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A review on the Optimization of Biogas production through Anaerobic Co-digestion of Biomass

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Abstract— ***Over the years, Anaerobic Co-digestion has emerged as a particularly convenient and efficient technology for the management and disposal of all types of crop residues, sludge produced from sewage treatments, livestock manure, food waste and other Municipal solid wastes, etc. Apart from saving a ton of cost, time and enhancing biogas yield, this process has a long list of other advantages like improved nutrient balance, stabilized digestion process, increased buffering capacity of the system, optimized biodegradability and generation of organic fertilizers, etc. Since biogas fuel is an excellent source of renewable energy, this idea can be especially useful for large plants and industries where biogas can be utilized as a source of electricity. This study reviews and summarizes the various kinds of research achievements in the area of Anaerobic Co-digestion of waste with different types of Co-substrates namely, activated sludge from sewage treatment, Fe3O4 nanoparticles, tannery waste, cattle manure, organic waste (vegetable and fruit waste),etc. The study assesses the merits and potential of the Co-digestion process with varying types and proportions of substrates. It also highlights the extent of influence of major factors like Carbon to Nitrogen ratio, inhibiting substances as well as effects of other parameters like pH, temperature and Alkalinity in the digestion Process.***

Index Terms— ***Co-digestion, cattle manure, activated sludge, organic waste, tannery waste, C/N ratio***

I. INTRODUCTION

Anaerobic digestion has proved to be a highly useful and methodical technology for the disposal of sewage sludge, agricultural wastes, food waste (raw and cooked) and livestock manure [1][2].This naturally occurring process offers a number of environmental and economical benefits.AD technology plays a very big role in climate change mitigation by capturing methane gas and reducing greenhouse emissions in the process. The major advantages of the process being the reduction in the amount of waste by digestion and production of renewable energy in the form of biogas. Other than that, there is also an additional benefit that nutrients that are accumulated in the digestion residue can be recycled [3] [4]. Although mono-digestion of wastes has been in practice since the concept of digestion of wastes came into existence but Co-digestion is a fairly new concept. Over the years, it has emerged as a viable and one of the most environment friendly technique to overcome the series of demerits that the mono-digestion process possesses. Co-digestion is usually defined as an activity/operation in which homogeneous mixture of multiple substrates are digested simultaneously. Here, the substrates can differ in range starting from crop residues, municipal solid waste, sewage sludge, animal manure to even food waste. When this co digestion process takes place without the presence of oxygen to recover the bio-energy (in the form of methane and carbon dioxide), then, it is known as Anaerobic co-digestion process.

The Co-digestion of multiple type of wastes not only produces biogas which is an excellent renewable source of electricity but it also solves solid waste disposal and management problems to some extent. It can be achieved by treatment of leftover residues which eventually leads to less amount of disposal in landfills [5][6][7]. Since this process saves a ton of cost, time and as well as enhances the biogas yield, this idea can be especially useful for large plants and industries. Process solid waste and sludge produced in the industry can be treated together and the enhanced biogas production can be used as a source of electricity for the plant. Thus, it can play a significant role in improving overall energy balance of the plant too [8].

Enhanced biogas yield, stabilized digestion and generation of organic fertilizer, etc. are the key reasons behind the increasing popularity of this process in the recent years [9].Other major characteristics of the process are: improved nutrient balance, optimized biodegradability, C/N ratio equilibrium, enhanced process stability and system buffering capacity, etc. leading to enhanced biogas yield [10][11][12][13][14]. The enhancement in the stabilization of the anaerobic process is credited to improved balance of carbon to nitrogen ratio [15][16].Co-digestion of waste also keeps the inhibitory actions of high concentrations of ammonia and sulfide in check, leading to more stable biogas production. Although this process is environmentally sound and efficient in itself but there are a number of factors that need to be taken in consideration while executing or employing this process. These are optimum (C/N) ratio, optimum mixing ratio of used substrates, presence or absence of inhibiting substances as well as appropriate pH, temperature and Alkalinity. Other factors like retention time and loading rate also play a particularly important role in the process. Relative proportions of proteins, lipids, carbohydrates, and cellulose in the waste also largely affects the potential for biogas production [18].

Objective of the present study is to review and summarize important research studies that have been performed on Anaerobic Co-digestion of solid wastes for enhancing the biogas yielding process. The effect of varying type and proportions of co-substrates like waste activated sludge, tannery waste, cattle manure and food waste have been studied here. The present paper also focuses on the role of the Fe3O4 nanoparticles in the enhancement of the biogas generation during the anaerobic co-digestion process. Moreover, this study also highlights the effects of the major parameters like (C/N) ratio, inhibiting substances as well as pH, temperature and Alkalinity, etc. on the Co-digestion Process.

II. Anaerobic Co-Digestion Of Municipal Solid Waste And Fruit And Vegetable Waste For Enhanced Biogas Production

A/c to Khalid et al., mono-digestion of Organic fraction of Municipal Solid waste (OFMSW) faces many shortcomings like long stabilization time, low rate of production of biogas as well as low removal efficiency of Volatile solids removal [14]. Scano et al. noted that during mono-digestion of fruit and vegetable waste (FVW), the high simple sugars present in it create major hindrance in the methanogenic activity, resulting in decreased biogas production [18].

Miranda et al. studied co-digestion of OFMSW (Substrate 1) and FVW (Substrate 2).OFMSW and FVW were collected from residences and Supermarket of São Leopoldo city, Brazil, respectively [19]. Anaerobic bio-digestive sludge was selected as inoculum here. It was collected from an anaerobic digestion plant (experimental) operating under mesophilic conditions (35°C). The anaerobic bio-digestive sludge used in this study had high alkalinity (bicarbonate), high pH as well as high buffering capacity.

Glass reactors having working capacity of 2 litres were employed for conducting the experiment in 4 batches. 4 different ratios of substrates i.e 1/0, 1/1, 1/3, and 0/1 were tested. Using previous studies, the substrate to inoculum ratio was adopted as 1/1 here.

The mixture ratio and S/I proportion both were based on the Volatile solids. Also, the mass of VS added to the reactors at every stage of the experiment was same. Water displacement method was employed to find the amount of biogas production. Daily, 50 ml digestate was collected for the analysis of pH while about 100 ml of digestate was collected for the analysis of other constituents like ammonia, total solids, etc. Similarly, for evaluating the percentage of methane present in the biogas produced, 300 ml of biogas was collected in the sampling bags, daily. For each batch, in total 9 samples were collected.

Literature reported that on comparison of Co-digestion results of methane generated to that obtained in the mono-digestion of the substrates, an average increase of 141% and 43.8% can be noted, respectively. Out of the 4 ratios, the optimal performance was recorded at 1/3 mixing ratio of the substrates (VS basis).This ratio recorded an optimum biogas yield of 433.9 N mL/g and an optimum methane yield of 396.6 N mL/g. The observed optimum Volatile Solids removal rate was 54.6% [19].It was further concluded that Carbon to Nitrogen ratio ranging from 30.5 to 34.7 provided the most optimum condition for this co digestion. The Inoculum provided much needed stability to the whole AD process for the substrate ratios. Also, no hindrance was observed in the methanogenic activity due to the undesirable accumulation of Volatile Fatty Acids.

III. ANAEROBIC CO-DIGESTION OF CATTLE MANURE AND FOOD WASTE FOR ENHANCED BIOGAS YIELD

Food waste is one of the most frequently used feed stocks for AD processes due to their great potential for producing methane [20].Despite that characteristic, it is difficult to biodegrade food waste through AD processes [20][21][22].Reason being the presence of the long chain fatty acids which causes hindrance in the acetogenic and methanogenic activities during AD process[23]. Similarly, mono digestion of cattle manure is also found to be a unstable process. Although, here the culprit is low Carbon to Nitrogen ratio [2].Therefore, it is absolutely necessary to overcome the deficiencies of mono-digestion by adopting an alternative and more efficient approach for the digestion process of substrates.

Talking about the present study, C. Zhang et al. aimed to assess the performance of anaerobic Co-digestion of food waste and cattle manure and to identify the major parameters that influence the rate of biogas generation [26].Cattle manure was obtained from a farm situated in Shandong province at Zaozhuang while the Food waste was obtained from the mess of the Beijing University of Chemical Technology. After manually selecting the organic substrates of the food waste, they were grinded into small sizes of 3mm or less. Anaerobically treated activated sludge was used as an inoculum in both digesters. The sludge was acclimatized in a 20 litre tank for about 14 months, under laboratory conditions.

To understand the differences in operating mechanism, results and affecting factors of mono-digestion and co-digestion processes, tests were done by varying proportions of substrates i.e Food waste and cattle manure. AD tests were done under mesophilic conditions (35 ± 1 ^{0}C) in both batch and semi continuous mode, in 1 litre glass digesters (effective volume = 0.8 l)). In batch tests, item units were named between R1 to R7 in which R1 to R3 were used for Co-digestion while R4 to R7 were used in mono-digestion. Similarly, for semi-continuous tests, item units were named between R8 to R16.In the co-digestion process, food waste was kept as the constant substrate whereas cattle manure was selected as the variable substrate.

Water displacement method was adopted for collection of biogas while gas chromatography (GC) was employed for determining the methane and carbon dioxide content in the biogas samples. The physicochemical analysis of the substrates was done as per the standard methods i.e APHA, 1998 guidelines. Kjeltec Nitrogen Analyzer and TOC analyzer was employed for determining total nitrogen and total carbon, respectively.

A. Batch tests:

When compared to Co-digestion units, lower rates of methane generation were examined in mono-digestion units. Total biogas production saw a significant enhancement of 41.1%, 13.9% and 4.0%, for the co-digestion units of R1, R2 and R3, respectively. The highest biogas yield was reported to be in digestion R1 (Co-digestion unit) which had the substrate ratio of 2 and Carbon to Nitrogen ratio of

15.8[26].Zhang et al.'s reported optimum Carbon to Nitrogen ratio matches to a great extent with the previous studies of some other researchers who obtained optimum C/N values of 15 [24] and 13.9– 19.6, respectively [25].Literature also reported that the trace elements in cattle manure play a significant role in improving the efficiency of the digestion process and aid in pH recovery of the system too. It does so by improving the methanogenic activity of the digestion system.

B. Semi-continuous mode tests:

Literature reported that methane yield could be enhanced by addition of cattle manure in this mode too. Corresponding to the Loading rate of 8 and 10 g VSFW/L/d, the total methane generation in Co-digestion was enhanced by 52.7% and 55.2%, respectively [26].Higher final pH, higher Volatile Fatty Acids generation and also, higher concentration of ammonia was observed in the effluent of the digestion system.

Thus, it can be interpreted from the results that, for attaining maximum biogas and methane yield, Co-digestion of the substrates required an optimum substrate ratio of 2 and an optimum Carbon to Nitrogen ratio of 15.8. The total methane yield saw a significant increment of 41.1% corresponding to a methane yield of 388 mL/g of Volatile Solids [26]. From the literature, it can be concluded that higher biodegradability of lipids and Optimum C/N ratio are one of the prime contributors for optimizing biogas and methane production during the digestion process. Furthermore, addition of cattle manure to the food waste enhanced the buffer capacity of the digesters and increased the stability of the anaerobic system.

IV. ANAEROBIC CO-DIGESTION OF TANNERY SOLID WASTES FOR ENAHNCED BIOGAS GENERATION

Cinar et al. revealed in his research studies that addition of primary sludge and waste activated sludge during co-digestion process boosts the stabilization process of solid waste [27].

In India, many industries face dual issues of managing both types of waste i.e solid waste generated at the end of every process and sludge produced from the effluent treatment plant. Tannery is also one of those industries.

Kameswari et al. did a study on the importance of optimization of mix ratios of substrates. The substrates in question were fleshing (F) solid waste and Primary (PS) and secondary sludge (SS) generated during tannery wastewater treatment. She also discussed the role of residence time in this co-digestion process for enhancing biogas production [8]. Fleshing residues have no potential of being reused or recycled, thus, disposal is the only option to deal with these nitrogen rich materials.

Author's main concern for the study was to provide solutions to make the waste management process more economical, feasible and less investment intensive for the tannery industries. Fleshing (F) are basically solid wastes collected at the end of each fleshing operation in the tannery. F, collected from a nearby commercial tannery is then cut into small pieces of dimension so that it can be fed into the reactor. Both the samples i.e of Inoculum and Primary and secondary sludge have been collected from the city of Chennai, India. Sludge samples have been obtained from an effluent treatment plant of a tannery while the inoculum was collected from an anaerobic digester operating for the treatment of domestic sewage.

This study consisted of 20 experiments in which each of the experiment is designed on the basis of the amount of wastes generated (Fleshing, Primary sludge and Secondary sludge) for processing 1 ton of raw skin to finished leather. In all these experiments, PS and SS ratio has been a variable while F proportion has been kept constant.

Physicochemical properties of inoculum and substrates were determined as per the Standard Methods of APHA, 1998 manual. Elemental Analysis was adopted for obtaining the empirical formulas and C/N ratios of the same. Mshandete et al. (2004) stated in his study that AD can be an appropriate option for these types of wastes which have low C/N ratios but are rich in nitrogenous substances [28].

Co-digestion studies were carried out by varying 10 different proportions of substrates to find the optimized proportion which has the potential to give the highest methane yield and highest percentage of reduction of Volatile solids. For these various mix ratios of substrates, VS inputs ranging between 5 to 12 grams and TS inputs varying between 8 to 21 grams were studied. Hydraulic Retention time of 50 days was adopted for this whole study. The results of experiment showed optimum biogas generation of 385 mL/g of VS added. This optimum biogas yield was obtained for the substrate mix ratio of 1:2.7:0.3 and for the residence time of 50 days [8].

Table 2
Characteristics of the materials used

Type of waste or Substrates	Amount quantity generated (kg)/tonne of raw skin processed
F	150
PS	88 to 123
SS	179 to 236

Table 3

Materials used	pH	VS
F	11-12	0.65–0.85 g/g
PS	8.1-8.6	19–49 g/L
SS	7.3-7.7	8–30 g/L
Inoculum	7.3-7.8	24-43 g/L

With careful analyzation of results, it was observed that the composition difference of Primary and secondary sludge was hugely affecting biogas generation. Increased proportion of Secondary sludge was causing reduction in the biogas yield while on the contrary, increased proportion of primary sludge was enhancing the biogas yield and was aiding in VS reduction as well. Although retention time of 50 days was adopted in the experiment but based on results, literature reported that a retention time of 45 days was enough for the digestion of this industry waste. From the literature, it can be concluded that co-digestion of tannery solid wastes can be an economical and environment friendly alternative because not only it saves a ton of time and space for treating the waste but it also improves the overall energy balance at the plant [8].

V. ENHANCEMENT IN THE BIOGAS PRODUCTION FACILITATED BY FE3O4 NANOPARTICLES

Over the years, nanotechnology has emerged as one of the most sought after fields in the area of research. There are wide applications of nanoparticles in various fields of study e.g engineering, biological treatment and medical field, etc. As per the previous studies, the Fe metal when combined with other metals is considered to be very effective for AD of the waste. Not just that, it also plays an important role in the synthesis of the methanogenic enzyme of any organic matter. The addition of the Fe significantly reduces the formation of volatile fatty acids (VFA) [29][30]. In the last few years, Fe3O4 nanoparticles have been part of profound number of researches because of their unique characteristics like catalytic properties, super magnetic behaviour, high surface to volume ratio and exceptional electronic properties [31]. Literature also reported that Fe3O4 nanoparticles can be easily recovered from the reaction medium because of their magnetic properties [32]. The present reviewed research article investigates the effect of the bio-compactable functionalized Fe3O4 nanoparticles on anaerobic digestion of organic portion of the municipal solid waste and on the metabolic activities of anaerobes. The hydrothermal method is used for the synthesis of the nanoparticles and approximately four different concentrations have been employed in each duplicated lab batch test. The mesophilic range of the temperature has been set.

The test results indicate:

1) Hematite based Fe3O4 nanoparticles in the AD enhances the methane gas generation by the enzymatic activities of the methanogenic bacteria.

2) Highest methane production is observed at the concentration of 50mg/l and 75 mg/l [33].Higher concentrations reduced the methane gas production.

3) There is a uniform distribution of the Fe ion in the solution due to the presence of the nanoparticles. Nanoparticles are responsible for the continuous supply of the iron ions in the bioreactors and for enhancing the methane production by stimulating the anaerobic digestion [33].

VI. IMPROVEMENT IN THE BIOGAS GENERATION BY ADOPTING BIOLOGICAL PRE-TREATMENT FOR CO-DIGESTION OF WASTE ACTIVATED SLUDGE AND FOOD WASTE

Every year, large quantities of food wastes (FW) are being generated at an increasing rate [35] [11]. There are environmental and health issues concerning the uncontrolled disposal of this food waste [20] [36]. Anaerobic degradation of waste is probably one of the cost-effective methods for solving this problem. Reason being the potential of the process to help in biological energy recovery [37] [38]. In the anaerobic digestion of FW, biogas is produced from decomposition of organic components of the waste like fats, proteins, and lipids, etc. There are many plants that are currently working on anaerobic mono-digestion of food waste. Most of these plants are operating at relatively low efficiency because of the various shortcomings of the mono-digestion process. Some of those demerits are as: nutrient profile imbalance, collection of volatile fatty acids (VFAs) and inhibition of Anaerobic digestion product [26]. To solve this issue, waste activated sludge is used as a co-substrate with food waste. It enhances the buffering capacity of the system by releasing NH4+, Na+, as well as adjusts the nutrient availability (C/N ratio)[39][40]. However, conversion of the particulate organic matter into soluble substances by hydrolysis of WAS is still a step which limits the rate of the AD process [41] [42]. Furthermore, positive impacts of WAS as co-substrate is limited on the enhancement FW digestion due to the extent of solubilization and WAS acidification. Hence to overcome this shortcoming, many pre-treatment technologies have been applied like thermal, ultrasound, chemical and thermochemical, etc. [43][44][45] to degrade the WAS and thus, enhance the solubilization efficiency. Not much research has been done on the co-pretreatment of the WAS with food waste before anaerobic co-digestion. Hence, nearly, 80 doubts are found in the literature on the improvement of the performance of the co-digestion of substrates, if hydrolysis is used concurrently. As per the study, the biological solubilization process is effective for the pretreatment of FW [34].During this process, particles of the substrate get reduced and solubilization is enhanced before the anaerobic digestion [46]. However, during hydrolysis of sole FW substrate, pH gets reduced sharply because of the VFAs accumulation and due to the low pH (<5).This will cause a negative impact on the hydrolysis and acidogenesis activity [47]. In comparison to the sole FW, the hydrolysis of the WAS is an alkali process [48] which is not even beneficial for the hydrolysis of WAS. Therefore, to improve the performance of the hydrolysis, WAS and FW have been used as the co-substrate here.

There are two basic reasons for the co-digestion of the FW and WAS:

1) WAS is an alkali process and produces alkali which can be used to buffer VFAs and can also provide an optimum pH for the hydrolysis process. 2) Low pH is useful for improving the WAS solubilization [49].It is also pretty much clear that enhanced efficiency of hydrolysis of the substrates can also improve the methane production in the subsequent anaerobic digestion.

Therefore, to make this concept clear, biological pre-treatment of the FW and WAS has been reviewed from the past study and result is obtained as:

1) This process improved the efficiency of the hydrolysis and acidogenesis of the substrates.

2) Co-pretreatment of the FW and WAS enhanced the methane yield by 24.6 % and also decreased the percentage of VFAs by 10.1% [34].

3) This method enhanced the synergy between FW and WAS through which efficiency of the subsequent anaerobic digestion process can be enhanced.

VII. CONCLUSION

Anaerobic Co-digestion has a positive impact on the process efficiency (i.e. yield of biogas and degree of degradation of the treated waste) and stability of the whole digestion process. Addition of optimized proportions of the substrates along with optimum C/N ratios in the Co-digestion heavily enhances the biogas generation and also overcomes the various shortcomings of the mono-digestion process. Other advantages of the process include: subsequent dilution of potential toxic compound, increased rate of biodegradation as well as enhanced balance of nutrients in the digestion system. The study made the following conclusions for each combination of Co-digestion of substrates:

a) In contrast to the mono digestion of organic fraction of municipal solid waste (OFMSW) and fruit and vegetable waste (FVW), the methane production in the co-digestion process increased by 141% and 43.8% ,respectively. This increase was observed at an optimum C/N ratio of 1/3. Moreover, volatiles solids reduced by 54.6%.

b) The methane production was enhanced by 41.1% at an optimized mix proportion of 2 for Food waste and Cattle Manure. Co-digestion with cattle manure increased the buffer capacity in the digester and contributed to more stabilized .Anaerobic digestion process which allowed the high organic load without pH control.

c) Enhancement by Fe3O4

Nano Particles(NPs): The methane production is much higher when the concentration of the NPs is 50 mg/l and 75 mg/l, as compared to the methane produced at NPs concentration of 100 and 125 mg/l. NPs also proved to be effective in uniform distribution of iron particles in the solution and biostimulating the anaerobic digestion.

d) Biological co-pretreatment process enhanced the performance of anaerobic co-digestion process by improving the process efficiency of hydrolysis and acedogenesis of the substrates i.e Activated Sludge and Food Waste, for methane production. Methane yield increased by 24.6% and 10.1% increasment was observed in the VS reduction.

In the Co-digestion of Tannery solid waste, composition difference of Primary and secondary sludge and residence time significantly affected the biogas generation. Optimum biogas yield of 385ml/g of Volatile Solids was obtained for the substrate ratio of 1:2.7:0.3 and for the residence time of 45 days.

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