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Anaerobic Transformation of Biodegradable Waste; Simultaneous Production of Energy and Fertilizer

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ABSTRACT

Almost 40% of the total waste produced in developing countries is made of biodegradable waste. Typically the waste including the biodegradable portion is transported to the so-called landfills without any segregation process, treatment and utilization in advance. Although mitigation practices such as source reduction, reuse and recycle are essential and required to be practiced in any integrated waste management plan, one of the best approaches to reduce the volume of the waste goes to the landfills is biological transformation. Biological transformation of waste occurs in two major categories; aerobic and anaerobic biodegradation. Anaerobic transformation of biodegradable waste produces methane gas (CH_4) which is the valuable source of energy. At first the gas has some impurities such as CO_2 and other trace materials which are required to be removed from the main stream before utilization. In addition to methane, the byproduct of the anaerobic process is slurry that can be used as soil amendment agent. It contains several vital elements such as nitrogen, phosphorous and potassium (N, P and K) for crops. The quality of slurry is required to be assessed since it affects the soil conditions and plants growth. In this study the importance of biological transformation in waste management systems has been discussed. Different methods and significant factors in methane production via anaerobic digestion have been highlighted and finally, the criteria of produced fertilizer have been elaborated.

Keywords: Methane, Slurry Quality Control, Integrated Waste Management

1. INTRODUCTION

Conventional waste disposal meets its limits throughout most of the world with increasing waste generation and rising population and proportions of packaging and toxic compounds in municipal solid waste. In majority of developing countries landfilling of waste has been practiced for many years as the only way to deal with day-to-day increasing rate of generated solid waste. This causes landfill operators to receive almost all produced comingled waste in their site. In this condition, operating of landfills in sanitary manners is becoming rather difficult and operators tend to process the waste in unsanitary manners which change the landfill into a dump site. In dumping sites, appropriate compaction, layering and covering of the waste are not practiced which causes the production of leachate through precipitation and releasing of corrosive gases such as CO_2, CH_4, NH_3 and H_2S from the dump sites. Leakage of the leachate and emission of gases affects the surrounding environment e.g., rivers, soil and air. Sanitary landfilling of all produced waste is not an easy and feasible approach and instead of that some mitigation measures are required to be implemented to

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reduce the quantity of waste reaching to the landfill. This is possible to be done by implementation of Integrated Solid Waste Management (ISWM).

1.1. Integrated Solid Waste Management

Integrated solid waste management is the selection and application of suitable techniques and management programs to achieve specific waste management objectives and goals (Malakahmad *et al*., 2010). For the reduction of the quantity of waste which is reaching to landfill a hierarchy of waste management activities has been established. A hierarchy in waste management is used to giving preference to implement it within the community. The elements of ISWM hierarchy are source reduction, recycling, waste transformation and landfilling (Tchobanoglous *et al*., 1993). Source reduction has the highest rank in the hierarchy as it is the most effective way to reduce the quantity of waste. The recycling involves the separation and collection of waste materials, the preparation of these recyclables for reuse, reprocessing and remanufacturing and finally reuse, reprocessing and remanufacturing of these materials. Waste transformation is physical, chemical or biological modification of waste. The aims of waste transformation are to save the capacity of the landfill, recover the reusable materials and conversion of waste to products and energy. Eventually, the solid waste which cannot be recycled or transformed and the residual matters from either recycling processes or waste transformation will end up to a sanitary landfill.

1.2. Organic Fraction of Municipal Solid Waste Transformation

Municipal refuse in majority of developing countries contains more than 40% organic materials, which can be converted to useful material or energy by waste transformation processes (Malakahmad *et al*., 2011a). The components of MSW of greatest interest in the bioconversion processes are food waste and yard wastes. The garbage fraction of refuse varies with geographical locations and seasons. Dietary habits, affect its compositions and quantity, as does the standard of living. The Organic Fraction of Municipal Solid Waste (OFMSW) has by far the highest moisture content of any constituent in MSW, but the moisture is rapidly transferred to absorbent materials such as newspapers as soon as contact is made. OFMSW also tends to be well mixed in waste and therefore it is difficult to find identifiable bits of OFMSW in mixed refuse other than the large pieces. Garbage is even better distributed in MSW if the waste is shredded. Anaerobic digestion and composting are broad-spectrum transformation processes, where the specific organisms responsible for the bioconversion of waste into useful products, particularly energy and fertilizer (Tchobanoglous *et al*., 1993).

1.3. Anaerobic Digestion of Organic Fraction of Municipal Solid Waste

Anaerobic treatment processes reach an average of 50-55% reduction of organic content in the treatment of residual waste. Practical tests have shown that threshold values can be achieved at the above-mentioned reduction of organic content with a post-decomposition duration of approximately 4-6 weeks (Fricke *et al*., 2005). The main purposes and benefits of anaerobic digestion technology can be classified as follow.

1.4. Production of Energy

The production of energy (biogas) from anaerobic digestion of organic waste is the most tangible benefit of this technology. The organic matter required for biogas production which is mainly food waste is abundant and readily available. In addition to avoid this valuable source to be buried in the landfills or unload in dumping sites, it will decrease the consumption of non-renewable sources such as fossil fuel.

1.5. Waste Stabilization

The biological reactions occurring during anaerobic digestion in the biogas digester reduce the organic content of waste materials and produce a stabilized sludge which can be used as fertilizer or soil conditioner. Although the practical studies show the stabilized sludge nutrient content (N = 0.95, P = 0.8 and K = 0.45) is not comparable to chemical fertilizer which has higher NPK value but it can comparatively reduce the usage of chemical fertilizer (Malakahmad *et al*., 2008). Anaerobic digestion does not remove or destroy any of the nutrients from domestic and farm wastes, but makes them more available to plants. In addition, the biogas digester slurry also acts as soil conditioner and helps to improve the physical properties of the soil. The application of digester slurry to unproductive soils would eventually improve the soil quality, or useless land could be recovered.

1.6. Nutrient Reclamation

The nutrients (N, P and K) present in the waste are usually in complex organic forms and difficult to be taken up by the crops. After digestion at least 50% of the N present is in the form of dissolved ammonia, which can be nitrified to become nitrate for application to crops so as to be readily available for uptake (Polprasert, 2007). Thus digestion increases the availability of N in organic wastes to above its usual range of about 30-60%. The phosphate and potash contents are not decreased and their availability of about 50 to 80%, respectively, is not changed during digestion.

1.7. Pathogen Inactivation

During the digestion process the waste is kept without oxygen for a long period of time (15-50 days) at about 35°C. These conditions are sufficient to inactivate some of the pathogenic bacteria, viruses and protozoa.

1.8. Environmental Requirements of Anaerobic Digestion

Anaerobic reactions in a digester start quickly with the presence of a good inoculum or seed, such as digested sludge. During start-up or acclimation, the seed material should be added to the influent feed material in sufficient quantity. The concentration of influent feed can increase gradually upon forming of steady state conditions in the bioreactor. At the end of the start-up period the influent feed can be fed alone without any dilution to the digester to support the growth of anaerobic bacteria. Anaerobic digestion is a multi-parameter controlled process and each individual parameter having control over the process either through its own effect on the system or through interaction with other parameters. These parameters are described at the following subsections:

1.9. Temperature

Temperature and its seasonal variations, has an obvious effect on the rate of gas production. Generally two ranges of temperature are considered in biogas production. These are mesophilic (25-40°C) and thermophilic (50-65°C) ranges. The rate of methane production increase as the temperature increases, but there is a distinct break in the rise at about 45°C, as this temperature favors neither the mesophilic nor the thermophilic bacteria. Above 30-35°C, operation of the digester depends upon a substantial energy input for digester heating and this might make the operation economically not practical. This suggests that the mesophilic range provides the optimal operational range of temperature, although pathogen inactivation will be less than that to be achieved in the thermophilic range. Successful operations of both mesophilic and thermophilic conditions have been reported. Thermophilic temperature was found optimal for digesting mechanically selected Organic Fraction of Municipal Solid Waste (OFMSW) by Cecchi *et al*. (1991) in a pilot-plant study. Its advantages were not the same when digesting source-sorted OFMSW. Malakahmad *et al*. (2013) in a laboratory test have shown that for a hydraulic retention time of 7 d at 55°C there was greater process stability than at 37°C. With a HRT of 7-12 d, the methane yield of thermophilic digestion was less than 10% above the yield of mesophilic digestion.

1.10. pH and Alkalinity

The operation range of pH in anaerobic digesters should be between 6.6 and 7.6, with the optimum range being 7-7.2. Although acid-forming bacteria can tolerate pH as low as 5, the methanogenic bacteria are inhibited at such low pH values. The pH of a digester may drop to below 6.6 if there is an excessive accumulation of volatile fatty acids. Such an accumulation occurs when the organic loading rates are excessively high and/or when toxic materials are present in the digester, all producing inhibitory affects to the methanogenic bacteria (Polprasert, 2007). Appropriate measures should be taken promptly when there is a lowering of pH in an anaerobic digester, due to accumulation of volatile fatty acids or increase in hydrogen gas partial pressure which cause the reduction in rate of CH_4 formation. In general, the feeding of the digester should be stopped to allow the methanogens to utilize the accumulated volatile fatty acids and H_2 at their own pace. When the optimal gas production rates are re-established the normal loading of the digester can be resumed. In addition, the pH of the digester needs to be adjusted to neutrality by the addition of lime or other basic materials. If the alkalinity of the digester slurry is maintained within the range 2,500-5,000 mg L^{-1}, a good buffering capacity is normally obtained in the bioreactor (Vesilind *et al*., 2002).

1.11. Nutrient Concentration

To guarantee normal biogas production, it is important to mix the raw materials in accordance with a proper C/N ratio. Bacteria use up Carbon (C) 25-30 times faster than they use Nitrogen (N). Therefore, at this ratio of C/N (25-30/l) the digester is expected to operate at the optimal level of gas production. The importance of other elements such as P, Na, K and Ca in gas production is also indicated. However, C/N ratio is considered to be the most essential factor (Polprasert, 2007). Animal manures and sewage sludge have C/N ratio lower than the optimum values and thus they may be mixed with other residues that have high C/N ratios. Examples of these residues are kitchen waste and some agricultural waste such as wheat and rice straw.

1.12. Loading

Loading can be expressed as organic loading (kg COD or volatile solids (VS/m^3day) and Hydraulic Retention Time (HRT). A high organic loading, especially in start-up period, will normally result in excessive volatile fatty acid production in the digester (sour condition) with a consequence decrease in pH and will adversely affect the methanogenic bacteria and causes less production of methane. On the other hand, a low organic loading will not provide a sufficient quantity of biogas production and will make the digester unnecessarily large. HRT has an equally significant effect on digester performance. Too short an HRT will not allow sufficient time for anaerobic bacteria, especially the methane-forming bacteria to metabolize the wastes. Too long an HRT could result in an excessive accumulation of digested materials in the digester and construction of a large digester. An optimum HRT depends on the characteristics of influent feed materials and environmental conditions in the digesters. For dispersed-growth digesters the optimum HRT falls within the range 10-60 days; while for the attached growth digesters, optimum HRT values are 1-10 and 0.5-6 days for anaerobic filters and upflow sludge blanket digesters, respectively.

1.13. Modes of Operation in Anaerobic Systems

There are different types of anaerobic digesters for experimental purposes, pilot plant investigations and actual field use. Their design, materials, system performance, price. Naturally vary a great deal. Operationally, it is required that air is excluded from the content of the digester and sufficient volume is provided within the digester for the biological reactions to take place. The successful application of anaerobic technology to treat municipal solid waste is critically dependent on the development and use, of high rate anaerobic bioreactors (Malakahmad *et al*., 2011b). These reactors achieve a high reaction rate per unit reactor volume (in terms of kg COD/m^3d) by retaining the biomass in the reactor independently of the incoming wastewater. Major modes of digester operation could be classified into three groups as the following:

1.14. Batch Operation

In this mode of operation the digester is filled completely with organic matter and seed inoculum, sealed and the process of decomposition is allowed to proceed for a long time until gas production is decreased to a low rate (duration of process varies based on regional variation of temperature, type of substrate,). Then it is unloaded, leaving 10-20% as seed, reloaded and then operation continues.

1.15. Semi-Continuous Operation

This involves feeding the digester on more regular basis. Feeding is done usually once or twice a day. The digested organic matter is also removed at the same time intervals. This type of operation is suitable when there is a steady flow of organic matter.

1.16. Continuous Operation

In this mode of operation the feeding and removal of organic matter take place continuously. The amount of material to be digested is kept constant in the digester by overflow of pumping. The process has been used in treatment of liquid wastes or organic wastes with low solid concentration. Continuous operation relies heavily on external energy inputs for pumping and mixing and therefore has limited application in areas where energy resources are limited.

1.17. Anaerobic Digesters

Various designs of biogas digesters are available for actual field operation range from a simple design to a sophisticated one. Double stage digesters (i.e., first stage for acid formation and second stage for CH_4 formation) are mostly designed for experimental purposes. Single-stage digesters, on the other hand, are of a more practical nature. In general, type of digesters can be divided into two main groups: those utilizing dispersed-growth bacteria and those utilizing attached-growth bacteria. To provide longer residence time in the digesters, attached-growth bacteria have been employed; in this case the anaerobic bacteria, attached or artificial media or settled as a blanket in the digesters, decompose the organic wastes.

1.18. Biological Reactions and Microbiology

The anaerobic digestion of organic material is biochemically a very complicated process, involving hundreds of possible intermediate compounds and reactions, each of which is catalyzed by specific enzymes or catalysts. However, the overall chemical reaction is often simplified to:

$$\text{Organic matter} \rightarrow CH_4 + CO_2 + H_2 + NH_3 + H_2S$$

In general, anaerobic digestion is considered to occur in the following stages.

1.19. Stage 1: Liquefaction

Organic wastes consist of complex organic polymers such as proteins, fats, carbohydrates, cellulose, lignin. In this stage this organic polymers are broken down by extracellular enzymes produced by hydrolytic bacteria and dissolves in water. The formed simple and soluble organic components (or monomers) which are easily available to any acid-producing bacteria. The hydrolysis reaction in this stage will convert protein into amino acid, carbohydrate into simple sugars and fat into long-chain fatty acids. However, the liquefaction of cellules and other complex compounds to simple monomers can be the rate-limiting step in anaerobic digestion, as this bacterial action is much slower in stage one than in either stage 2 or 3.

1.20. Stage 2: Acid Formation

The monomeric compounds released by the hydrolytic break down in stage 1 are further converted to acetic acid (acetate), H_2 and CO_2 by the acetogenic bacteria. Volatile fatty acids are produced as the end products of bacterial metabolisms of protein, fat and carbohydrate; in which acetic, propionic and lactic acids are the major products. Carbon dioxide and hydrogen gas are also released during carbohydrate catabolism, with methanol and other simple alcohols, being other possible by-products of carbohydrate break down.

1.21. Stage 3: Methane Formation

The products of the stage 2 are finally converted to CH_4 and other end products by a group of bacteria called methanogens. Methanogenic bacteria obligate anaerobes whose growth rate is generally slower than the bacteria in stage 1 and 2. The methanogenic bacteria use acetic acid, methanol, or carbon dioxide and hydrogen gas to produce methane. The methanogenic bacteria are also dependent on the stage 1 and stage 2 bacteria to provide nutrients in a usable form. Besides producing CH_4 gas, the methanogens also regulate and neutralize the pH of the digester slurry by converting volatile fatty acids in to CH_4 and other gases. The conversion of H_2 into CH_4 by the methanogens helps reduce the partial pressure of H_2 in the digester slurry, which is beneficial to the activity of the acetogenic bacteria.

1.22. Slurry Characteristics

Slurry obtained from the processing of organic fraction of municipal solid waste such as food waste, can be used effectively as an organic fertilizer on agricultural soil. The high content of stabilized organic matter and the presence of nutrients are guarantee of agronomic advantages and at the same time, the utilization of digested sludge makes the reuse of organic wastes possible. An increase in soil organic matter and nutrient availability will be obtained after slurry of anaerobic bioreactor application. It is also beneficial for the soil's physical properties by increasing porosity, structural stability, available water content and reduction of erosion.

1.23. Slurry Quality

Produced sludge quality refers to the overall state of the compost in regard to physical, chemical and biological characteristics, which indicate the ultimate impact of the substance on the environment. The quality is determined by the sum of its different features and properties. The criteria that are relevant to the evaluation of quality depend on what purpose it is used for, the relevant environmental protection policies and the market requirements. A number of characteristics determine produced sludge quality, such as moisture level, organic matter and carbon content, concentration and composition of humus-like substances, nitrogen content and forms of N, phosphorus and potassium, heavy metals, water holding capacity, porosity and bulk density, pathogens and state of maturity or stability. However, the most important factors are those related to standards for the protection of public health as well as the soil and the environment. In general, these parameters are relating to pathogens, inorganic and organic potentially toxic compounds (heavy metals, PCBs and PAHs), stability, the latter determining compost nuisance potential, nitrogen immobilization and leaching (Hogg, 2002).

In addition, to ensuring a safe product, standard guidelines provide a valuable marketing tool. The consumers can be satisfied with the knowledge that the product quality is consistent and suitable for the desired application. This is important for commercial and agricultural operations where a relationship exists between predictable results and repeated sales. The supply must also be reliable since inability to meet market commitments affects customer relations (Albrecht, 1989). Quality criteria define as the parameters which are considered to be important for marketing of produced sludge. Some associations such as Agriculture and Agri-Food Canada (AAFC) have developed the important parameters to be measured and controlled before advertising and trading the product. These criteria are summarized as follow.

1.24. Maturity

The maturity is an important characteristic to consider when evaluating the quality of the product, given the harmful effects of immature product use on plant growth. Maturity can be measured using the following:

- A C/N ratio below 25/1
- An oxygen uptake less than 150 mg O_2 kg^{-1} volatile solids per hour and
- A germination and growth test using cress (Lepidium sativum) seeds and radish (Raphanus sativus) seeds, which demonstrates an absence of phytotoxic effects

1.25. Foreign Matter

When developing an industry standard for produced sludge quality, the presence of foreign matter should be taken into consideration since its negative impacts on consumers and on the agricultural industry in general. Foreign matters can be defined as any matter over a 2 mm dimension that results from human intervention and having organic or inorganic constituents such as metal, glass and synthetic polymers (e.g., plastic and rubber) that may be present in the product but excluding mineral soils and woody materials.

1.26. Trace Elements

It is defined as chemical elements present in the product at very low concentrations. The considered trace elements include those that are essential to plant growth (particularly Cu, Mo, Zn) and heavy metals (Hg, Pb, Cd,) which, depending on their concentration in the soil, could be harmful to human health and to the environment (Ghaly and Alkoaik, 2010). In United States according to Brinton (2000) the standard guideline for allowable level of heavy metals in the product has been published (**Table 1**).

Table 1. Allowable heavy metals levels in produced sludge

Metal	Limit (mg kg^{-1})
Cadmium	39
Chromium	1200
Copper	1500
Mercury	17
Nickel	420
Lead	300
Zinc	2800

1.27. Pathogenic Organisms

In production of slurry from organic fraction of municipal solid waste different communities of microorganisms predominate during the various phases. The pathogenic organism content including fecal coliform less than 1000 Most Probable Number (MPN)/g of total solids calculated on a dry weight basis and Salmonella species of less than 3 MPN/4g total solids calculated on a dry weight basis are acceptable in produced sludge.

2. CONCLUSION

Anaerobic biodegradation of Organic Fraction of Municipal Solid Waste (OFMSW) produces methane gas and useful by-product in form of slurry. The methane gas is a precious source of energy and the slurry can be used as soil amendment and crop growth improvement agent. In addition, application of anaerobic transformation techniques in any waste management system reduces considerable waste volume transported to the landfill. This volume reduction will resulted in decrease of capital costs for waste transportation, disposal as well as lands acquisition. Although the anaerobic biodegradation is a promising method for management of biodegradable waste and has many advantages over landfilling and incineration, it is a complex technique and its operational conditions should be monitored well by experts throughout the process. Also quality of the gas stream and its further treatment as well as trading of the slurry in some regions would be challenging. Even though anaerobic transformation of waste is been distinguished in this study, it is an obvious fact that an integrated solid waste plan accomplished by all management and engineering tools, techniques and technologies from source reduction to waste disposal.

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