ISSN (Online) : 2319 - 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization Volume 3, Special Issue 4, March 2014

National Conference on Recent Advances in Civil Engineering (NCRACE-2013)

During 15-16 November, 2013

Organized by

Department of Civil Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli, Itanagar, Arunachal Pradesh, India.

Anaerobic Digestion of Municipal Solid Waste: A Critical Analysis

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Abstract—The undisposed and untreated amount of municipal solid waste (MSW) generated by different sources is a concern of the world today. There are millions of tonnes of solid waste being produced every year and amount of MSW is increasing day by day. Co-digestion of waste with other substrate mechanism may be used to decompose the maximum biomass waste generated from different source. The MSW has to be safely disposed without any negative impact to the environment. On the other hand, the generation of energy from renewable sources of energy due to depleting natural non renewable sources of energy has been becoming world's main interest. The MSW can be one of the energy sector dreamt by the world today by use of co-digestion process. Also, the energy produced by non renewable sources of energy contributes to environmental problems such as water, land and air pollution or even global climate change. Anaerobic co-digestion as a pre-treatment prior to landfill disposal or composting offers several advantages, such as minimization of masses and volume, inactivation of biological and biochemical processes in order to avoid landfill-gas and odour emissions, reduction of landfill settlements and energy production in the form of methane. Furthermore, co-digestion of biowaste with other substrate can be considered as an alternative option to improve the environment condition caused by organic solid waste and at the same time taking an advantage as an environmentally-friendly resource of energy. In this paper a critical analysis of some research papers in the field of anaerobic co-digestion process is done.

Keywords—Anaerobic co-digestion, methane, biogas, MSW, C/N ratio, hydraulic retention time

I. INTRODUCTION

Anaerobic digestion of organic solid waste from Urban areas, is of great importance in management of the solid waste. By application of anaerobic digestion of organic fraction of MSW will considerably decrease the volume of waste that is destined to the sanitary landfills. On the other hand, as one of the driving forces for economic and social development is the availability of energy in sufficient and sustainable amount has been becoming world's main interest. However, depending on the way the energy is produced, distributed and used, it may contribute to environmental problems such as water, land and air pollution or even global climate change. Anaerobic digestion as a pre-treatment prior to landfill disposal or composting or at landfill site offers several advantages, such as minimization of masses and volume, inactivation of biological and biochemical processes in order to avoid landfill-gas and odor emissions, reduction of landfill settlements and energy production in the form of methane. Therefore, anaerobic digestion of bio-degradable solid wastes can be considered an alternative option to improve the environment condition caused by organic solid waste and at the same time taking an advantage as an environmentally-friendly resource of methane.This paper is presented critically analysing the studies carried out by the different authors in the field of MSW specially the process of anaerobic digestion for biogas generation from the MSW for use in household and community purpose, characterization of MSW, the 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 biogas generation due to co-digestion of MSW with other substrate in varying amount have been given the prime importance.

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II. METHODOLOGY OF ANAEROBIC DIGESTION OF MSW

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% ([1] Chea Eliyan 2007, Lissens et al., 2001).

B) Batch and continuous feeding systems

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) Commercial processes of anaerobic digestion of organic solid waste

Stimulated by the increasing demand of anaerobic digester for organic solid wastes, several commercial anaerobic digester plant designs have been developed over the past two decades. Especially in European countries, The processes are patented according to several basic characteristics as previously discussed (batch or continuous feeding, number of stages, total solids content of waste and operating temperature). Mixing methods (gas injection or mechanical stirrers), reactor type (vertical or horizontal, rectangular or cylindrical) and process flow (completely mixed or plug-flow) are also parameters to obtain patent rights are as shown below in fig 1.

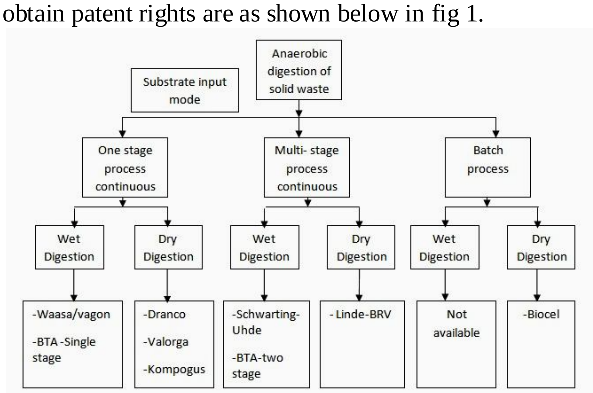

Fig 1. Available technology at present

1) DRANCO; The DRANCO (dry anaerobic composting) process employs a one-stage anaerobic digestion system, which is followed by a short aerobic maturation phase. Although mostly operated under thermophilic temperature (reportedly to be 50-55°C), mesophilic operation (35-40 $^{\circ}$C) can also be applied for specific waste streams (Satato Endar Nayono 2009, de Baere, 2008) [2].

2) VALORGA; The Valorga system is a one-stage dry anaerobic digestion process which uses a vertical cylindrical reactor which can be operated at both, mesophilic and thermophilic temperature. In order to obtain a horizontal plug-flow process, the digester is equipped with a vertical median partition wall on approximately 2/3 of their diameter.

3) KOMPOGA; The KOMPOGAS system is a one-stage dry anaerobic digestion process. The fermentation process takes place in a horizontal plug-flow reactor at thermophilic temperature (typically 55-60°C).

4) Waasa; The Waasa process is a wet, one-stage anaerobic digestion system and is operated at both, mesophilic and termophilic temperatures.

5) BTA; The BTA process consists of two major steps: the hydro-mechanical pretreatment and the anaerobic digestion processes.

6) Schwarting-Uhde; The Schwarting-Uhde process adopts a two-stage wet anaerobic digestion process which is performed in a series of two vertical plug-flow reactors. The first reactor is operated at mesophilic temperature for hydrolysis and acidification processes while the second reactor is operated at thermophilic temperature for methanogenesis.

7) Linde-BRV; The Linde-BRV process can be considered as two-stage dry anaerobic digestion. After pre-treatment to reduce the particle size and to remove impurities, the solids concentration of source-separated biowastes is adjusted to 34 %. The slurry is then pre-digested in an aerobic upstream stage where the organic materials are partially hydrolyzed ([2] Satato Endar Nayono 2009, Vandevivere et al., 2002).

III. PARAMETERS AFFECTING AD OF MSW

A. Physical Parameters

1) Specific Weight (Density); Specific weight is defined as the weight of a material per unit volume (e.g. kg/m^3),

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usually it refers to uncompacted waste, it varies with geographic location, season of the year, and length of time in storage.

2) Moisture Content; The moisture in a sample is expressed as percentage of the wet weight of the MSW material,

Analysis Procedure:

- Weigh the aluminum dish
- Fill the dish with SW sample and re-weigh
- Dry SW + dish in an oven for at least 24 hrs at 105°C.
- Remove the dish from the oven and allow it to cool in a desiccator, and weight.
- Record the weight of Dry SW + dish.
- Calculating the moisture content (M in %) of the MSW sample using the equation given above.

$$M = \frac{w-d}{w} x100 \quad \text{(i)}$$

3) Particle size and distribution; The size and distribution of the components of wastes are important for the recovery of materials, especially when mechanical means are used, such as trammel screens and magnetic separators.

For example, ferrous items which are of a large size may be too heavy to be separated by a magnetic belt or drum system. The size of waste components can be determined using the following equations:

$$Sc = L \quad \text{(ii)}$$

$$Sc = \frac{L+w}{2} \quad \text{(iii)}$$

$$Sc = \frac{L+w+h}{3} \quad \text{(iv)}$$

Sc : size of component, mm
L : length, mm
W : width, mm
h : height, mm

4) Field Capacity; The total amount of moisture that can be retained in a waste sample subject to the downward pull of gravity. Field capacity is critically important in determining the formation of leachate in landfills. It varies with the degree of applied pressure and the state of decomposition of wastes, but typical values for uncompacted commingled wastes from residential and commercial sources are in the range of 50-60%.

5) Permeability of Compacted waste; The permeability (hydraulic conductivity) of compacted solid waste is an important physical property because it governs the movement of liquids & gases in a landfill.

Permeability depends on:

- Pore Size distribution
- Surface area
- Porosity

B. Chemical Properties of MSW

Chemical properties of MSW are very important in evaluating the alternative processing and recovery options:

1) Proximate analysis; Proximate analysis for the combustible components of MSW includes the following tests:

- Moisture (drying at 105^{o}C for 1 h)
- Volatile combustible matter (ignition at 950^{o}C in the absence of oxygen)
- Fixed carbon (combustible residue left)
- Ash (weight of residue after combustion in an open crucible)

2) Fusing point of ash; Fusing point of ash is the temperature at which the ash resulting from the burning of waste will form a solid (clinker) by fusion and agglomeration. Typical fusing temperatures: 1100-1200^{o}C

3) Ultimate analysis (Major elements); Involves the determination of the percent C (carbon), H (hydrogen), O (oxygen), N (nitrogen), S (sulfur) and ash. The determinations of halogens are often included in an ultimate analysis. The results are used to characterize the chemical composition of the organic matter in MSW. They are also used to define the proper mix of waste materials to achieve suitable C/N ratios for biological conversion processes.

4) Energy content: Energy content can be determined by using a full scale boiler as a calorimeter, a laboratory bomb calorimeter or by calculation most of the data on the energy content of the organic components of MSW are based on the results of bomb calorimeter tests.

C. Biological Properties of MSW

The organic fraction of MSW (excluding plastics, rubber and leather) can be classified as

- Water-soluble constituents like sugars, starches, amino acids and various organic acids.
- Hemicellulose - a product of 5 and 6-carbon sugars.
- Cellulose - a product of 6-carbon sugar glucose.
- Fats, oils and waxes - esters of alcohols and long-chain fatty acids.
- Lignin - present in some paper products.

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- Lingocellulose - combination of lignin and cellulose.
- Proteins - amino acid chains.

IV. Important Operating Parameter in AD Process

The rate at which the aerobes and anaerobes grow is of paramount importance in the AD process. The operating parameters of the digester must be controlled so as to enhance the microbial activity and thus increase the anaerobic degradation efficiency of the system. Some of these parameters are discussed in the following section.

A. Waste composition/Volatile Solids (VS)

The wastes treated by AD may comprise a 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 stones, glass, sand, metal, 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.

B. pH Level

Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions. The acid concentration in aqueous systems is expressed by the pH value, i.e. the concentration of hydrogen ions. At neutral conditions, water contains a concentration of 10^{-7} hydrogen ions and has a pH of 7. Acid solutions have a pH less than 7 while alkaline solutions are at a pH higher than 7. It has been determined ([2] Satato Endar Nayono 2009, RISE-AT, 1998) that an optimum pH value for AD lies between 5.5 and 8.5.

C. Temperature

There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between $20^{\circ}C$-$40^{\circ}C$ and the optimum temperature is considered to be $30^{\circ}C$-$35^{\circ}C$. The thermophilic temperature range is between $50^{\circ}C$-$65^{\circ}C$ ([2] Satato Endar Nayono 2009, RISEAT, 1998).

D. Carbon to Nitrogen Ratio (C/N)

The relationship between the amount of carbon and nitrogen present in organic materials is represented by the C/N ratio. 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 sewage or animal manure.

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

F. Retention (or residence) Time

The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition. The retention time for wastes treated in mesophilic digester range from 10 to 40 days. Lower retention times are required in digesters operated in the thermophilic range.

G. 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.

H. Compost

When the digestion is complete, the residue slurry, also known as digestate, is removed, the water content is filtered out and re-circulated to the digester, and the filter cake is cured aerobically, usually in compost piles, to form compost. The compost product is screened for any undesirable materials, (such as glass shards, plastic pieces etc) and sold as soil amendment. The quality of compost is dependent on the waste composition.

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V. MICROBIOLOGICAL PROCESS IN ANAEROBIC DIGESTION OF MSW

Anaerobic digestion is described as a series of processes involving microorganisms to break down biodegradable material in the absence of oxygen. The overall result of anaerobic digestion is a nearly complete conversion of the biodegradable organic material into methane, carbon dioxide, hydrogen sulfide, ammonia and new bacterial biomass ([2] Satato Endar Nayono 2009, Veeken, 2000; Kelleher, 2002, Gallert and Winter, 2005, Buswell (1952 as cited in Gallert and winter, 2005) proposed a generic formula describing the overall chemical reaction of the anaerobic fermentation process of organic compounds which can be used for the prediction of biogas production:

– H_2O =

–) CO_2

+ –) CH_4

+ $nNH_3 + sH_2S$ (v)

In the anaerobic digestion process different types of bacteria degrade the organic matter successively in a multistep process and parallel reactions. The anaerobic digestion process of complex organic polymers is commonly divided into three interrelated steps: hydrolysis, fermentation (also known as acidogenesis), s-oxidation (acetogenesis) and methanogenesis which are schematically illustrated in Fig. 2.

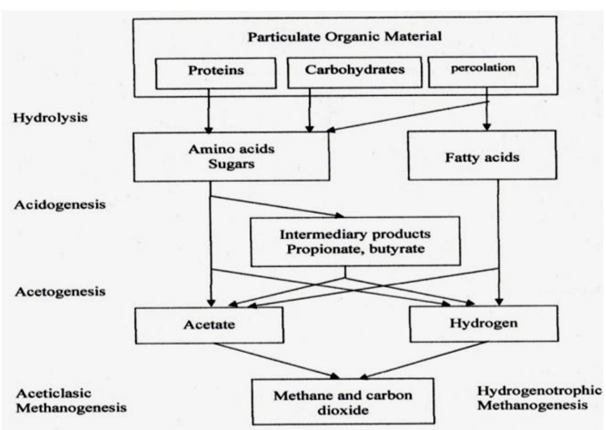

Fig.2 Schematic diagram of complete anaerobic digestion of complex polymers

A. Hydrolysis

In the first stage of hydrolysis, or liquefaction, fermentative bacteria convert the insoluble complex organic matter, such as cellulose, into soluble molecules such as sugars, amino acids and fatty acids. The complex polymeric matter is hydrolyzed to monomer, e.g. cellulose to sugars or alcohols and proteins to peptides or amino acids, by hydrolytic enzymes, (lipases, proteases, cellulases, amylases, etc.) secreted by microbes.

Lipid $\longrightarrow$ Fatty Acids
Polysaccharides $\longrightarrow$ Monosaccharrides

B. Fermentation (acidogenesis)

Soluble organic components including the products of hydrolysis are converted into organic acids, alcohol, hydrogen, and carbon dioxide by the action of acid forming bacteria known as acidogens. The monomers produced from the hydrolysis process are then degraded by a large diversity of facultative anaerobes and anaerobes through many fermentative pathways.

{Soluble organic (Amino acid, Monosaccharide, Fatty acids)} $\xrightarrow{\text{Acidogen}}$ {(Intermediate products, Propionate, butyrate, Alcohol etc.)}

C. Acetogenesis

The simple monomer blocks formed in hydrolysis act as substrate feedstock for the fermenting, acid forming anaerobic bacteria. It may be difficult to distinguish this stage from the previous one for some molecules which will be absorbed without further break down and can be degraded internally. Acetogenic bacteria, also known as acid formers, convert the products of the first phase to simple organic acids, carbon dioxide and hydrogen. The principal acids produced are: acetic acid (CH_3COOH), propionic acid (CH_3CH_2COOH), butyric acid ($CH_3CH_2CH_2COOH$), and ethanol (C_2H_5OH). The products formed during acetogenesis are due to a number of different microbes, e.g., syntrophobacter wolinii, a propionate decomposer and syntrophomonas wolfei, a butyrate decomposer. Other acid formers are clostridium species, peptococcus anerobus, lactobacillus, and actinomyces [2] (Satato Endar Nayono 2009, Verma, 2002).

{Intermediate Products (Propionate, butyreate, alcohol etc)} $\xrightarrow{\text{Acetoogen}}$ {acetate, Carbon dioxide and hydrogen}

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D. Methanogenesis

Finally, in the third stage, methane is produced by bacteria called methane formers (also known as methanogens) in two ways: either by means of cleavage of acetic acid molecules to generate carbon dioxide and methane, or by reduction of carbon dioxide with hydrogen. Methanogenic bacteria are highly sensitive to oxygen concentration in the system, resulting in an inactive phase in the system as well as a high concentration of fatty acids in the environment ([2] Satato Endar Nayono 2009, Sharma, 2000). Consequently, the pH value will be lower. Methane production is higher from the reduction of carbon dioxide but limited hydrogen concentration in digesters results in an acetate reaction, which is the primary producer of methane. The 4 methanogenic bacteria include methanobacterium, methanobacillus, methanococcus and methanosarcina. Methanogens can also be divided into two groups: acetate and H_2/CO_2 consumers. Methanosarcina species and methanothrix species or methanosaeta; are considered to be important in AD both as acetate and H_2/CO_2 consumers. The methanogenesis reactions can be expressed as follows:

$$CH_3COOH \longrightarrow CH_4 + CO_2 \quad \text{(vi)}$$
$$2C_2H_5OH + CO_2 \longrightarrow CH_4 + 2\,CH_3COOH \quad \text{(vii)}$$
$$CO_2 + 4H_2 \longrightarrow CH_4 + 2\,H_2O \quad \text{(viii)}$$

About two thirds of methane is derived from acetate conversion by methanogens. The other is the result of carbon dioxide reduction by hydrogen [2](Satato Endar Nayono 2009, WD, 2006). Although AD can be considered to take place in these four stages, all processes occur simultaneously and synergistically, in as much as the first group has to perform its metabolic action before the next can take over, and so forth [2] Satato Endar Nayono 2009, (Ostrem, 2004).

VI. Critical Review of Research Papers on Works Done so far in Anaerobic Process Involving Co-Digestion of MSW with Other Substrate

A. Hong-Wei Yen, David E. Brune: Anaerobic co-digestion of algal sludge and waste paper to produce methane. Bioresource Technology 98 (2007) 130–134.[3]

1) Analysis of results; In this research work, used Bench-top anaerobic digesters with gas storage tanks were fabricated from 25mm Plexiglas sheet and contained with a temperature-controlled water bath at 35±1°C. Digesters were connected to gas storage tanks and gas sampling ports using silicone tube. The digester and gas storage tank measured 12.5x14x30 cm and 16.5x15.2x30 cm, respectively (working volume, 4–l).

Semi-continuously feeding type was adopted and digesters were fed once per day following the removal of the same volume of effluent.

2) Effects on performance due to co-digestion of wastes.

TABLE 1. Digestion of algal sludge alone

Loading Rate (gVS/lday)	CH_4(ml/lday)	CO_2(ml/lday)	VFAs(mg/l)	TAN (mg/l)
2	180±8	72±5	1305±148	589±86
4	573±28	258±15	4978±635	837±65
6	818±96	384±44	5862±1769	998±29

Digesters fed with algal sludge alone at 2, 4 and 6 g VS/lday loading rate, Methane, VFAs, TAN and CO_2 production rates increased in proportion to increases in loading rate. It is seen that the VFAs and TAN concentration is exponentially increasing would achieve toxicity concentration in reactor, and limit the reaction, if the loading rate increased further.

TABLE 2. Co-digestion of algal sludge and waste paper at loading rate of 4 g VS/l day

Feedstock	C/N	CH_4 (ml/lday)	CO_2 (ml/lday)	VFA (mg/l)	TAN (mg/l)
A/Sludge	6.7	573±28	258±15	4978±635	837±65
25%W/Paper+A/Sludge	11.8	968±73	556±37	3480±679	697±51
50%W/Paper+A/Sludge	18.0	1170±75	769±49	3912±1290	524±24
75%W/Paper+A/Sludge	36.4	317±114	277±82	10848±713	65±10
100%W/Paper.	21.5	452±36	278±22	7350±1259	629±51

The loading rate is maintained at 4 g VS/l day for mixture of substrate. The result in Table 2.shows that, with paper addition at 50% of VS, is significant phase in the methane

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production rate of 1170±75 ml/l day; or two-fold higher than that in algal sludge digestion alone, TAN levels decreased with the increased feedstock C/N ratio to the minimum of 65±10 mg/l at 75% of waste paper fraction. Addition of 50% paper yielded relatively low VFA levels of 3912±12 mg/l compared to 4978±635 mg/l during algal sludge digestion alone. At 75% paper, the digester performance turned to be unstable. Possible reasons for this observed instability could be (1) toxicity of high VFAs at 10,848±713 mg/l, and (2) low TAN concentrations of 65±10 mg/l.

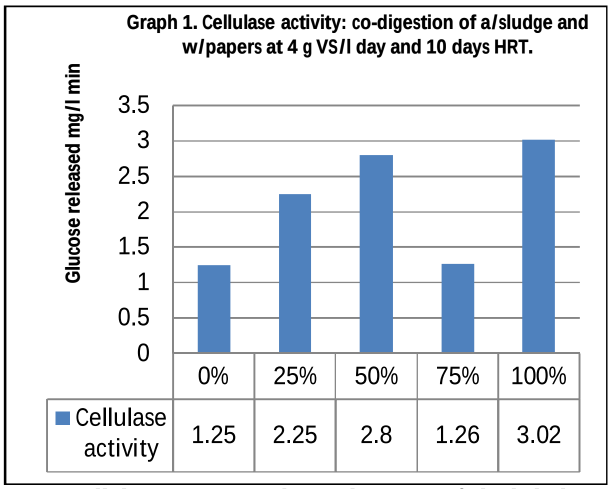

Fig.1 Cellulose activity in the co-digestion of algal sludge and waste paper at 4 g VS/l day

At 75% paper fraction, elevated VFA concentrations suppressed cellulase activity to 1.26 mg/l min. The highest level of cellulase activity 3.02 mg/l min was during paper digestion alone.

These results in Table 2 suggested that breakdown of algal biomass contributed some key components to the improvement of methanogenic activity. Therefore, a low methane production rate was observed in the digester fed paper alone, even if there were no nutrients limitation and had high cellulase activity in the digester see in graph.

B. Wilton Silva Lopes a, Valderi Duarte Leite b, Shiva Prasad: Influence of inoculum on performance of anaerobic reactors for treating municipal solid waste. Bioresource Technology 94 (2004) 261–266 [4]

1) Experimental set up; The experimental system consisted of four anaerobic batch reactors of 20 l capacity each. The reactors were constructed from rigid plastic buckets, in which the following devices were installed

1. Recorder for biogas produced;
2. Device for biogas collection;
3. Device for recirculation of water;
4. Leachate collection tap.

2) Analysis of results:

TABLE 3. Biostabilization Constants of TVS

Reactor	Proportion MSW/Inoculum	Models
A	100%/0%	$TVS = 1431.e^{-0.001028t}$
B	95%/5%	$TVS = 1431.e^{-0.001536t}$
C	90%/10%	$TVS = 1431.e^{-0.001453t}$
D	85%/15%	$TVS = 1431.e^{-0.002105t}$

One of the kinetic parameters used for evaluation of performance of the anaerobic treatment process in this work was the biostabilization constant, whose values indicate the velocity with which the organic material is degraded. The biostabilization constants of TVS were determined by using Eq.1.

.

$$S = So.e^{-kt} \quad \text{...} \quad (ix)$$

Where S is the mass of substrate at time t (kg), so the initial mass of substrate (kg), k the biostabilization constant (day^{-1}), t the time (days), higher the value of the constant the less will be the time necessary for biostabilization of the organic matter.

- [3]Borzacconi et al. (1997), who studied the anaerobic degradation of municipal solid waste obtained the value of the constant equal to 1.6 x 10^{-3} day^{-1} for a reactor of 200 l capacity, a value which is close to the value obtained in this work for the Reactor B, whereas for the Reactor D the value of the constant was 2.1 x 10^{-3} day^{-1}.

Analyzing the data presented in Table 3. it is verified that the biostabilization constant value was a direct function of the inoculum percentage used. The higher the values of biostabilization constant the better the performance of the process.

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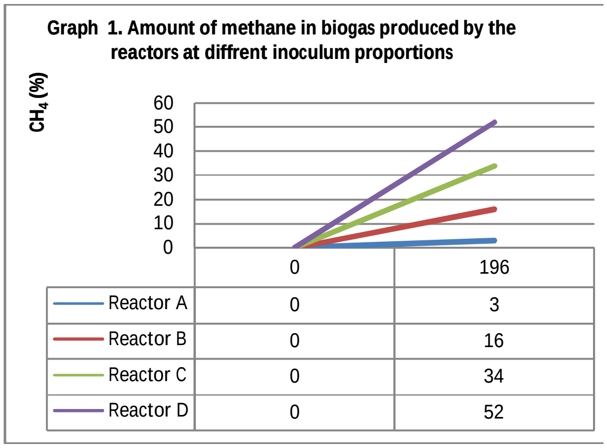

Fig.2 Amount of methane produce in reactors at different inoculums proportions.

From graph 1 it is found that, at 196 days of reaction period Reactor D yielded 52% methane in the biogas produced, whereas in the Reactors A, B and C the amount of methane detected was just 3%, 16% and 34%, respectively.

- [3]Callaghan et al. (2002), while studying the co-digestion of cattle slurry with fruit and vegetable wastes and chicken manure obtained a rate of methane production as 0.37 m^3 kg^{-1} of TVS added.

C. Anthony Mshandete a, b, Amelia Kivaisi a,*, Mugassa Rubindamayugi a, Bo Mattiasson : Anaerobic batch co-digestion of sisal pulp and fish wastes. Bioresource Technology 95 (2004) 19–24[5]

1) Experimental set up; In this experiment used 1000 ml bioreactors constructed by using conical glass flasks with a working volume of 600 ml. Wastes 1) Sisal pulp (SP), a leafy biomass waste produced during sisal decortications, was obtained from a sisal processing factory (Ubena Zomozi, Coast Region, Tanzania). 2). The fish waste (FW) obtained from the landing beach in Dar es Salaam City in Tanzania, consisted of offal's, scales, gills and washing water. Sisal wastewater sludge (SWS) is used as inoculum.

2) Analysis of results;

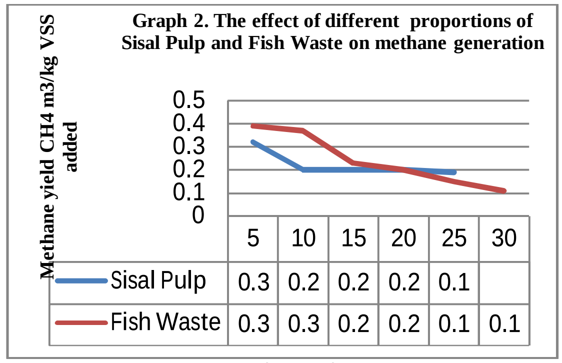

Fig.2 Biodegradability of pure fish and sisal pulp wastes

It is clear from the Graph 2, that, the methane yield decreases with an increase in solid substrate content. In this study the highest methane yield of 0.32CH_4 m^3/Kg VSS_{added} for SP and 0.39CH4 m^3/Kg VS_{added} for FW, were obtained at 5% of TS. The ratio of waste/inoculum is a critical parameter for this study with solid content higher than 5%, since the methane yield increased significantly when the waste/inoculum ratio decreased from 1.6 to 0.05 for fish and 2.5 to 0.09 for sisal pulp, respectively, this is due to result of increased substrate content.

- [5] Ahring et al. (1992) reported methane yield in the range of 0.450–0.500 $m^3CH_4/kgVS_{added}$ from fish oil sludge which is similar to what was found in the present investigation.

TABLE 4. Co-digestion of sisal pulp and fish wastes

% Wet Weight	C/N ratio	% TS	Total (CH_4)	Yield CH_4 m^3/kg VSS
50 FW : 50 SP	12	20.6	0.38	0.31
33 FW : 67 SP	16	16.6	0.77	0.62
25 FW : 75 SP	18	14.8	0.57	0.48
20 FW : 80 SP	23	13.6	0.50	0.44

The total methane production and methane yields varied between 0.38–0.77 l and 0.30–0.62 CH_4 $m^3/kgVS_{added}$, respectively with values being highest for mixture containing 33% FW:67% SP and lowest for 50% FW:50% SP.

By analysis, the fraction with 33% FW:67% SP wet weight found to be suitable for successful co-digestion for enhanced methane production, co-digestion of the fish

ISSN (Online) : 2319 - 8753
ISSN (Print) : 2347 - 6710

International Journal of Innovative Research in Science, Engineering and Technology

An ISO 3297: 2007 Certified Organization Volume 3, Special Issue 4, March 2014

National Conference on Recent Advances in Civil Engineering (NCRACE-2013)

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Department of Civil Engineering, North Eastern Regional Institute of Science and Technology, Nirjuli, Itanagar, Arunachal Pradesh, India.

waste and sisal pulp at 33% FW:67% SP wet weight proportions, with 16.6% of TS and a C:N ratio of 16, enhanced the methane yield by 59–94%. [5] Kaparaju et al. (2001) reported an enhancement of about 60% in the methane yield with co-digestion of industry confectionery waste with cow manure. The average CH4 content of the biogas produced from 50:50 was (61%), 33:67 (64%); 25:75 (65%) and 20:80% (58%).

D. P. Sosnowski, A.Wieczor ek, S. Ledakowicz: Anaerobic co-digestion of sewage sludge and organic fraction of municipal solid waste [6]

1) Experimental set up

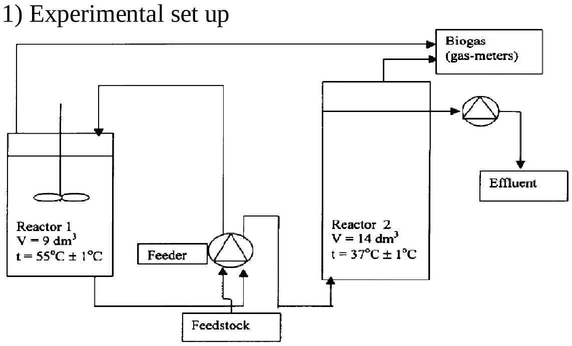

Fig 3. Experimental setup

Experiments were carried out in two systems: A 40 dm^3 bioreactor operated thermophilically in batch mode wise. Another bioreactor system operated in quasi-continuous mode shown in fig.3 above.

TABLE 5. Experimental conditions:

Parameters	Experiment I,II	Experiment III,IV,V	
		Reactor 1	Reactor 2
Reactor Type	Semi UASB	CSTR	Semi UASB
Active Reactor Volume (dm^3)	30	9	14
Mixing mechanism	Mechanical	Mechanical	Mechanical
Heating	Electric	Electric	Electric
Operating temperature (^oC)	56	56	36

In the first experiment used the primary sludge and thickened excess activated sludge (1:1) from mechanical–biological Municipal Wastewater Treatment Plant (MWTP) in Lodz, Poland was fed into the bioreactor. This batch process was conducted under thermophilic conditions for 35 days. The second experiment was conducted as a co-fermentation of the mixture of sewage sludge (75% vol.) and OFMSW (25% vol.), The third experiment was conducted in quasi-continuous mode in the two-stage arrangement with the substrate-OFMSW only, In the fourth run only sewage sludge (primary sludge and thickened excess activated sludge 1:1 in quasi continuous mode. Whereas, in the fifth experiment arrangements and conditions were the same as in the experiments III and IV but in this case the mixture of sewage sludge (75% vol.) and OFMSW (25% vol.) was used.

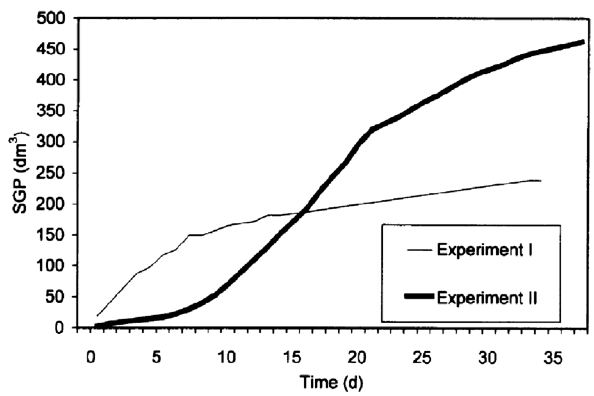

Fig 4. Comparison of experiments I and II.

Comparing our results of SGP in experiment I (0.580dm^3/g VVS_{added}) with the corresponding results of SGP for digestion of sewage sludge presented by [6] Del Borghi et al. (1999) (0.19 dm^3/g VVS_{added}), a higher biogas yield was achieved in our experiment. Similarly, in experiment II the SGP was 0.427 dm^3/g VVS_{added} compared with 0.36dm^3/gVVS_{added} for the corresponding feedstock and experimental conditions of [6] Del Borghi etal. (1999).

Thus for experiment 1, the initial SGP is very high upto 2 weeks period because of presence of large numbers of readily available microbes corresponding to degradable biomass. The SGP of experiment II, increases slowly till days period, thereafter, it increases exponentially as a results of the multiplication of numbers of microbes and rapid decomposition of OFMSW. However, after 2 weeks of digestion the cumulative biogas production in both experiments were equal. Ultimately, the biogas volume produced from the mixture of sewage sludge and OFMSW was twice the biogas amount obtained from the sewage sludge only.

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Parameters	Exp.I,	Exp. II	Exp III		Exp IV		Exp V	
			Rtr 1	Rtr 2	Rtr 1	Rtr 2	Rtr 1	Rtr 2
Temp (^{o}C)	56	56	56	36	56	36	56	36
Average OLR(gVSS/dm^3/day	0.392	1.512	2.76		0.669		3.084	
HRT (d)	35	38	8.9	20.9	17.33	44.2	11.1	17.30
VSS inoculum (g/dm^3)	16.2	15	4.79	1.34	20	16.2	25.6	18.4
SGP (dm^3/gVSS$_{add}$)	0.580	0.427	0.419		0.554		0.532	
Yield of biogas (dm3/dm3/gVSS)	0.019	0.014	0.018		0.024		0.023	

TABLE 6. Summary of digester performances and characteristic of feedstock and biogas

Comparison of experiments III, IV and V

Comparison of the SGP values in experiment III (0.419dm^3/g VSS$_{add}$), experiment IV (0.554 dm^3/g VSS$_{added}$) and experiment V (0.532dm^3/VSS$_{added}$) with literature data of [6] Cecchi et al. (1993) (0.42 dm^3/g VSS$_{added}$), for OFMSW and with [6] Garcia-Heras etal. (1999) (0.28–0.4 dm^3/g VSS$_{added}$), also proved the consistency of our results.
Comparison data from experiment II and experiment V show that the two-phase system is more effective. In both experiments the mixture of sewage sludge and OFMSW was used. In experiment II an SGP of 0.427dm^3/g VSS$_{added}$ was obtained and while in experiment V SGP was 0.532dm^3/g VSS$_{added.}$

It is observed that. The experiment iii operated in quasi-continuous mode with OFMSW substrate only has less SGP value because of non addition of inoculum, in experiment IV, the reactor operated in similar condition, the substrate used is only sewage sludge and activated sludge in 1:1 ratio, the initial SGP values will be very high because of rapid decomposition of sewage sludge with excessive readily present micro organisms, whereas, in experiment V, the co-digestion of sewage sludge and OFMSW (75%:25% Vol), the SGP value obtained in this case is 0.532dm^3/VSS$_{added.}$ The SGP value in this case will increase exponentially with increase in loading rate till the toxicity level of VFA is reached.

VI. CRITICAL CONCLUSION AND RECOMMENDATION

In this paper, a critical analysis and review of four research papers in the field of co-digestion of different substrate in anaerobic digestion process presented by different authors reveals that:

i. Hydraulic retention time (HRT): HRT is a critical parameter in AD of substrate for yield of methane and biogas, higher is the HRT, lower will be the loading rate. HRT can be a factor for selection of reactor, shortening the HRT and increasing the loading rate will minimize the reactor volume, which will help in economical selection of reactor.

ii. C/N ratio: Optimum C/N ratios in anaerobic digesters are between 20–30. A higher C/N ratio indicates rapid consumption of nitrogen by methanogens and results 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 can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure.

iii. The effect of inoculum co-digested with any kind of bio waste substrate in production of methane and biogas is significant, higher the ratio/quantity of inoculum higher will be the methane produce and hence, higher will be the biostabilization constant and lesser will be the biostabilization time.

iv. Temperature: There are mainly two temperature ranges that provide optimum digestion conditions for the production of methane – the mesophilic and thermophilic ranges. The mesophilic range is between 20°C-40°C and the optimum temperature is considered to be 30°C-35°C.

v. Optimum pH value for AD lies between 5.5 and 8.5 for anaerobic digestion process, pH less than 5 will lead to acidic condition and higher than 8 makes solution basic due to increase of amount of ammonia.

vi. In totality, the performance efficiency of the anaerobic reactor for any kind of co-digestion of bio waste depends on, types of waste, place of sampling, characteristic of waste, methods of AD process, C/N ratio, organic loading rate, hydraulic retention time, volatile solids, volatile fatty acid, total ammonia nitrogen, temperature of reactor, p^H, mixing,

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