits are minimization of retention time and maximizing of biogas production efficiency due to the presence of a variety of organic material and consequently available nutrient for bacteria (Callaghan *et al*., 1999; Zhang *et al*., 2013; Abudi *et al*., 2016; Guven *et al*., 2017; Pavi *et al*., 2017; Matheri *et al*., 2017; Negi *et al*., 2018).

Conclusions

Municipal solid waste is managed through waste diversion (reduction, reuse, recycling and recovery) and waste disposal (controlled incineration, landfilling and controlled dumping). The generation rate and composition of MSW as well as the characteristics of OFMSW feedstock for anaerobic digestion are required for the design of a full scale biodigester for municipal use. AD feedstock includes agricultural waste/residues, animal wastes, energy crops, food waste, forestry crops and residues, organic industrial waste and wastewater, weeds, aquatic algae, sewage and organic fraction of municipal solid waste. They are characterized by determining their physicochemical properties which include total solids (TS), volatile solids (VS), moisture content, biochemical methane potential and carbon to nitrogen (C/N) ratio. The essential factors that influence the production of biogas are temperature, pH, mixing rate, carbon/nitrogen ratio, organic loading rate, micro and macro-nutrient availability, retention time, nature of the feedstock and digester type. Anaerobic co-digestion of OFMSW with other substrates results in improved AD process stability, enhanced biogas productivity, maximization of the capacity of available feedstock for anaerobic digestion and better handling of mixed waste as slurry. It is also a cost-effective and better technique to optimize anaerobic digestion process via the increase in nutrients and bacterial variety in substrates. The information provided in this review is invaluable to researchers, governments, industries and other stakeholders interested in anaerobic conversion of biodegradable municipal solid waste to bioenergy.

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