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Designs of anaerobic digesters for producing biogas from municipal solid-waste

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Abstract

The production of biogas is of growing interest as fossil-fuel reserves decline. However, there exists a dearth of literature on the design considerations that would lead to process optimization in the development of anaerobic digesters aimed at creating useful commodities from the ever-abundant municipal solid-waste. Consequently, this paper provides a synthesis of the key issues and analyses concerning the design of a high-performance anaerobic digester.

Keywords: Anaerobic digesters; Biogas; Design parameters; Economic considerations; Municipal solid-waste; Technical considerations

1. Introduction

The processing of refuse was usually undertaken to reduce the pollution potential and volume for ease of handling and disposal. This perspective has since been adjusted to include the transformation of the waste, which was hitherto unwanted, into useful end-products. This is the case with municipal solid-waste (MSW), which has a high potential for the generation of biogas (and hence energy) when subjected to anaerobic digestion [1]. So batch and continuous anaerobic-digesters have been designed for the treatment of MSW to yield biogas [2]. A preliminary design procedure includes an investigation of the properties of the refuse, with a view to establishing appropriate principles and considerations for the design of the digesters. Coupled with other relevant information from the literature, this leads to the formulation of design criteria. This report

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Abbreviations: AD, anaerobic digestion; LFG, land-fill gas; MSW, municipal solid-waste; pH, hydrogen-ion concentration; TS, total solids; VFA, volatile fatty-acid.

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integrates these technical with economic considerations to form basis for the design of anaerobic digesters for the release of biogas.

1.1. Biogas production

When organic refuse decays, it does so in the presence or absence of air (and hence oxygen) and is referred to as aerobic or anaerobic decomposition respectively. This decomposition could be naturally occurring or may be artificially induced, under controlled conditions. In either case, there are several by-products as shown in Fig. 1, which has been adapted from Ref. [3].

One of the end-products of anaerobic decay is biogas, which is produced naturally from decay under water or in the guts of animals, and artificially in airtight digesters. Itodo and Phillips [4] described biogas as “a methane-rich gas that is produced from the anaerobic digestion of organic materials in a biological-engineering structure called the digester”. This definition suggests that biogas is only produced artificially, but this is not the case. It is believed that the scope of their definition may perhaps have been limited by their comparison of artificial production-processes, thus ignoring the natural occurrence of biogas. However, Itodo and Phillips are not alone in this way of defining biogas. GEMET [5] states that biogas is “gas rich in methane, which is produced by the fermentation of animal dung, human sewage or crop residues in an air-tight container”.

The decomposition of organic matter in the absence of air could be elicited by the use of physical or chemical processes at high temperature and/or pressure, or the use of microorganisms at near ambient temperature and atmospheric pressure; the preferred method being dependent on the relative polluting impacts on the environment. However, irrespective of the method used, gas is produced; it is referred to as biogas if generated as a result of the action of microorganisms on the organic wastes [6]. This is why biogas – see Table 1 – is now defined as “a by-product of the biological breakdown, under oxygen-free conditions of organic wastes such as plants, crop residues, wood and bark residues, and human and animal manure — and is known by such

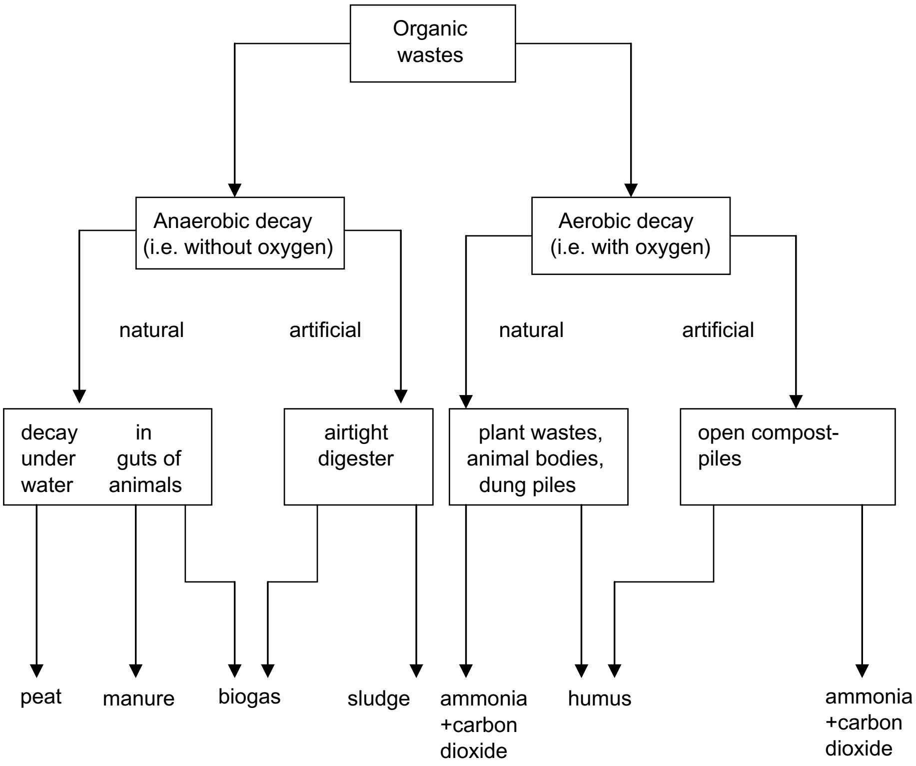

Fig. 1. Organic-decay processes.

Table 1
Composition of biogas

Constituent	Composition
Methane (CH_4)	55–75%
Carbon dioxide (CO_2)	30–45%
Hydrogen sulphide (H_2S)	1–2%
Nitrogen (N_2)	0–1%
Hydrogen (H_2)	0–1%
Carbon monoxide (CO)	Traces
Oxygen (O_2)	Traces

other names as swamp gas, marsh gas, ‘will o’ the wisp’ or gobar gas” [7], digestion gas [8], natural gas [9], landfill gas (LFG), and sewage gas [10]. The gas is colourless, relatively odourless and flammable: it is also stable and non-toxic. It burns with a blue flame and has a calorific value of 4500–5000 kcal/m^3 when its methane content ranges from 60% to 70% [11].

1.1.1. Sources of biogas

The generation of biogas has traditionally been from feedstocks such as “livestock farm-waste (e.g. various manures, slurries and waste waters) and agro-industrial waste (from abattoirs, wineries, vegetable-processing plants, etc.)” [12]. This is why biogas is also described as the fuel produced through anaerobic fermentation of manure and vegetable matter in digesters, or the fermentation of animal dung, human sewage or crop residues in an airtight container [5]. Hence, the general belief is that liquid-manure systems work best for anaerobic digestion in the production of biogas. However, this is not so, except that the generation of biogas was indeed first associated with liquid wastes and sludge. So Kiely [13] explained that anaerobic digestion is used worldwide for the treatment of industrial, agricultural and municipal waste-water and sludge: he also noted that, in recent years, it has also been applied for the treatment of municipal solid-wastes. Hence Vassiliou [12], after successfully generating biogas from wastes of raw manure plus wash-water from large livestock-farms, and the wastes from food and drink industries, explained that the second stage of any project should be to generate biogas from the organic components of source-separated municipal solid-wastes (MSWs).

1.1.2. Uses of biogas

Biogas is increasingly becoming an attractive source of energy in many nations of the world. For example, the Finnish magazine *Suomen iuonto* reported that the gas is used to fuel a car owned by a farm owner. Sweden too has a similar story as many city-buses are powered by biogas, and some gas stations there offer biogas in addition to other fuels. In fact, all over the world, biogas has been variously used for heating purposes and/or electricity generation. For example, in the UK, Xuereb [10] reported that, although the use of biogas for electricity generation was still at an experimental stage, it already accounts for about 0.5% of the total electricity-output; and biogas fuels account for about 1% of US electricity generation, while achieving a climate-change benefit equivalent to reducing CO_2 emissions in the electricity sector by more than 10%. Biogas is also presently used in India, China, Taiwan, Brazil, Singapore, etc. Tchobanoglous and Burton [14] stated that, in large plants, digester gas may be used as a fuel for the boiler and internal-combustion engines, which are in turn used for pumping waste water, operating blowers and generating electricity. Despite the heating-and-electricity generation uses of biogas, in addition, the residues of such biogas production can be used as low-grade fertilizers.

Xuereb [10] enumerated the characteristics of biogas:-

- It is flammable, potentially explosive and a readily controllable source of energy.
- Its use helps to reduce the amount that would otherwise be released naturally into the atmosphere, and so reduces the excessive greenhouse-effect.
- Although on burning biogas, carbon dioxide is released, it is not considered as a net contributor to the global carbon-dioxide level because it originated from plants, which have absorbed it from the atmosphere. Hence this carbon dioxide does not make a net contribution to the ‘greenhouse effect’.

- The harnessing of biogas also helps to minimize the unpleasant decomposition smells produced in landfill sites because, otherwise, these gases would be released directly into the atmosphere. Hence, especially where landfills are situated close to inhabited areas, the harnessing of LFG makes landfills slightly more socially acceptable.

1.2. Municipal solid-waste

Generally, such refuse is regarded as useless material that is unwanted and therefore discarded. The New Edition Concise English-Dictionary [15] explains that "waste" is "anything or anyone rejected as useless, worthless, or in excess of what is required". But Byrne [16] was more comprehensive with his description of waste, when he stated that waste is material, which has no direct value to the producer and so must be disposed of. This could be why Bailie et al. [17] insist that "for practical purposes, the term waste includes any material that enters the waste-management system". A waste-management process and pertinent system are an organized programmes and central facility respectively established, not only, for the final disposal of waste but also for recycling, reuse, composting and incineration. From the foregoing, it is apparent that materials enter a waste-management system when no one who has the opportunity to retain them wishes to do so.

Wastes are usually classified, as gaseous-, liquid- or solid-wastes, depending on their phase. Materials which fall within the solid-waste category form the subject of the present study. Bailie et al. [17] defined solid-wastes to include all refuse materials that are not hazardous, liquid wastes or atmospheric emissions. While Kiely [13] specified solid wastes as including those from human and animal activities, and include liquid wastes like paints, old medicines, spent oils, etc. It is possible to have solid-waste intermixed with liquid waste. Nevertheless, in whichever manner the waste occurs, this study considers solid waste as largely non-flowing, which makes its handling and management relatively difficult, compared with those for liquid and gaseous wastes [18]. Its non-flowing nature requires its continual retention at the site of generation or deposition, until it is removed for disposal. Consequently, solid waste poses many environment problems, including offensive odours; obstruction of traffic flow; as well as blocking of waterways and drains, so leading to flooding, environmental degradation and pollution of the atmosphere, with the concomitant unfavourable effects on public health, etc. The common way of describing the solid-waste menace is usually with respect to its place of generation or point of origin.

Municipal solid-waste (MSW) is defined as all waste collected by private and public authorities from domestic, commercial and some industrial (non-hazardous) sources. Furthermore, Kiely [13] and Bailie et al. [17] posited that MSW in particular comprises small and moderately sized solid-waste items from houses, businesses and institutions. Also Byrne [16] stated that municipal waste is that generated from urban areas, particularly houses and shops.

2. Digester-design considerations

In the design of a digester suitable for the biodegradation and indeed stabilization of MSW, with the attendant production of biogas, several factors are considered, such as the type of waste, the rate of waste generation and local environmental conditions, like the ambient temperature.

2.1. Type of digester

A variety of digester types exists for the anaerobic treatment of organic wastes. The selected type depends on operational factors, including the nature of the waste to be treated, e.g. its solid content. The Oregon State Department of Energy [8] in its classification of types of digester explains that 'a covered lagoon digester' is used for liquid-manure of less than 2% solids; 'a complete-mix digester is suitable for manure that is 2–10% solids'; and 'plug-flow digesters are suitable for ruminant animal excreta having solid concentrations of 11–13%". The type and solid contents of the waste they considered were such that the wastes are capable of flowing on their own, or forming slurries with water and eventually flowing and so could be used in a continuous operation.

MSW is predominately solid and non-flowing. Hence Kahaynian et al. [19], as reported by Kiely [13], suggested the use of 'high-solids digesters'. This was expounded by Hobson et al. [6] when they posited that solid-state digestion, though still largely theoretical with only some small units having being built, is always a batch process. But continuous-flow digesters, which are by nature low-solids digesters, have been employed to generate methane from human, animal and agricultural wastes, and from the organic fraction of MSW [20]. This process always required more water to be added to the waste in order to get it to flow.

Hobson et al. [6] reported an experimental digestion of domestic garbage diluted with sewage to a total solids concentration of between 5 and 7%. Fig. 2 shows the flow process in a low-solids digester using MSW, as described by Tchobanoglous et al. [20]. The authors [6] maintained that stirred – tank digesters can deal with slurries of about 3–10% total solids (TS), much of which are suspended solids. In their analysis of what they described as 'solid feedstock', including green-vegetable matter of about 20% solid concentration, they explained that, if these materials are to be used as feed for a stirred-tank digester, then they will have to be made into slurries. According to their experience, a slurry of about 10% TS is the maximum that can be pumped and piped even if the particle size is small, and 7–8% TS may be the maximum which can be handled by smaller pumps and pipelines.

2.2. Temperature control

The temperature of MSW affects the success of the digestion process, as the activities of the anaerobes causing waste decomposition are temperature dependent. The optimal temperature ranges are the mesophilic, namely 30–38 °C, and the thermophilic 44–57 °C [14], respectively. The rate of decomposition and gas production is sensitive to temperature, and, in general, the process becomes more rapid at high temperatures [3]. Despite this 'thermophilic benefit', the digestion process becomes increasingly unstable with rising temperature, and requires higher rates of heat inputs, and produces poorer-quality supernatant containing larger quantities of dissolved solids [14]. However, Kiely [13] insists that most digesters now operate at mesophilic temperatures, for which good stability and gas production occur. In addition, Tchobanoglous et al. [21] posited that reactor temperatures between 25 °C and 35 °C are generally the preferred optima to support biological-reaction rates yet provide a more stable treatment. Mattocks [7] previously noted that choosing the

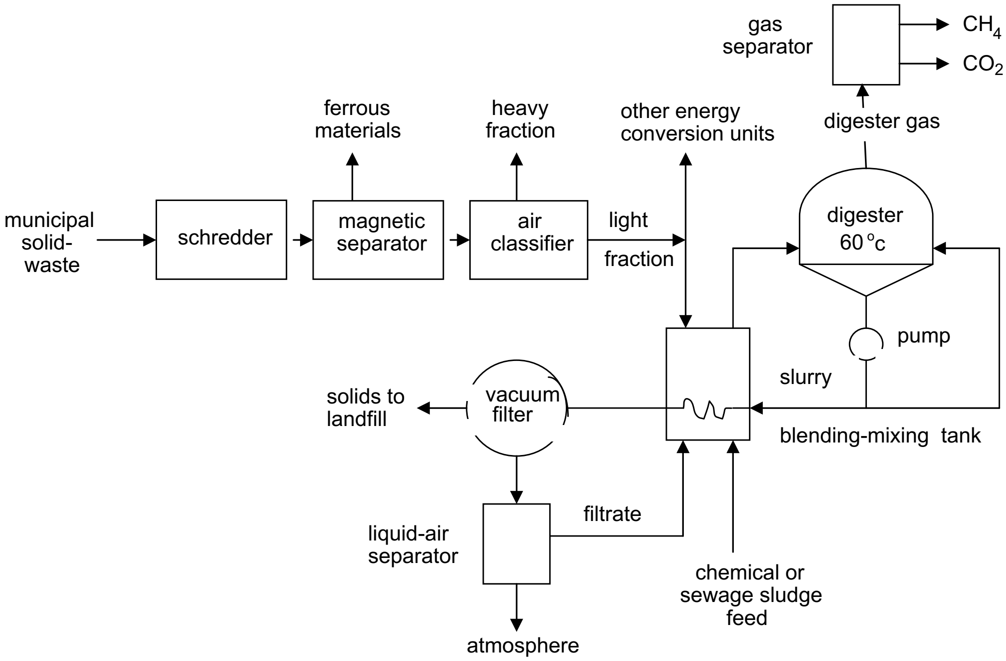

Fig. 2. Flow diagram for the low-solids anaerobic-digestion process for the organic fraction of MSW.

appropriate operating temperature is vital, but stabilizing it is even more important. He concluded that variations of ±1 °C in a day may force the methane producing organisms into periods of dormancy. However, according to Viessman and Hammer [22], the rate of biological activity in the range between 5 °C and 35 °C doubles for every 10–15 °C temperature rise. This is possibly why Kiely [13] and Viessman and Hammer [22] agree that thermophilic digestion has not been successful in practice because thermophilic bacteria are very sensitive to small temperature-changes. Eckenfelder [23] added to this by stating that the maintenance of higher temperatures is usually not economically justifiable, so corroborating the view of Mattocks [7], who, after noting that at an elevated temperature minor changes in system conditions could reduce digester efficiency or productivity, stressed that an additional source of energy will likely be required to maintain the digester contents at a constant higher-temperature.

It is important to state that psychrophilic temperature ranges (say at ∼20 ° C) are not suitable for anaerobic digestion, as, according to Tchobanoglous et al. [21], the degradation of long-chain fatty-acids is often rate limiting. If long-chain fatty-acids accumulate, foaming may occur in the reactor and so inhibit process continuity.

Fortunately, the average ambient temperature at Port Harcourt (which was the considered region), at the time of this study, was 32 °C, so leading easily to the adoption of the optimal mesophilic temperature of 35 °C in the digester.

2.3. Hydrogen-ion (pH) concentration control

The level and variation of pH in the digesting material affect the anaerobic-digestion process. Viessman and Hammer [22] and Steadman [3] concluded that the hydrogen-ion concentration of the culture medium has a direct influence on microbial growth because the digestion is inhibited by excessive acidity. The bacteria involved in anaerobic digestion have a pH range of 6–8 with values close to 7 for optimal activity. In the initial phase of the process, the production of volatile fatty-acids depresses the pH, but the reaction of CO_2, which is soluble in water, with hydroxide ions for bicarbonate ions, so forming HCO_3, tends to restore the neutrality of the process pH, thus making the process self-stabilizing or 'well buffered'. When the rate of acid formation exceeds the rate of breakdown to methane, a process imbalance results in which the pH decreases, gas production falls off, and the CO_2 content of the gas increases [23]. The overall effect, according to Mattocks [7], is impedence of the whole biogas-process. Sufficient alkalinity has to be available at all times, up to a level of approximately 3000 mg/l, for sufficient buffering to be maintained, to ensure a high rate of methane production. Eckenfelder [23] says lime is commonly used to raise the pH of an anaerobic system when there is a process imbalance. However, care must be taken not to apply excess lime, because this will result in the precipitation of calcium carbonate: alternatively, sodium bicarbonate can be used for the pH adjustment.

2.4. Carbon–nitrogen ratio

The concentrations of carbon and nitrogen determine the performance of the anaerobic, digestion process, as one or the other usually constitutes the limiting factor. Whereas carbon constitutes the energy source for the microorganisms, nitrogen serves to enhance microbial growth. If the amount of nitrogen is limiting, microbial populations will remain small and it will take longer to decompose the available carbon. Excess nitrogen, beyond the microbial requirement, is often lost from the process as ammonia gas [24]. It has been found that the bacteria in the digestion process use up the carbon present 30–35 times faster than the rate at which they convert nitrogen. So, for the optimal operation, the ratio of the carbon, to, nitrogen should be about 30:1 in the raw material. Richard [24] says that usually, nitrogen is the limiting element in the processing of MSW, and additives such as manure, clean sewage-sludge (biosolids), septage and urea can be used as a supplemental nitrogen source.

2.5. Moisture content of the waste in the digester

Moisture is essential for the activities of the waste-decomposing anaerobes and hence for effective anaerobic digestion.

2.6. Waste-particle size

The particle size of MSW affects the biological transformation of the waste, and so equipment sizing. The relatively-large particle-sizes of MSW [13], considerably retard decomposition; hence the necessity for the reduction of the average particle size of the MSW. For a container filled with particles, reducing the individual particle-size increases the total surface area of the particles in the container. This is desirable for the process operation, as decomposition occurs on the surfaces of the organic materials [25]. The particle-size reduction of MSW could be achieved through shredding or grinding: the ultimate objective is to improve the efficiency of the operation by presenting a larger surface area for microbial activity to occur [26].

2.7. Mixing

This is another important operation in achieving optimal anaerobic-digestion [14]. It is desirable to maintain uniformity of (i) substrate concentration, (ii) temperature and (iii) other environmental factors as well as prevent scum formation and solids deposition [26]. For solid matter like MSW, and therefore employing a ‘dry solid’ digestion process, mixing becomes rather difficult and can be highly expensive. Even the mixing via gas re-circulation may also entail a loss of valuable gas. However, mixing via mechanical stirrers and gas re-circulation respectively are employed for high and low-solids digesters, depending on the eventual total solids (TS) concentrations of the systems.

2.8. Digester’s heat-requirements

The consensus opinion [13,21,27] is that the heat requirements of digesters are used to:

(i) raise the temperature of the incoming sludge to that of the digestion tank;
(ii) compensate for the heat losses through the walls, floor and roof of the digester; and
(iii) make up the losses that might occur in the piping between the source of heat and the tank.

It is important to state that, in most research and operational digesters which require external heating, the ambient temperature falls within the psychrophilic range ($\leqslant$20 °C). Because the optimal temperature for the maximum rate of reaction is around 35 °C, the digester would require external heating to get its temperature up to the mesophilic range. Hence digester heating is necessary in moderate and cold climates, especially during winter, to maintain the digester temperature within the desired range [27]. However external heating of the digester in Nigeria is probably unnecessary. Therefore, because the anaerobic-digestion process is an exothermic one leading to variations in the internal and external temperatures of the digester, considerations should be given to (i) the microbial heat-generation in the digester and (ii) the heat flows across the digester boundaries.

2.9. Costs

In addition to the cost of an anaerobic digester for processing of MSW for harnessing energy, there will be the costs of (i) constructing and maintaining the plant, (ii) obtaining the feedstock and (iii) preparing the MSW for digestion. Process costs (i.e. capital, operating and maintenance) are extremely important in selecting the type and size of reactor [14]. The bio-kinetic and design models for the reactor will directly affect the digester’s cost, particularly in terms of the digester and feedstock volumes required to yield the desired quantity of gas via batch digestion. Steadman [3] stated that the simplest type of methane digester is just a closed container such as a drum, tank or pit in the ground into which the digestible material is loaded, that is, a batch digester. The simplicity of the batch-digester design clearly should also influence the process cost. The Oregon State Department of Energy [8], after describing three types of digesters, namely a covered-lagoon digester (i.e. a batch digester), a complete-mix digester, and a plug-flow digester, stated that the batch digester was the least expensive of the three.

2.10. Loading rate of organic materials into the digester

This specification greatly affects the anaerobic-digester's design, particularly the volume of the digester, and indeed the overall process-performance. The loading rate is an important parameter because it indicates the amount of volatile solids to be fed into the digester each day [7]. Volatile solids represent that portion of the organic-material solids that can be digested, while the remainder of the solids is fixed. The 'fixed' solids and a portion of the volatile solids are non-biodegradable. The actual loading rate depends on the types of wastes fed into the digester [7], because the types of waste determine the level of biochemical activity that will occur in the digester.

Wide variations in (i) the composition of the incoming flow and (ii) the organic loads can upset the balance between acid fermentation and methanogenesis in the anaerobic processes [21]. For soluble, easily degradable substrates, such as sugars and soluble starches, the acidogenic reactions can be much faster at high loadings and may increase the reactor's volatile fatty-acids (VFAs) and hydrogen concentrations and depress the pH value. The loading rate also affects the food-to-microbes (F/M) ratio [13]. The system achieves equilibrium when the food substrates and the micro-organisms consuming them are in balance. When out-of-balance, there could be too much substrate or too little substrate, or too many organisms or too few organisms. Any of these situations would destabilize the process: the equilibrium parameter is the F/M ratio.

2.11. Pretreatment of the waste

This is the preparation of the waste for the anaerobic-digestion process. For instance, MSW, particularly in Nigeria, is a complex mixture of both organic and inorganic materials [28]. So, because the digestion process is for the decomposition of the organic components, it would be preferable to sort the organic components from the inorganic ones. Also in general, the particle sizes of the organic waste are such that they will require reduction. These and the other processes that the waste may undergo before being fed into the digester are termed as waste pretreatment.

3. Conclusion

The key analyses involved in the design of anaerobic digesters for the production of biogas from municipal solid-waste have been reviewed. There is a need for proper comminution (i.e. size reduction) of MSW, while ensuring that other important aspects of the digestion process, such as temperature, hydrogen-ion concentration, carbon–nitrogen ratio, loading rate, as well as moisture and heat contents are manipulated to achieve an optimal design of the anaerobic digester. The batch digestion system yields a cost-effective and economically viable means for the conversion of the ever-abundant municipal solid-waste to useful energy. It is therefore recommended that such anaerobic digestion systems be increasingly employed in order to (i) harness this source of "waste" energy and (ii) simultaneously protect the environment.

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