The accumulation of solid organic waste is thought to be reaching critical levels in almost all regions of the world. These organic wastes require to be managed in a sustainable way to avoid depletion of natural resources, minimize risk to human health, reduce environmental burdens and maintain an overall balance in the ecosystem. A number of methods are currently applied to the treatment and management of solid organic waste. This review focuses on the process of anaerobic digestion which is considered to be one of the most viable options for recycling the organic fraction of solid waste. This manuscript provides a broad overview of the digestibility and energy production (biogas) yield of a range of substrates and the digester configurations that achieve these yields. The involvement of a diverse array of microorganisms and effects of co-substrates and environmental factors on the efficiency of the process has been comprehensively addressed. The recent literature indicates that anaerobic digestion could be an appealing option for converting raw solid organic wastes into useful products such as biogas and other energy-rich compounds, which may play a critical role in meeting the world’s ever-increasing energy requirements in the future.

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1. Introduction

Solid organic waste removal has become an ecological problem, brought to light as a result of an increase in public health concerns and environmental awareness. The average solid waste generation rate in 23 developing countries is 0.77 kg/person/day (Troschinetz and Mihelcic, 2009) and is increasing. At present, worldwide municipal solid waste generation is about two billion tons per year, which is predicted to increase to 3 billion tons by 2025 (Charles et al., 2009). The production of fruit and vegetable waste is also very high and becoming a source of concern in municipal landfills because of its high biodegradability (Bouallagui et al., 2005).


Recently, the organic fraction of solid waste has been recognized as a valuable resource that can be converted into useful products via microbially mediated transformations (Yu and Huang, 2009; Lesteur et al., 2010). There are various methods available for the treatment of organic waste but anaerobic digestion appears to be a promising approach (Lee et al., 2009c). Anaerobic digestion involves a series of metabolic reactions such as hydrolysis, acidogenesis and methanogenesis (Themelis and Ulløa, 2007). Anaerobic digestion of organic waste in landfills releases the gases methane and carbon dioxide that escape into the atmosphere and pollute the environment (Zhu et al., 2009). Under controlled conditions the same process has the potential to provide useful products such as biofuel and organic amendment (soil conditioner) and the treatment system does not require an oxygen supply (Chanakya et al., 2007; Guermoud et al., 2009). Further, methane and hydrogen as potential fuels are considered comparatively cleaner than fossil fuel. In addition, this has the benefit of not depending on fossil fuel for energy consumption (Jingura and Matengaifa, 2009). Thus, anaerobic digestion represents an opportunity to decrease environmental pollution and at the same time, providing biogas and organic fertilizer or carrier material for biofertilizers.

The anaerobic treatment of solid organic waste is not as widespread as the aerobic process, mainly due to the longer time required to achieve biostabilization (Fernandez et al., 2010). The process is also sensitive to high levels of free ammonia resulting from anaerobic degradation of the nitrogen rich protein components (Fountoulakis et al., 2008). The specific activity of methanogenic bacteria has been found to decrease with increasing concentrations of ammonia (Zhang et al., 2008).

Recent advancements in bioreactor designs have increased the use of anaerobic digestion for the treatment of solid organic waste. To date, a number of novel bioreactor designs have been developed where anaerobic digestion can be performed at a much higher rate than the conventional methods. Many factors, including the type and concentration of substrate, temperature, moisture, pH, etc., may affect the performance of the anaerobic digestion process in the bioreactor (Behera et al., 2010; Jeong et al., 2010). This manuscript reviews the potential of anaerobic digestion for recycling solid organic waste.

There are some components in wastes (metals and some recalcitrant organic compounds, often toxic) that will not be broken down and will therefore become concentrated in the residue. Although this is an important consideration and must be considered when applying digestions, it is a huge topic and will not be reviewed here.

2. Anaerobic digestion

With the introduction of both commercial and pilot anaerobic digestion plant designs during early 1990s, anaerobic digestion of organic waste has received worldwide attention (Karagiannidis and Perkoulidis, 2009). It is a process by which almost any organic waste can be biologically transformed into another form, in the absence of oxygen. The diverse microbial populations degrade organic waste, which results in the production of biogas and other energy-rich organic compounds as end products (Lastella et al., 2002; Lata et al., 2002). A series of metabolic reactions such as hydrolysis, acidogenesis, acetogenesis and methanogenesis are involved in the process of anaerobic decomposition (Park et al., 2005; Charles et al., 2009).

Anaerobic digestion is applicable for a wide range of material including municipal, agricultural and industrial wastes, and plant residues (Kalra and Panwar, 1986; Gallert et al., 1998; Chen et al., 2008). Furthermore, this process has some advantages over aerobic process due to a low energy requirement for operation and a low biomass production (Wang et al., 1999; Steyer et al., 2002; Angenent et al., 2004; Kim et al., 2006), and it is considered a viable technology in the competent treatment of organic waste and the simultaneous production of a renewable energy (De Baere, 2006; Jingura and Matengaifa, 2009).

The anaerobic digestion of organic waste is also an environmentally useful technology. Ward et al. (2008) described the benefits of this process to reduce environmental pollution in two main ways: the sealed environment of the process prevents exit of methane into the atmosphere, while burning of the methane will release carbon–neutral carbon dioxide (no net effect on atmospheric carbon dioxide and other greenhouse gases).

On the other hand, the anaerobic process has some disadvantages such as long retention times and low removal efficiencies of organic compounds (Park et al., 2005). The chemical composition and structure of lignocellulosic materials hinders the rate of biodegradation of solid organic waste. It has been documented that hydrolysis of the complex organic matter to soluble compounds is the rate-limiting step of anaerobic processes for wastes with a high solid content (Chullhwan et al., 2005; Mumme et al., 2010). Consequently, various physical, chemical and enzymatic pre-treatments are required to increase substrate solubility and accelerate the biodegradation rate of solid organic waste (Torres and Llorens, 2008; Charles et al., 2009).

3. Anaerobic co-digestion

Co-digestion is a waste treatment method in which different wastes are mixed and treated together (Agdag and Sponza, 2007). It is also termed as “co-fermentation”. Co-digestion is preferably used for improving yields of anaerobic digestion of solid organic wastes due to its numerical benefits. For example, dilution of toxic compounds, increased load of biodegradable organic matter, improved balance of nutrients, synergistic effect of microorganisms and better biogas yield are the potential benefits that are achieved in a co-digestion process. Co-digestion of an organic waste also provides nutrients in excess (Hartmann and Ahring, 2005), which accelerates biodegradation of solid organic waste through bio-stimulation. Additionally, digestion rate and stabilization are increased (Sosnowski et al., 2003; Lo et al., 2010). Jingura and Matengaifa (2009) described the following multiple benefits of co-digestion: the facilitation of a stable and reliable digestion performance and production of a digested product of good quality, and an increase in biogas yield.

It has been observed that co-digestion of mixtures stabilizes the feed to the bioreactor, thereby improving the C/N ratio and decreasing the concentration of nitrogen (Cuetos et al., 2008). The use of a co-substrate with a low nitrogen and lipid content waste increases the production of biogas due to complementary characteristics of both types of waste, thus reducing problems associated with the accumulation of intermediate volatile compounds and high ammonia concentrations (Castillo et al., 2006).

Several studies have shown that mixtures of agricultural, municipal and industrial wastes can be digested successfully and efficiently together (Table 1). A stimulatory effect on synthesis of methane gas has been observed when industrial sludge was co-digested with municipal solid waste (Agdag and Sponza, 2007). The co-digestion of municipal solid waste with an industrial sludge ratio of 1:2 yielded the highest amount methane gas, compared to municipal solid waste alone. Similarly, in a two-phase anaerobic digestion system, Fezzani and Cheikh (2010) recorded the highest methane productivity when a mixture of olive mill wastewater and olive mill solid waste was co-digested. The process has also been useful in obtaining a valuable sludge which can eventually be used as a soil amendment after minor treatments (Gomez et al., 2006).
4. Anaerobic bioreactors

Anaerobic bioreactors have potential application for rapid digestion of solid organic waste constituents to reduce the environmental load as compared to conventional sanitary landfills (Açdag and Sponza, 2007). Bioreactor design has been found to exert a strong influence on the performance of a digester (William and David, 1999). As described earlier (Table 2), a variety of new bioreactor designs have been developed in recent years, which facilitate a significantly higher rate of reaction for the treatment of waste (Bouallagui et al., 2003; Mumme et al., 2010; Xing et al., 2004). On the other hand, batch reactors have quick digestion with simple and inexpensive equipment, and also tied. Anaerobic batch reactors are useful because they can perform separately for each stage (Demirer and Chen, 2005). All the major groups of bioreactors commonly in use include batch reactors, a one stage continuously fed system and a two stage or multi-stage continuously fed system. Batch reactors are the simplest, filled with the feedstock and left for a period that can be considered to be the hydraulic retention time, after which they are emptied. Anaerobic batch reactors are useful because they can perform quick digestion with simple and inexpensive equipment, and also are helpful in assessing the rate of digestion easily (Parawira et al., 2004; Weiland, 2006). On the other hand, batch reactors have some limitations such as high fluctuations in gas production as well as gas quality, biogas losses during emptying the bioreactors and restricted bioreactor heights (Linke et al., 2006). The second type of bioreactors is known as 'one-stage continuously fed systems', where all the biochemical reactions take place in one bioreactor. The third type of bioreactors are 'two-stage' or 'multi-stage continuously fed systems', in which various biochemical processes such as hydrolysis, acidification, acetogenesis and methanogenesis take place separately (Ward et al., 2008). The two-stage system is considered a promising process to treat organic wastes with high efficiency in terms of degradation yield and biogas production (Fezzani and Cheikh, 2010). According to Demirer and Chen (2005), a two stage system allows the selection and enrichment of different bacteria in each phase. The complex organic materials are degraded by acidogenic bacteria to volatile fatty acids and alcohols, which are then easily metabolized into methane and carbon dioxide by methanogens or archaea. Further, this type of system increases the stability of the process by controlling the acidification phase through optimization of the hydraulic retention time to prevent overloading and the build-up of toxic material. The biomass concentration and other conditions can also be optimized independently for each stage (Demirer and Chen, 2005). All the above three types of bioreactors, along with a variety of methanizers such as continuously stirred tank bioreactor, tubular bioreactor, anaerobic sequencing batch bioreactor, up flow anaerobic sludge blanket and anaerobic filters are applied for the treatment of different types of waste (Bouallagui et al., 2005).

Biodigesters are also classified as “wet” or “dry” solid waste digesters. According to Ward et al. (2008), wet bioreactors have total solids of 16% or less, while dry bioreactors contain 22–40% total solids, with the intermediate rating termed ’semi dry’, while according to Karagiannidis and Perkoulidis (2009), dry systems contain 30–40% dry matter where as wet systems contain 10–25% dry matter. Another type of bioreactor based on operating temperatures (i.e., thermophilic or mesophilic) are also available (Kuo and Cheng, 2007; Karagiannidis and Perkoulidis, 2009).

5. Biogas yield from anaerobic digestion of solid organic waste

The process of biogas generation from solid organic waste is often carried out by several different anaerobic bacteria (jingua and...
Matengaifa, 2009). Several reports indicate that anaerobic digestion of the organic fraction of solid waste yields promising amounts of biogas (Table 3). Biogas is generally composed of 48–65% methane, 36–41% carbon dioxide, up to 17% nitrogen, <1% oxygen, 32–169 ppm hydrogen sulphide and traces of other gases (Ward et al., 2008). Unlike fossil fuel, biogas does not contribute much to the greenhouse effect, ozone depletion or acid rain (Nath and Das, 2004). This is one of the main reasons that anaerobic digestion may play a very crucial role in meeting energy challenges of the future generation.

The biogas yield is affected by many factors including type and composition of substrate, microbial composition, temperature, moisture and bioreactor design, etc. Hernandez-Berriel et al. (2008) studied the methane production from biodegradation of municipal solid waste. They found that the process reached the onset of the methanogenic phase at day 63 and the methane production rate was greater at a moisture level of 70%. However, a decrease in biogas production was observed due to high amount of free ammonia at high organic loading rate (OLR). A decrease in biogas production was observed due to high amount of free ammonia at high organic loading rate (OLR) (Bouallagui et al., 2009b).

Continuously stirred tank reactors

Industrial food waste

Full-scale anaerobic digester

Kitchen waste

Integrative biological reactor

Laboratory-scale semi continuous reactors

New starch based flocculant-anaerobic fluidized bed bioreactor

Rotating drum mesh filter bioreactor

Self mixing anaerobic digesters

Submerged anaerobic membrane bioreactor

Two-phase anaerobic semi-continuous digester

Two stage anaerobic hydrogen and methane production reactor

Up flow anaerobic solid-state bioreactor

Organic loading rate (kg/m³/d)

Comments

Table 2
Different types of bioreactors used for anaerobic digestion.

<table>
<thead>
<tr>
<th>Bioreactor type</th>
<th>Type of substrate</th>
<th>Organic loading rate (kg/m³/d)</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic sequencing batch bioreactor</td>
<td>Fruit and vegetable waste and abattoir wastewater</td>
<td>2.6</td>
<td>A decrease in biogas production was observed due to high amount of free ammonia at high organic loading rate (OLR)</td>
<td>Bouallagui et al. (2009b)</td>
</tr>
<tr>
<td>Continuously stirred tank reactors</td>
<td>Municipal solid waste</td>
<td>15</td>
<td>The reactor showed superior process performance as the OLR progressively increased up to 15 kg/m³/d</td>
<td>Angelidaki et al. (2006)</td>
</tr>
<tr>
<td>Full-scale anaerobic digester</td>
<td>Industrial food waste</td>
<td>17</td>
<td>Methane yield of 360 l/kg feed waste with 40 days retention time was observed</td>
<td>Ike et al. (2010)</td>
</tr>
<tr>
<td>Integrative biological reactor</td>
<td>Kitchen waste</td>
<td>8.0</td>
<td>Integrative biological reactor showed the best performance and biogas production rate was higher than the single reactor</td>
<td>Guo et al. (2011)</td>
</tr>
<tr>
<td>Laboratory-scale semi continuous reactors</td>
<td>Municipal solid waste and press water from municipal composting plant</td>
<td>20</td>
<td>The reactor performance for biogas production was higher up to 20 OLR but further increase in OLR did not affect the biogas production</td>
<td>Nayono et al. (2010)</td>
</tr>
<tr>
<td>New starch based flocculant-anaerobic fluidized bed bioreactor</td>
<td>Primary treated sewage effluent with or without refractory organic pollutants</td>
<td>43</td>
<td>The efficiency and microbial activity at high OLR was higher than conventional anaerobic fluidized bed bioreactor</td>
<td>Xing et al. (2010)</td>
</tr>
<tr>
<td>Rotating drum mesh filter bioreactor</td>
<td>Municipal solid waste</td>
<td>15</td>
<td>The reactor proved to be stable and helpful in mixing the waste at high OLR, which is usually not possible in mechanically stirred digesters</td>
<td>Walker et al. (2009)</td>
</tr>
<tr>
<td>Self mixing anaerobic digesters</td>
<td>Poultry litter</td>
<td>16</td>
<td>Self mixing at high OLR and high biomethanization of the poultry litter was observed</td>
<td>Rao et al. (2011)</td>
</tr>
<tr>
<td>Submerged anaerobic membrane bioreactor</td>
<td>Sewage sludge, food waste and livestock wastewater</td>
<td>1.8</td>
<td>The reactor showed unstable performance during the initial stage, but performed superior after acclimation formation</td>
<td>Jeong et al. (2010)</td>
</tr>
<tr>
<td>Two-phase anaerobic semi-continuous digester</td>
<td>Olive mill wastewater and olive mill solid waste</td>
<td>14</td>
<td>The best performance in terms of methane productivity, soluble COD and phenol removal efficiencies and effluent quality was observed</td>
<td>Fezzani and Cheikh (2010)</td>
</tr>
<tr>
<td>Two stage anaerobic hydrogen and methane production reactor</td>
<td>Organic waste</td>
<td>3.0</td>
<td>Compared to a single-stage methanogenic reactor, 11% higher energy was achieved</td>
<td>Luo et al. (2011)</td>
</tr>
<tr>
<td>Up flow anaerobic solid-state bioreactor</td>
<td>Mixture of maize silage and straw</td>
<td>17</td>
<td>The UASS reactor showed the highest methanogenic performance for the digestion of solid biomass</td>
<td>Mumme et al. (2010)</td>
</tr>
</tbody>
</table>

Table 3
Biogas yield recorded from anaerobic digestion of the solid organic waste.

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Methane yield (l/kg VS)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Municipal solid waste</td>
<td>360</td>
<td>Vogt et al. (2002)</td>
</tr>
<tr>
<td>Fruit and vegetable wastes</td>
<td>420</td>
<td>Bouallagui et al. (2005)</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>530</td>
<td>Forster-Canero et al. (2007)</td>
</tr>
<tr>
<td>Fruit and vegetable waste, and abattoir wastewater</td>
<td>850</td>
<td>Forster-Canero et al. (2007)</td>
</tr>
<tr>
<td>Swine manure</td>
<td>337</td>
<td>Ahn et al. (2009)</td>
</tr>
<tr>
<td>Municipal solid waste</td>
<td>200</td>
<td>Walker et al. (2009)</td>
</tr>
<tr>
<td>Food waste leachate</td>
<td>294</td>
<td>Behera et al. (2010)</td>
</tr>
<tr>
<td>Rice straw</td>
<td>350</td>
<td>Lei et al. (2010)</td>
</tr>
<tr>
<td>Maize silage and straw</td>
<td>312</td>
<td>Mummé et al. (2010)</td>
</tr>
<tr>
<td>Jatropha oil seed cake</td>
<td>422</td>
<td>Chandra et al. (2011)</td>
</tr>
<tr>
<td>Palm oil mill waste</td>
<td>610</td>
<td>Fang et al. (2011)</td>
</tr>
<tr>
<td>Household waste</td>
<td>350</td>
<td>Ferrer et al. (2011)</td>
</tr>
<tr>
<td>Lignin-rich organic waste</td>
<td>240</td>
<td>Jayasinghe et al. (2011)</td>
</tr>
<tr>
<td>Swine manure and winery wastewater</td>
<td>348</td>
<td>Riano et al. (2011)</td>
</tr>
<tr>
<td>Food waste</td>
<td>396</td>
<td>Zhang et al. (2011)</td>
</tr>
</tbody>
</table>

VS: Volatile solids.
concluded that the bioreactors with efficient leachate collection and gas recovery facilities could be effective to treat non-hazardous liquid organic wastes for energy recovery. Likewise, Lee and his co-workers (2009b) suggested that anaerobic digestion of FOWL in bioreactor landfills or anaerobic digesters (with a preferred control of alkalinity and salinity) could be a sustainable solution to convert biomass to biogas and achieve high biodegradability potential.

6. Role of microorganisms in anaerobic digestion

The anaerobic digestion process can be catalyzed by a variety of microorganisms that convert complex macromolecules into low molecular weight compounds. An inoculum source is crucial for the optimization of the waste/inoculum ratio (Lopes et al., 2004; Forster-Carneiro et al., 2007). Sludge is commonly used as inoculum for the treatment of waste (Forster-Carneiro et al., 2007; Dong et al., 2009); although naturally selected strains or artificially mixed strains of microorganisms are also employed. In addition, cell aggregates in the form of flocs, biofilms, granules, and mats, with dimensions that typically range from 0.1 to 100 mm may also be used in the treatment system (Jeong et al., 2010).

A wide variety of microbial communities have been reported to be involved in the anaerobic decomposition process. Fricke et al. (2007) reported that organic material is most likely decomposed by heterotrophic microorganisms. Lee et al. (2009a) reported that Clostridium species are most common among the degraders under anaerobic condition. However, it is very unusual for a biological treatment to rely solely on a single microbial strain and generally a microbial consortium is responsible for the anaerobic digestion process (Fantozzi and Buratti, 2009). According to Ihe et al. (2010), a group of microorganisms such as actinomyces, Thermomonospora, Raistonia and Shewanella are involved in the degradation of food waste into volatile fatty acids, but Methanosarcina and Methanobrevibacter/Methanobacterium mainly contribute in methane production. Similarly, Charles et al. (2009) reported the presence of Methanosarcina thermophila, Methanococcus thermophilus, and Methanobacterium formicicum during anaerobic digestion. Using denaturing gradient gel electrophoresis and DNA sequencing techniques, Trzcinski et al. (2010) found hydrogenotrophic species (mainly, Methanobrevibacter sp., M. formicicum and Methanosarocina sp.) active in methane synthesis. An increase in methane content was also observed with the increase in the number of hydrogenotrophic species (Trzcinski et al., 2010). However, high concentration of organic acid like acetic acid (>5000 mg L\(^{-1}\)) and butyric acid (>3000 mg L\(^{-1}\)) in the biodigester has been found to inhibit the growth of microorganisms and consequently the production of energy rich compounds (Kim et al., 2008).

7. Factors affecting anaerobic digestion

The anaerobic digestion of organic material is a complex process, involving a number of different degradation steps. The microorganisms that participate in the process may be specific for each degradation step and thus could have different environmental requirements.

7.1. Temperature

Many researchers have reported significant effects of temperature on the microbial community, process kinetics and stability and methane yield (Dela-Rubia et al., 2002; Bouallagui et al., 2009b; Riau et al., 2010). Lower temperatures during the process are known to decrease microbial growth, substrate utilization rates, and biogas production (Kim et al., 2006; Trzcinski and Stuckey, 2010). Moreover, lower temperatures may also result in an exhaustion of cell energy, a leakage of intracellular substances or complete lysis (Kashyap et al., 2003). In contrast, high temperatures lower biogas yield due to the production of volatile gases such as ammonia which suppresses methanogenic activities (Fezzani and Cheikh, 2010).

Generally, anaerobic digestion is carried out at mesophilic temperatures (El-Mashad et al., 2003). The operation in the mesophilic range is more stable and requires a smaller energy expense (Fernandez et al., 2008; Ward et al., 2008). Castillo et al. (2006) found that the best operational temperature was 35 °C with an 18 day digestion period while a little fluctuation in temperature from 35 °C to 30 °C caused a reduction in the rate of biogas production (Chae et al., 2008). Overall, a temperature range between 35–37 °C is considered suitable for the production of methane and a change from mesophilic to thermophilic temperatures can cause a sharp decrease in biogas production until the necessary populations have increased in number. Briski et al. (2007) reported that for biodegradation, the temperature must be below 65 °C because above 65 °C denaturation of enzymes occurs. However, thermophilic conditions have certain advantages, such as a faster degradation rate of organic waste, higher biomass and gas production, less effluent viscosity and higher pathogen destruction (Zhu et al., 2009). Ward et al. (2008) has shown optimal growth temperatures for some methanogenic bacteria: 37–45 °C for mesophilic Methanobacterium, 37–40 °C for Methanobacterium formicicum, 35–40 °C for Methanobacterium, Methanococcus, Methanoculleus, Methanospirillum and Methanolumos, 30–40 °C for Methanoplanus and Methanocorpusculum and 50–55 °C for thermophilic Methanothaloalobium and Methanosarcina.

7.2. pH

A range of pH values suitable for anaerobic digestion has been reported by various researchers, but the optimal pH for methanogenesis has been found to be around 7.0 (Huber et al., 1982; Yang and Okos, 1987). Agdag and Sponza (2007) reported a very narrow range of suitable pH (7.0–7.2) in the industrial sludge added bioreactors during the last 50 days of the anaerobic incubation. Similarly, Ward et al. (2008) found that a pH range of 6.8–7.2 was ideal for anaerobic digestion. Lee et al. (2009b) reported that methanogenesis in an anaerobic digester occurs efficiently at pH 6.5–8.2, while hydrolysis and acidogenesis occurs at pH 5.5 and 6.5, respectively (Kim et al., 2003). From the batch experiments, it was shown that the appropriate pH range for thermophilic acidogens was 6–7 (Park et al., 2008). Dong et al. (2009) suggested that the hydrogen production will be at a maximum if the initial pH of a biosystem is maintained at 9. However, similar results can also be achieved at pH 5–6 (Kapdan and Kargi, 2006). Liu et al. (2008) showed that the most favorable range of pH to attain maximal biogas yield in anaerobic digestion is 6.5–7.5.

7.3. Moisture

High moisture contents usually facilitate the anaerobic digestion; however, it is difficult to maintain the same availability of water throughout the digestion cycle (Hernandez-Berriel et al., 2008). Initially water added at a high rate is dropped to a certain lower level as the process of anaerobic digestion proceeds. High water contents are likely to affect the process performance by dissolving readily degradable organic matter. It has been reported that the highest methane production rates occur at 60–80% of humidity (Bouallagui et al., 2003). Hernandez-Berriel et al. (2008) studied methanogenesis processes during anaerobic digestion at different moisture levels i.e., 70% and 80%. They found that the
onset of the methanogenic phase took place around day 70 in both cases, at 70% and 80% moisture. However, bioreactors under the 70% moisture regime produced a stronger leachate and consequently a higher methane production rate. At the end of the experiment, 83 ml methane per gram dry matter were produced at the 70% moisture level, while 71 ml methane per gram dry matter were produced with the 80% moisture. Nonetheless, bioreactors from both moisture regimes showed similar ratios (0.68) of biochemical oxygen demand (BOD) to chemical oxygen demand (COD).

7.4. Substrate/carbon source

The rate of anaerobic digestion is strongly affected by the type, availability and complexity of the substrate (Ghanjinary-Benis et al., 2009; Zhao et al., 2010). Different types of carbon source support different groups of microbes. Before starting a digestion process, the substrate must be characterized for carbohydrate, lipid, protein and fiber contents (Lesteur et al., 2010). In addition, the substrate should also be characterized for the quantity of methane that can potentially be produced under anaerobic conditions. Carbohydrates are considered the most important organic component of municipal solid waste for biogas production (Dong et al., 2009). However, starch could act as an effective low cost substrate for biogas production compared to sucrose and glucose (Su et al., 2009). It was reported that the initial concentration and total solid content of the substrate in the bioreactor can significantly affect the performance of the process and the amount of methane produced during the process (Fernandez et al., 2008).

7.5. Nitrogen

Nitrogen is essential for protein synthesis and primarily required as a nutrient by the microorganisms in anaerobic digestion (Kayhanian and Rich, 1995). Nitrogenous compounds in the organic waste are usually proteins which are converted to ammonium by anaerobic digestion (Sawayama et al., 2004). In the form of ammonium, nitrogen contributes to the stabilization of the pH value in the bioreactor where the process is taking place. Microorganisms assimilate ammonium for the production of new cell mass. A nutrient ratio of the elements C:N:P at 600:15:5:3 is considered sufficient for methanization (Fricke et al., 2007). Ammonia in high concentration may lead to the inhibition of the biological process and it inhibits methanogenesis at concentrations exceeding approximately 100 mM (Fricke et al., 2007; Sterling et al. (2001)) found that the amount of ammonia in the digester may also affect the production of hydrogen and removal of volatile solids. Total biogas production was unaffected by small increases in ammonia nitrogen while higher increases reduced the biogas production by 50% of the original rate. In the fluidized-bed anaerobic digester, the methane formation decreased at ammonium concentrations of greater than 6000 mg NH₄⁻N/l. It was reported that methanogenic activity is decreased by 10% at ammonium concentrations of 1670–3720 mg NH₄⁻N/l, while by 50% at 4090–5550 mg NH₄–N/l, and completely zero at 5880–6000 mg NH₄⁻N/l (Sawayama et al., 2004).

7.6. C/N Ratio

The C/N ratio in the organic material plays a crucial role in anaerobic digestion. The unbalanced nutrients are regarded as an important factor limiting anaerobic digestion of organic wastes. For the improvement of nutrition and C/N ratios, co-digestion of organic mixtures is employed (Cuetos et al., 2008). Co-digestion of fish waste, abattoir wastewater and waste activated sludge with fruit and vegetable waste facilitates balancing of the C/N ratio. Their greatest advantage lies in the buffering of the organic loading rate, and anaerobic ammonia production from organic nitrogen, which reduce the limitations of fruit and vegetable waste digestion. The C/N ratio of 20–30 may provide sufficient nitrogen for the process (Weiland, 2006), and Bouallaguhi et al. (2009a) suggested that a C/N ratio between 22 and 25 seemed to be best for anaerobic digestion of fruit and vegetable waste, whereas, Guermoud et al. (2009) and Lee et al. (2009b) reported that the optimal C/N ratio for anaerobic degradation of organic waste was 20–35.

8. Conclusions

The preceding review clearly indicates that anaerobic digestion is one of the most effective biological processes to treat a wide variety of solid organic waste products and sludge. The prime advantages of this technology include (i) organic wastes with a low nutrient content can be degraded by co-digesting with different substrates in the anaerobic bioreactors, and (ii) the process simultaneously leads to low cost production of biogas, which could be vital for meeting future energy-needs. However, different factors such as substrate and co-substrate composition and quality, environmental factors (temperature, pH, organic loading rate), and microbial dynamics contribute to the efficiency of the anaerobic digestion process, and must be optimized to achieve maximum benefit from this technology in terms of both energy production and organic waste management. The use of advanced molecular techniques can further help in enhancing the efficiency of this system by identifying the microbial community structure and function, and their ecological relationships in the bioreactor. This technology has tremendous application in the future for sustainability of both environment and agriculture, with the production of energy as an extra benefit.

References


