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Anaerobic digestion of Municipal Solid biodegradable wastes for methane production:A Review

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Abstract- The untreated and undisposed municipal solid waste generated through different sources is a major concern of the world now-a-days. There are millions of tonnes of municipal solid waste produced every year and the amount is rapidly increasing day by day. Anaerobic digestion is historically one of the oldest processing technologies used by human beings. Anaerobic Digestion is a multistep process in which the organic matter is degraded into a gas mixture of methane and carbon dioxide by microorganisms. It is a series of reactions during which organic material is decomposed through the metabolic pathways of naturally occurring microorganisms in an oxygen depleted environment. Anaerobic digestion could be an appealing option for converting solid organic wastes into valuable product like biogas, which plays an major role in the world's ever increasing energy demand in the future periods. The full process occurs in four stages namely Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. (Amani et al.,2010). Anaerobic digestion is a promising technology which could effectively address the problems of waste thereby yielding valuable outputs like biogas and fertilizers. Anaerobic digestion gives an opportunity to take responsibility for all the waste generated while ensuring environmental and economic benefits.
Key Words: Anaerobic Digestion, Co-digestion, biodegradable waste, Digesters, Methane Production

I. INTRODUCTION

Anaerobic digestion gains more attention now-a-days, both as a solution to environmental concerns and also as an energy resource for today's energy demanding life style. Anaerobic digestion is considered as the most promising technology to give a proper treatment disposal method to the biodegradable waste coming from source or separate collecting systems. As per the Central Pollution Control Board (CPCB,2000) report that more than 90% of Municipal Solid Wastes in India is directly disposed of on land in an unscientific manner. As per the Municipal Solid Wastes (Management and Handling) Rules,2000, "Land-filling shall be restricted to non-biodegradable, inert waste and other waste that are not suitable either for recycling or for biological processing". Municipal Solid Waste (MSW) in India is defined as the non-industrial and non-hazardous solid waste. The Municipal Solid waste amount is expected to increase significantly in the near future as India strives to attain an industrialized nation status by the year 2020 (Kaushal et al.,2012). Anaerobic digestion is a collection of processes by which microorganisms break down biodegradable waste in the absence of oxygen. The process is used for industrial or domestic purposes to manage waste and or to produce valuable end products. Anaerobic digestion is a pre-treatment prior to landfill disposal or composting offers several advantages like minimization of volume of wastes, inactivation of biological and biochemical processes in order to avoid landfill-gas and odour emissions, energy production in the form of methane. Anaerobic digestion of bio-degradable solid wastes can be considered an alternative technique to improve the environment condition caused by organic solid waste and as an environmental-friendly by-product of methane. This paper is reviewed the process of anaerobic digestion for biogas generation from Municipal Solid Waste, parameters affecting the anaerobic digestion (AD) process, studies of effects of various parameters on amount of biogas generation and the different methodology used in managing the anaerobic digestion of MSW. The studies on the variation of generation of biogas due to co-digestion of MSW with other organic wastes in varying amount is also reviewed.

II. ANAEROBIC DIGESTION PROCESS

The Anaerobic digestion process can be classified in four major steps. It starts with hydrolysis of the input materials, in order to break down the insoluble and soluble organic polymers in their monomers, making them available for the subsequent steps. In acidogenesis, also known as fermentation, sugars, amino acids and long chain fatty acids are converted into Carbon Dioxide, Hydrogen, Ammonia, Alcohols and Organic acids. In acetogenesis, these intermediates such as organic acids and alcohols are converted into acetic acid, H_2 and CO_2. Finally, in methanogenesis these products are converted to CH_4 and CO_2 which are schematic illustrated in Figure 1.

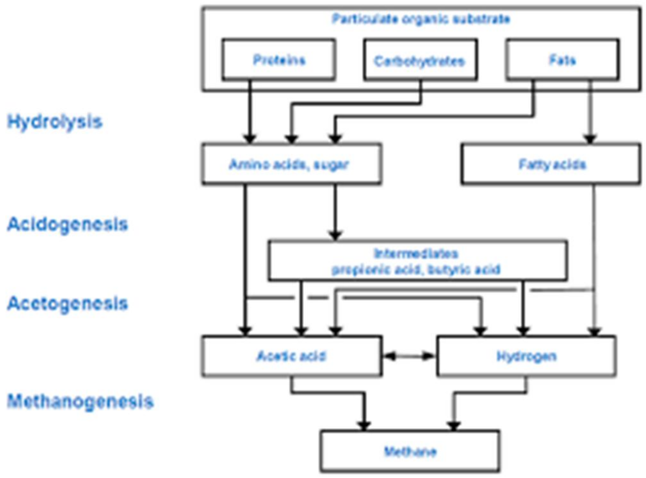

Fig.1 Schematic Diagram of complete Anaerobic Digestion process

A. Hydrolysis

In the first stage of hydrolysis, fermentative bacteria transform the particulate organic substrate into liquefied monomers and polymers i.e. proteins, carbohydrates and fats are transformed to amino acids, monosaccharides and fatty acids respectively. An example of hydrolysis reaction where organic waste is broken down into a simple sugar, in this case, glucose (Ostrem, 2004) is given in Equation 1.

Equation 1: $C_6H_{10}O_5 + 2H_2O \rightarrow C_6H_{12}O_6 + 2H_2$

B. Acidogenesis

In the second stage of acidogenesis, acidogenic bacteria transform the products of the first reaction into short chain volatile acids, ketones, alcohols, hydrogen and carbon dioxide. The principal acidogenesis stage products are propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), acetic acid (CH_3COOH), formic acid ($HCOOH$), lactic acid ($C_3H_6O_3$), ethanol (C_2H_5OH) and methanol (CH_3OH), among other. The monomers produced from the hydrolysis process are then degraded by a large diversity of facultative anaerobes and anaerobes through many fementative pathways. Equations 2,3 (Ostrem, 2004) and Equation 4 (Bilitewski et al., 1997) represent three acidogenesis reactions where glucose is converted to ethanol, propionate and acetic acid respectively.

Equation 2: $C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2$

Equation 3: $C_6H_{12}O6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O$

Equation 4: $C_6H_{12}O_6 \rightarrow 3CH_3COOH$

C. Acetogenesis

In the third stage of acetogenesis, the remaining products like propionic acid, butyric acid and alcohols are transformed by acetogenic bacteria into hydrogen, carbon dioxide and acetic acid. Hydrogen plays and intermediary role in this process as the reaction will only occur if the hydrogen partial pressure is low enough to thermodynamically allow the conversion of all the acids. The partial pressure is carried out by hydrogen scavenging bacteria, thus the hydrogen concentration of a digester is an indicator of its health (Mata-Alvarez, 2003). Equation 5 represents the conversion of propionate to acetate, only at low hydrogen pressure. Equation 6 (Glucose) and Equation 7 (Ethanol) among others are also converted to acetate during the third stage of anaerobic fermentation (Ostrem, 2004).

Equation 5: $CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3^- + 3H_2$

Equation 6: $C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2$

Equation 7: $CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^+$

D. Methanogenesis

In the fourth stage of methanogenesis, microorganisms convert the hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide (Equations 8,9,10) (Verma, 2002). The bacteria responsible for this conversion are called methanogens and are anaerobes. Waste stabilisation is accomplished when methane gas and carbon dioxide are produced.

Equation 8: $CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

Equation 9: $2C_2H_5OH + CO_2 \rightarrow CH_4 + 2CH_3COOH$

Equation 10: $CH_3COOH \rightarrow CH_4 + CO_2$

III. PROCESS TECHNOLOGY FOR ANAEROBIC DIGESTION OF MSW

Typically anaerobic reactors of solid waste can be classified into several types, mostly according to the feeding mode (continuous mode : single stage, two stages and batch mode) and the moisture content or total solid of the substrate (wet or dry digestion).According to digestion process temperature (mesophilic or thermophilic) and the shape of the reactors (vertical or horizontal).A wide variety of systems have been developed to treat MSW anaerobically. They can be split into different categories as follows:

A. Wet and Dry anaerobic digestion

Anaerobic digestion processes can be termed as “wet” and “dry” digestions depending on the total solids concentration of the feed substrate. Anaerobic digestion is defined as a wet process if the total solids concentration of the substrate is less than 15% and as a dry process if the concentration reaches 20-40% (Lissens et al ., 2001). However, disadvantages, such as complicated pre-treatment, high consumption of water and energy for heating and the reduction of working volume due to sedimentation of inert materials have to be taken into account (Vandevivere et al., 2002; Banks and Stentiford, 2007). The reactors used in dry anaerobic digestion processes generally do not apply mechanical mixers and may use biogas injection to perform mixing of the digester content (Luning et al., 2003). However, using this technique, complete mixing of the digestate is almost impossible; thus, the ideal contact of microorganisms and substrate cannot be guaranteed. As a consequence, individual processes may run in different parts of the reactor, which limits an optimal co-operation of the microbial groups involved in the digestion process (Hartmann and Ahring, 2006). Thus, the digesters used in dry anaerobic digestion can be considered as plug flow reactors. Dry anaerobic digestion offers less complicated pre-treatments and higher loading rate (10 kg VS.m3.d.1 or more). However, the systems require more sophisticated mechanical equipment (Lissens et al., 2001) and less possibility to dilute the inhibitory substances (Vandevivere et al., 2002). In general, both anaerobic digestion processes can be considered a proven technology for the treatment of organic solid waste.

B. Batch and continuous feeding systems

There are generally two feeding modes are generally used in anaerobic digestion of solid waste: the batch system and the continuous system. In the batch system, digesters are filled once with fresh feedstock, with or without addition of inocula, and sealed for the complete retention time, after which it is opened and the effluent removed. Where as in continuous process, a fresh feedstock continuously enters the digester and an equal amount of digested material is removed.

C. Mesophilic and thermophilic digestion

Anaerobic digestion can take place at psychrophilic temperature at about 20^oC, but it is commonly operated at two temperature ranges: at mesophilic temperature around 35^oC and at thermophilic temperature range from 50^oC to 60^oC. Mesophilic bacteria are active in a wider temperature ranges than thermophilic bacteria and can tolerate greater changes in the environmental parameters.

D. Single stage and multi stage digestion

Continuous digestion systems can be divided into single stage and multi-stage processes. The digester operations consist of feeding and with-drawal, mixing, heating and gas collection. A single stage system consists of one reactor, in which all biochemical reactions occur. The different microbial groups involved in anaerobic digestion for biogas production have different growth rates and tolerance of fluctuations in operational conditions. This can cause an imbalance between the volatile fatty acid production rate and methane production rate. Therefore, the single stage system is more sensitive for disturbances than multistage systems. The multi-stage system consists of at least two reactors. In most multi-stage systems volatile fatty acid production takes place in one reactor and acetogenesis, as well as methanogenesis occur in the second reactor. The multistage system can optimise the conditions for each phase by providing separate reactors. In praxi, single stage systems are preferred because they have less investment costs and require simple technical support. For example the Dranco, Kompogas and Linde BRV processes are all single stage DAD systems. The single stage WAD systems are commonly referred to as continuous stirred tank reactors (CSTR). Examples of multi-

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stage DAD systems are the Portagester manufactured Bioplex and the Dutch Biothane process (Banks and Stentiford, 2007).

IV. PARAMETERS AFFECTING ANAEROBIC DIGESTION OF MSW

A. pH value and Alkalinity

During digestion, the two processes of acidification and methanogenesis require various pH levels for optimum process control of pH. The ideal pH for methanogens ranges from 6.8 to 7.6 and their growth rate will be reduced below pH 6.6 (Mosey et al.,1989).The optimum pH for Hydrolysis and Acidogenesis is between 5.5 to 6.5 (Arshad et al.,2011). The retention time of digestate affects the pH value. Variation in pH affects the anaerobic digestion because the hydrogen ion concentration has direct influence on microbial growth.

The alkalinity is a measure of the capacity of the solution to neutralize acids. Optimal anaerobic is characterised by neutral conditions. Process imbalance can be due to low pH that can be caused by two sources of acidity, H2CO3 and VFAs. The major requirement for a well operating digester is the neutralization of the high carbonic acid concentration which results from the high partial pressure of carbon-dioxide in the reactor. Sufficient alkalinity is essential for pH control and it serves as a buffer that prevents change in pH. The alkalinity is the result of the release of amino acids and the production of ammonia and the protein wastes are degraded.

B. Temperature

Temperature is a main environmental factor affecting the performance of anaerobic digester. It affects the physical and physico-chemical properties of compounds present in the digester and the kinetics and thermodynamics of biological processes (Boe, 2006). There are two main temperature ranges that provide optimum digestion conditions for the production of methane i.e., the mesophilic and thermophilic ranges. 1) Mesophilic digestion takes place optimally around 30 to 38°C, or at ambient temperatures between 20 and 45°C, where mesophilic are the primary microorganism present. 2) Thermophilic digestion takes place optimally around 49 to 57°C, or at elevated temperatures up to 70°C, where thermophilic are the primary microorganisms present.

C. Carbon to Nitrogen Ratio (C/N)

The relationship between the amount of carbon and nitrogen present in feedstock is represented by the C/N ratio. It is a very important process parameter of the process as a low ratio can cause ammonia inhibition whereas a high ratio will lead deficiency (Mata-Alvarez, 2000). The adjustment of the ratio to be within the optimum range (25-30) can be achieved through the co-digestion of different waste streams (Monnet, 2003). Optimum C/N ratios in anaerobic digesters are between 20 & 30. A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production. On the other hand, a lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria. Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with animal manure or sewage.

D. Volatile Solids (VS)

Volatile solids (VS) means how much mass of a dry sample that is oxidized when combusted at temperature 550^{o}C. Dry digesters can tolerate much higher OLR that the wet anaerobic digestion process. There is an optimum feed rate for a particular reactor which will produce maximum gas, and beyond which further increases in the quantity of substrate will not proportionately produce more gas. (Yadvika et al.,2004)

The wastes treated from Anaerobic Digestion may comprise of biodegradable organic fraction, a combustible and an inert fraction. The biodegradable organic fraction includes kitchen scraps, food residue, and grass and tree cuttings. The combustible fraction includes slowly degrading lignocellulosic organic matter containing coarser wood, paper, and cardboard. As these lignocellulosic organic materials do not readily degrade under anaerobic conditions, they are better suited for waste-to-energy plants. Finally, the inert fraction contains sand, stones, metal, glass, etc. This fraction ideally should be removed, recycled or used as land fill. The volatile solids (VS) in organic wastes are measured as total solids minus the ash content, as obtained by complete combustion of the feed wastes.

E. Total solids content (TS)/Organic Loading Rate (OLR)

Low solids (LS) AD systems contain less than 10% TS, medium solids (MS) about 15-20% and high solids (HS) processes range from 22% to 40% (Satato Endar Nayono 2009, Tchobanoglous, 1993). An increase in TS in the reactor results in a corresponding

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decrease in reactor volume. Organic loading rate (OLR) is a measure of the biological conversion capacity of the AD system.

F. Volatile Fatty Acids Concentration (VFA)

Volatile Fatty Acids (VFA) are important intermediate compounds in the metabolic pathway of methane fermentation and cause microbial stress if present in high concentrations. The intermediates produced during the anaerobic biodegradation of an organic compound are mainly acetic acid, propionic acid, butyric acid and Valerie acid (Nayono.S.E. 2010). Among these acetic and propionic acids are the major VFAs present during anaerobic biodegradation and their concentrations provide a useful measure of digester performance. Acetate yield is increased slightly with increasing pH, whereas butyrate yield is increased with decreasing pH. Propionate yield was found to be unrelated to pH. The VFAs uptake might play a crucial role in the whole degradation kinetics of solid organic waste digestion, as the accumulation of the intermediate products, VFAs is the rate-limiting step (Guendouz et al.,2010).

G. Hydraulic Retention Time (HRT)

The Hydraulic Retention Time (HRT) is a measure to describe the average time that a certain substrate resides in a digester. The required retention time for completion of the anaerobic digestion reactions varies with technologies, process temperature, Total solids content and waste composition. The retention time for wastes treated in mesophilic digester is usually higher (upto 40 days) than that of thermophillic digesters which can be upto 8 days (Cecchi et al.,1991). Shortening the retention time decreases the reactor volume and hence saves capital cost. Increase in retention time however increases the reactor stability. (Hartmann and Ahring (2006) compiled the reports from other researchers and found that the HRT of anaerobic digesters treating solid wastes varied from 3 to 55 days, depending on the type of waste, operational temperature, process stage(s) and configuration of the digesters. The HRT for dry anaerobic digestion ranges between 14 and 32 days and for wet anaerobic processes it can be as low as 3 days (Zeshan 2012)., Thus feedstock with high Total solids content need long Retention Time for digestion. The HRT is the ratio of the digester volume to the influent substrate flow rate.

HRT (d) = V/Q

where V= digester volume (m^3)

Q =flow rate (m^3/d)

Waste containing readily available biodegradable compounds such as sugar, required low HRT, whereas the complex waste. E.g. lignin organic compounds is slowly degradable and needs longer HRT for their decomposition.

H. Mixing

The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes. Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester. However excessive mixing can disrupt the microbes so slow mixing is preferred. The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester. The advantages of mixing include i) Eliminates or reduces scum build up ii) Eliminates thermal pockets of depressed temperature iii) Maintains digester sludge's physical and chemical uniformity throughout the tank iv) stimulates the rapid dispersion of metabolic wastes produced during substrate digestion v) minimizing toxicity vi) mixing also prevents deposition of grit.

I. Nutrients

Methane forming bacteria have specific growth requirements. It has demonstrated that specific metals like iron, nickel, cobalt etc are necessary for optimal growth and methane production (Speece et al.,1987). The recommended requirements for iron, nickel, cobalt and zinc are 0.002, 0.003, 0.004 and 0.02 mg/g acetate produced respectively. It is of anaerobic digesters with solutions of metal ions can improve the performance of the system.

Advantages of Anaerobic Digesters	Disadvantages of Anaerobic Digesters
Generation of biogas	Small- and middle-scale anaerobic technology for the treatment of solid waste in middle- and low-income countries is still relatively new
Reduction of greenhouse gas emissions through methane recovery	Experts are required for the design and construction, depending on scale may also for operation and maintenance

Combined treatment of different organic waste and wastewaters	Reuse of produced energy (e.g. transformation into, fire/light, heat and power) needs to be established
Reduction of solids to be handled	High sensitivity of methanogenic bacteria to a large number of chemical compounds
Good pathogen removal depending on temperature	Sulphurous compounds can lead to odour
Process stability	

V. ANAEROBIC CO-DIGESTION

Anaerobic co-digestion is the simultaneous treatment of two or more organic biodegradable wastes by anaerobic digestion for the proper disposal of organic fraction of solid waste from source or from separate collection systems. The general idea is to maximize the production of biogas in an Anaerobic Digestion plant by adding substrates that produce much more biogas per unit mass than the base substrate. This type of treatment offers the possibility of using existing anaerobic reactors with minor modifications and some additional requirements. Now-a-days, the anaerobic digestion became more stable when the various substrates used at the same time is increased. When major amount of main substrate is mixed and digested together with minor amount of single or variety of substrates are added. The advantage of co-digestion improved the biogas yield from the digester.

Advantages of anaerobic co-digestion	Disadvantages of anaerobic co-digestion
Additional biogas collection	Additional pre-treatment requirements
Improved nutrient balance and digestion	Increased mixing requirements
Additional fertilizer	Increased digester effluent COD
Renewable biomass disposable for digestion	Restrictions of land use for digestate

VI. REVIEW OF PREVIOUS STUDIES OF ANAEROBIC CO-DIGESTION FROM VARIOUS WASTES

A. Review on Biogas production from Co-Digestion of Cow dung and food waste with Water hyacinth

Dinesh kumar and Rajakumar (2016) have review the anaerobic digestion of cow dung and food waste with water hyacinth to enhance biogas production. Water hyacinths are treated as waste in rivers, ponds but they have high potential in biogas production. Food wastes are having rich organic nutritive value and high calorific value. By anaerobic digestion water hyacinths are mixed with cow dung which acts as the inoculums for the digester. Kitchen waste is added as the daily feed substrate to the digester. The digested slurry from the digester is rich in nitrogen. Phosphorus and potassium content so they can be used as fertilizers and the biogas.

B. Biogas Production from Sawdust Waste, Cow Dung and Water Hyacinth-Effect of Sawdust Concentration

Ipeghan J. et.al.,(2013) studied the effect of sawdust concentration with cowdung and water hyacinth. This work proposed the utility of sawdust, co-digested with cowdung and water hyacinth to generate biogas as a means of its disposal. Various amounts of sawdust waste with a fixed amount of cow dung and water hyacinth was anaerobically fermented in batch-fed digesters in the laboratory at the same operating conditions. Biogas was measured for a period of 64 days at an average ambient temperature of 30^oC. The results show that the efficient biogas production rate was maximum of 0.045litres/TS fed when about 11.48g of sawdust waste was digested in a fixed amount of cowdung and water hyacinth (7g). This corresponds to about 8 to 9.5% total solid content in the anaerobic digester which lies within the recommended percentage range for optimum biogas production.

C. High Solid Anaerobic Co-digestion of Household Organic Waste with Cow Manure

Nuruljannah Khairuddin et.al., (2015) investigated the different mixture ratio of household organic waste (HOW) and cow manure (CM) for biogas production. The main objective was to explore possible significant synergistic effect obtained from the combination of these different substrates in Reactor 1 – 4 (R1 – 4) batch experiment. The highest methane yield, 247 mL/g VS was obtained from R3 and 243 mL/g VS in R4. Co-digestion in R4 increased to 9% for CM and 78% for HOW in methane production. The results clearly demonstrate synergistic effect from nutrient balanced that improves the stability of anaerobic process.

D. Anaerobic slurry co-digestion of poultry manure and straw: effect of organic loading and temperature

Azadeh Babaee et.al.,(2013) analysed to obtain basic design criteria for anaerobic digestion of a mixture of poultry manure and

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wheat straw, the effects of different temperatures and organic loading rates on the biogas yield and methane contents were evaluated. Since poultry manure is a poor substrate, in term of the availability of the nutrients, external supplementation of carbon has to be regularly performed, in order to achieve a stable and efficient process. The complete-mix, pilot-scale digester with working volume of 70 L was used. The digestion operated at 25°C, 30°C and 35°C with organic loading rates of 1.0, 2.0, 2.5, 3.0, 3.5 and 4.0 kg Volatile solid/m3d and a HRT of 15 days. At a temperature of 35°C, the methane yield was increased by 43% compared to 25°C. Anaerobic co-digestion appeared feasible with a loading rate of 3.0 kg VS/m3d at 35°C. At this state, the specific methane yield was calculated about 0.12 m^3/kg VS with a methane content of 53–70.2% in the biogas. The volatile solid (VS) removal was 72%. As a result of volatile fatty acid accumulation and decrease in pH, when the loading rate was less than 1 or greater than 4 kg VS/m^3d, the process was inhibited or overloaded, respectively. Both the lower and higher loading rates resulted in a decline in the methane yield.

E. Evaluation of Methane Production and Biomass Degradation in Anaerobic Co-digestion of Organic Residuals

Kwanyong Lee et.al.,(2013) studied the characterization of two different types of municipal organic waste sources; septage and primary sludge (PS) in order to evaluate potential methane production and co-digestability. The highest specific biogas yields of PS and septage and were 629.6 and 568.3 mL-biogas/g-VS at biological methane potential test, respectively. The results revealed that there was a significant difference in chemical composition and carbon to nitrogen ratio between primary sludge and septage. Co-digestion of mixed substrate enhanced the digestion performance in terms of biogas production and composition.

F. Anaerobic digestion of municipal solid waste and agricultural waste and the effect of codigestion with dairy cow manure.

Samani et al.(2008), carried out the experiment of anaerobic digestion of the organic fraction of municipal solid waste (OFMSW) and dairy cow manure (CM) alone and compared the results with the co-digestion of the same. The results were when OFMSW was digested alone produced 62m^3 methane/ton and CM produced 37m^3 methane/ton of dry waste. Co-digestion of OFMSW and CM produced 172m^3 methane/ton of dry waste. Comparing the single waste digestions with codigestion of combined wastes, it was shown that codigestion resulted in higher methane gas yields.

G. Anaerobic digestion of municipal solid waste and co-digestion with manure.

Hartmann et al (2005), investigated anaerobic digestion of the organic fraction of municipal solid waste (OFMSW). This was carried out in two thermophilic (55 0 C) wet digestion treatment systems R1 and R2. Initially OFMSW was co-digested with manure with a successively higher concentration of OFMSW, at a hydraulic retention time (HRT) of 14-18 d and an organic loading rate (OLR) of 3.3-4.0 g-VS/l/d. Over a period of 6 weeks adaptation of the co-digestion process was established to a OFMSW:manure ratio of 50% (VS/VS). This co-digestion ratio was maintained in reactor R2 while the ratio of OFMSW to manure was slowly increased to 100% in reactor R1 over a period of 8 weeks. Use of recirculated process liquid to adjust the organic loading to R1 was found to have a beneficial stabilization effect. The pH raised to a value of 8 and the reactor showed stable performance with high biogas yield and low VFA levels. The biogas yield from source-sorted OFMSW was 0.63-0.71 l/g-VS both in the co-digestion configuration and in the treatment of 100% OFMSW with process liquid recirculation. This yield is corresponding to 180-220 m3 biogas per ton OFMSW. VS reduction of 69-74% was achieved when treating 100% OFMSW. None of the processes showed signs of inhibition at the free ammonia concentration of 0.45-0.62 g-N/l.

VII. CONCLUSION

A. Co-digestion of various wastes improves the balance of nutrients and enhances pH value.
B. Comparison of single waste digestions with co-digestion of combined wastes seen that it was resulted in higher biogas yields.
C. The co-substrates improves the biogas yields from anaerobic digester due to positive energy mechanisms developed in the digesters.
D. The advantages of co-digestion can result from shared equipment, easier handling of feedstock, and a more stable process in general
E. The main disadvantage of co-digestion is that it still remains largely unstudied.

In total, the efficient performance of an anaerobic reactor for any kind of co-digestion of biowaste depends on type of waste, sampling place, characterisation of waste, methods of Anaerobic Digestion process, Carbon to Nitrogen ratio, Organic loading rate, Hydraulic Retention Time (HRT), Volatile Solids (VS), Volatile fatty Acid (VFA), total ammonia nitrogen, temperature, pH, mixing and nutrients.

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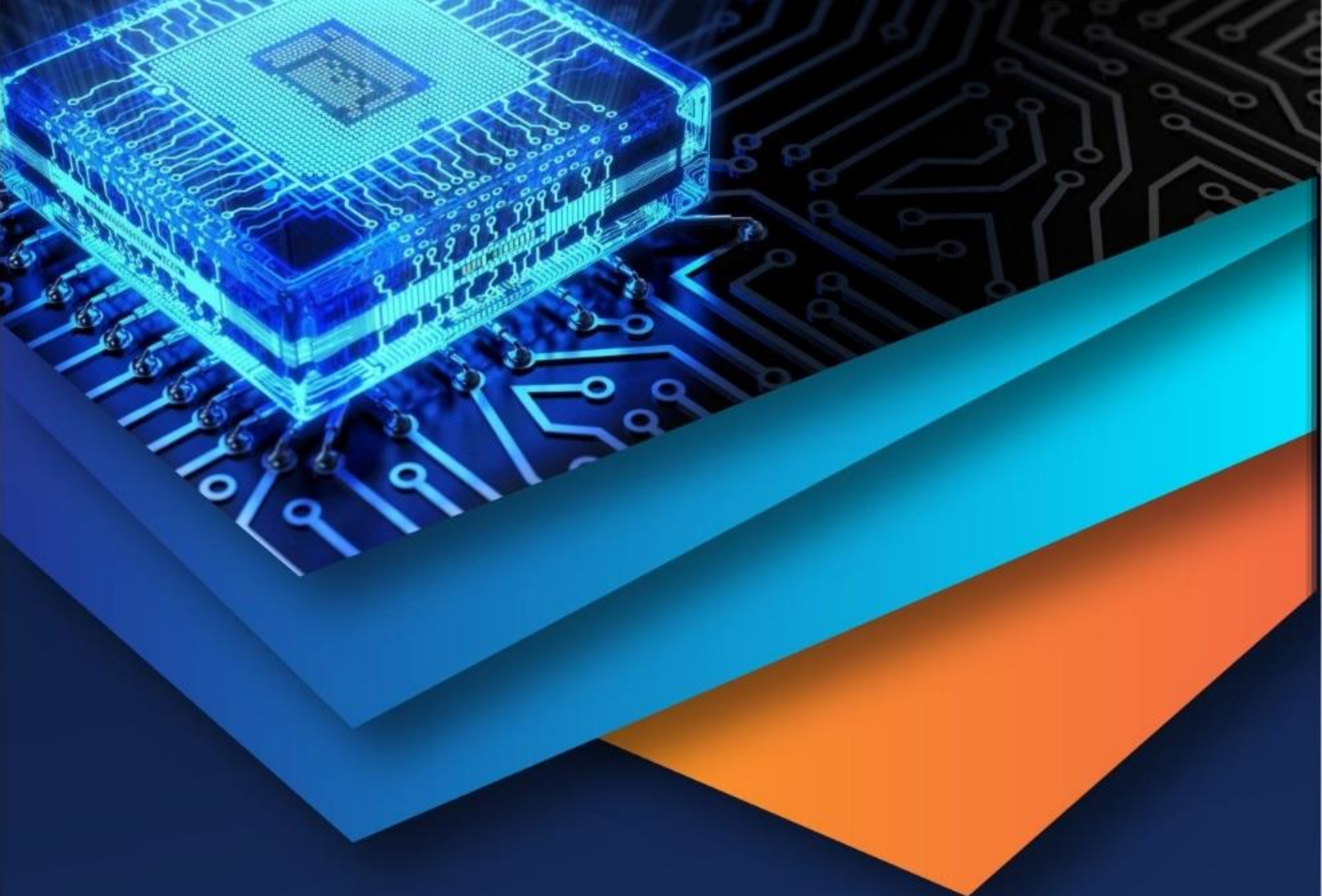

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