International Journal of Engineering Trends and Technology
ISSN: 2231 – 5381 /doi:10.14445/22315381/IJETT-V68I12P202
Volume 68 Issue 12, 10-15, December 2020

Biomethane Production by Dry and Continuous Anaerobic Digestion of Food Waste in a Pilot-Scale Plug-flow Digester Maintained at Thermophilic Conditions

Narayana Swamy G[1*], Nageswara Rao T[2], Venkatesh. G. S[3]

[1]*Research Scholar &Assistant Professor,*

[3]*Professor & Programe coordinator (CAE),*

[1,3]*Department of Mechanical Engineering, VTU-CPGS, Visvesvaraya Institute of Advanced technology, Muddenahalli Chikkaballapura, Karnataka 562101, India.*

[2]*Professor & Head, Department of Mechanical Engineering, GITAM School of Technology Bengaluru campus, NH 207, Nagadenehalli, Doddaballapur Rd, Bengaluru, Karnataka 561203, India.*

[1]narayanaswamyg@vtu.ac.in

Abstract - *Dry and continuous anaerobic digestion of organic waste is a globally promising process of waste management. Researchers have carried out numerous researches on Anaerobic Digestion (AD), which are limited to laboratory scale. Very few attempts were made on a large scale and pilot scale. There is no much data on the long term operation of Pilot-scale plug-flow anaerobic digester under thermophilic conditions in terms of the operational parameter's feasibility and stability. The objective of the study is to maximize anaerobic digestion to manage food waste effectively. In connection with a single-stage plug-flow anaerobic digester (PFD), it was designed and developed as a pilot-scale model and studied. To actuate the digestion and acclimatize the reactor, fresh food waste (FW) is co-digested with cow dung and previous digestate with an inoculum ratio of 2:1:1. The digester operated with different organic loading rates ranging from 2.4 to 12 with a fixed total solid concentration of 22.3% and Hydraulic Retention Time from 64 to 16 days. The Maximum biogas yield of 0.9144 m^3 was observed at an organic loading rate of 7.5 kg VS/m^3.day.*

Keywords — *Dry continuous anaerobic digestion, organic loading rate, Volatile Solid reduction, Plug flow Anaerobic Digester, Thermophilic Dry fermentation.*[1]

I. INTRODUCTION

Food waste (FW) is that left uneaten or superfluous. It is not only after the chain but also at the beginning from the time of making, trading, and consumption. According to the United Nations Food and Agriculture organization, 1/3rd of the global food production wasted in a year is a prominent municipal solid waste generation [1]. Close to 31 million (70-75%) of trash dumped into landfill sites costing the world economy $750 billion annually. A shocking report on food wastage has revealed that India wastes 67 million tons of food every year, and India ranks 7th globally. The metropolitan city's contributions are high viz Mumbai 9400 metric tons, Delhi 9000 metric tons, Chennai 6404 metric tons, Kolkata 12060 metric tons, and Bangalore 6233 metric tons and remaining from all other cities. With these high numbers, the country's current systems are unable to cope with the burden. Subsequently, it leads to environmental pollution and health issues. Open landfilling is a non-scientific way of disposing of the waste, which spoils the soil and groundwater and pollutes the air.

Food Waste has been recognized as an alarming threat to the well-being of humans and also the surroundings. It generates many pathogens, pollutants, and contaminants such as organic matter, nutrients, greenhouse gases, and odors if it is not disposed of and handled scientifically [2]. Therefore, FW usage can drastically curtail both operational expenses of FW treating systems and harm to the surroundings. The use of renewable energy increases the financial benefits attain from production and consumption. Anaerobic dry fermentation is an attractive and feasible way to treat FW since it transforms biodegradable matter in food waste into methane-rich biogas [3]. Food Waste is rich in organic

[1] This research work supported by grants from the Ministry of Science and Technology, Govt. of India under (Project No.: SB/EMEQ-337/2014) by Science and Engineering Research Board, Department of Science and technology.
*Corresponding author. E-mail address: narayanaswamyg@vtu.ac.in
Contact no: +919481372504, +919448212106

content, and it is a promising source of raw material for methane generation through Anaerobic Digestion. However, the AD of FW has functional limitations associated with features of Food Waste, such as lower pH, lower alkalinity content, Lower methane (CH4) produce, and operational instabilities are the frequently occurred uncertainties in Anaerobic Digestion [3], [4]. A large variety of inhibitory materials are prime reasons for AD's failure because of the presence of essential concentrations [5]. The operational limiting factors such as pH, temperature, digestor configurations, OLR, and HRT [6], are examined for different digestion systems and reported as one of the significant variables which affect microbial activity and characteristics in continuously stirred tank reactor (CSTR) [3]. In the mesophilic anaerobic co-digestion of enacted slop, fruit, and vegetable waste in a two-phase batch process, acidogenesis [6], and methanogenesis CSTR [7], accomplished stable AD at a stacking rate of 5.7 g VS/L d, overall HRT of 13 days (3 days Acetogenic HRT and 10 days methanogenic HRT), with 40% reduction in Volatile solids (VS) and 0.37 m^3/kg of process biogas yield, per kg of VSadded [6], [8].

Among many operational parameters, pH is the most sensitive to environmental conditions. The system is stable or not is measured based on the pH of the effluent discharged from the reactors, and its imbalance is determined by the buffering ability of the AD [5]. In higher OLRs, Lower pH and alkalinity of Food Waste debilitates the buffering limit and the digesters' operational steadiness [3]. Inadequate trace elements that blend necessary enzymes involved in the methanogenic reaction were reported as a primary reason for failure in anaerobic digestion of food waste. Volatile solids represent the organic matter in the feedstock that is biodegradable, while other remnants of the organic matter are treated as fixed, which are imperishable. The practical OLR relies upon the kinds of waste fed into the digesters. Food waste is bio-degradable with ease and has high energy potential per dry mass. However, it has a lower total solid (TS) with a higher feasible organic substance [5]. Aggregation of additional alkali and Volatile unsaturated fats (VFAs) increases as TS content in FW increases. Co-processing of FW with lignocellulosic biomass and two-stage fermentation used to resolve these problems [9], [10], the increased OLR reduces the VS loss and biogas generation, utilized fruits and vegetable waste in a digestor at a loading rate of 1.6 kg VS/m^3day, and informed the highest biogas yield of 0.47 m^3/kg.VS, with 88% VS loss [5]. Anaerobic digestion of FW had an average methane yield of 435 mL/g VS after 28 days of dry fermentation at thermophilic conditions at 50± 2 oC [11], and around 80 % of the methane produced in the initial 10 days. Co-digestion of dissimilar substrates can be an advantage due to the reduction in toxic chemicals and the improved firmness of nutrients in the cumulative effect of microbes [5], [12]. Various researchers have carried out extensive research on Anaerobic Digestion, which is limited to laboratory scale. Very few attempts were made on a large scale and pilot scale [25]. On date, there is not much data available on the long-term operation of Pilot-scale plug-flow anaerobic digester under thermophilic conditions in terms of the operational parameter's feasibility and stability.

Therefore, an attempt was made in this work to (1). Study the performance of PFD for dry and continuous anaerobic fermentation with thermophilic conditions of Food Waste under variable organic loading rates (OLR) that were augmented in various steps ranging from 2.4 to 12 kg VS/m^3day with a constant TS concentration of 22.3% [1]. (2). Effect of OLR on the Volatile Solid (VS) reduction. (3). Effect of OLR on biogas generation for different HRTs (4) effects of alkalinity and pH on dry and continuous AD [14].

II. METHODOLOGY

A. Features of Food Waste (FW) and inoculums

Solid wastes from the canteen utilized as feedstock for the PFD, which contains cooked food waste and vegetable waste collected in a bin. After sorting manually, the biodegradable wastes are crushed into an average size of 6 mm by using the shredder. Smaller the size increases the surface area and the hydrolytic reaction, which inhibits methane generation in anaerobic fermentation. Food Waste was blended with the previous digestate to boost the startup phase and fed into the digester. An inoculum source is a critical functional parameter, which is vital in selecting waste to inoculum ratio and the estimation of anaerobic biodegradability of solid wastes. To actuate the anaerobic digestion process and acclimatize the reactor, the constituents of inoculum cow dung, digestate material, and FW were mixed in the ratio 2:1:1, and the motive behind utilizing these blends is to build the assorted bacterial variety within the reactor to improve C/N ratio [15], [16], [17]. Organic waste characteristics, such as Moisture content (MC), Total Solid (TS) content, Volatile solids content (VS), Total chemical oxygen demand (TCOD), and Carbon Nitrogen ratio of the Food Waste and inoculum were shown in TABLE-I.

TABLE-I
ORGANIC MATTER CHARACTERISTICS OF FW AND INOCULUM

Parameters	pH	Moisture content (MC) %	Total solids (TS) %	Volatile solids (VS) %	TCOD mg/kg	C/N ratio
Food Waste	5.34	77.7	23	81.5	220350	22
Inoculum	7.8	80.07	19.53	11.5	71850	--

B. Experimental setup and feedstock preparation

A single-stage Plug-flow anaerobic digester (PFD) operated at different organic loading rates (OLR) to regulate the biogas generation and study the functional variables selected as per designed organic loading rate and hydraulic retention time. It comprises stainless steel inner tank of 1000 mm diameter and 2000 mm length Fig. 1(a), and the inner tank is concentrically covered with mild steel outer layer and 20 mm thick rock wool in-between. The rock wool provides thermal insulation by preventing heat loss to the surroundings. To maintain the PFD temperature to thermophilic conditions, in the inner side of the digester, a steel tube is attached helically throughout its length. Furthermore, to maintain the center's temperature, a stainless-steel tube is extended with hollow protrusions on its surface, as shown in Fig. 1(b), and it is attached to the cylinder with a bearing, which also works as a stirrer for mixing the digestate.

(a)

(b)

Fig. 1. (a). Assembled picture of the PFD system (b) Inside view of the digester.

Plug-flow digester is also fitted with other accessories such as geyser to enable convective heat transfer by circulating hot water to maintain thermophilic conditions and flow meter to measure the biogas obtained. An inlet pipe is attached to the top of the tank at 1700 mm from the base to load feedstock through a progressive pump connected to a 300 L hopper. Two Outlets are provided, one at the bottom to remove the digestate without air intrusion, and another one connected to a $7m^3$ biogas storage balloon. The PFD is mounted on a mild steel stand, at an inclination of 38° to ensure smooth loading of feedstock and ease of digestate removal as shown in Fig. 1(a). Circulation of food waste, water, and the gas produced is carried through PVC pipes by a progressive screw pump, a geyser, a pressure booster pump, and a compressor.

Initially, PFD was loaded with 600 kg of cow dung, 300 kg fresh FW, and 300 kg of digestate to reach 3/4th of the actual digester volume with an inoculum ratio of 2:1:1 [18], as per previous studies with some modifications. Homogenization of inoculums and FW is done before loading into the PFD [19], [20], [21].

The PFD is run in batch mode for eight weeks as a startup procedure under mesophilic conditions (32°C) to acclimatize the population of microorganisms and rescue them from thermal shock. Subsequently, the temperature is gradually increased to 5°C until it reaches thermophilic conditions (55°C) [2]. Once the AD reaches stability by attaining the methanogenic phase, daily and cumulative biogas productions are noted for a hydraulic retention time of 100days. Subsequently, the compositions were analyzed. It is clear from the results that a lower pH value (below 6.0) indicates the accumulation of volatile fatty acids, which inhibits the methanogenic activity. Hence carbon dioxide is high in the initial stage due to the captured air within the PFD, and the CH_4 concentration was close to zero in that duration. Ammonium concentration is a vital limiting factor for an anaerobic digester's buffering limit, which is up to 1000 mg/L. To stabilize the pH value, caustic soda (NaOH) is added whenever the system's pH falls below 6.0 [22]. High methane yield was achieved from anaerobic digestion when input digestate was maintained with a pH range of 6.8 - 7.4 [23]. The PFD is operated with various organic loading rates (OLRs) once it reaches steady and stable conditions. OLR varied gradually from 2.4 to 7.2 $kgVS/m^3day$ at a constant total solid concentration of 22.3% allied with hydraulic retention time (HRT's) from 64 days to 22 days, respectively. Summary of the AD process strategies and operational parameters shown in TABLE-II.

TABLE-II
ANAEROBIC DIGESTION PROCESS STRATEGIES AND OPERATIONAL PARAMETERS

Phase		Hydraulic Retention Time (HRT)	Organic Loading Rate (OLR) kg VS/m^{3}day	Solid Loading Rate (SLR) kg TS/m^{3}day
Phase 1	Startup	100	Batch mode	Batch mode
Phase 2	Run 1(R_1)	64	2.4	3.06
	Run 2(R_2)	32	4.8	6.0
	Run 3(R_3)	22	7.5	8.92

To verify the effects of OLR on the performance of PFD for each Run, various quantities of FW were added to the digester once in the daytime for the entire duration. The OLR's, are kept at 2.4 ± 0.88 kg VS/m^{3}day for R_1, 4.8 ± 0.75 kg VS/m^{3}day for R_2, 7.2 ± 0.62 kg VS/m^{3}day for R_3 and 12 ± 0.36 kg VS/m^{3}day for R_4 with HRTs of 64, 32, 22 and 16 days respectively (TABLE-II). A gradual increment of OLR at the calculated step was done, so it has to transform PFD from Batch mode to continuous mode. Furthermore, at each increment of OLR, continuous monitoring of AD must attain stable results until the designed load.

C. Solid waste characteristics and Biogas composition measurement

The fresh inoculum samples, effluent, and biogas obtained from PFD were analyzed daily during each phase to improve the performance. Digestate sample characteristics were measured by the TS, VS concentration, and pH concentration according to the standard methods [24]. Daily biogas generated is measured with a wet gas meter (Elster BK G 1.6, India), and samples were collected in Tedlar bar sample covers to measure the gas composition (CH4, CO_2, H_2S & O_2) using a biogas analyzer (IRCD4, Beijing shi'an technology instrument co., ltd, China).

III. RESULTS AND DISCUSSION

A. Effect of OLR on the Volatile Solid reduction

In General, this research's outcomes have shown that VS reduction of the AD system increases when the digester is operated with a stable condition, and it is directly proportional to the OLR for all the runs. VS removal efficiency in the PFD after stabilization for the second phase during each run R_1, R_2, R_3, and R_4 was 80.61 %, 76.90 %, 93.92 %, 80.84 %, respectively, as shown in Fig 2.

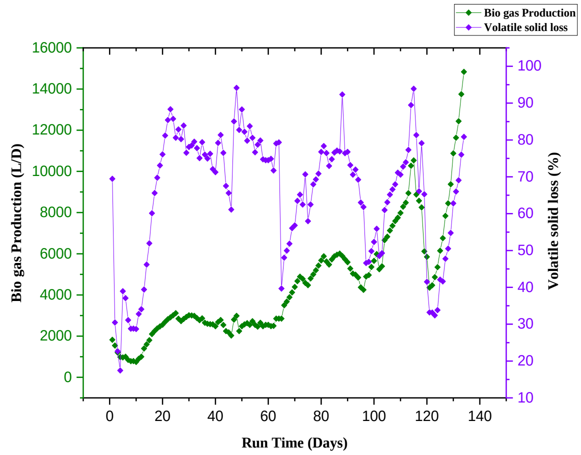

Fig 2. Volatile solid reduction in the digester V/s Organic Loading Rate

Initially, there were fluctuations in VS removal efficiency as the PFD shifted from batch mode in phase1(startup) to continuous mode of operation with different OLR rates. The results show that biogas generated per kg of VS removed, in R_1 is 784.4 liters/m^3, in R_2 is 894.4 liters/m^3, in R_3 is 914 liters/m^3 and in R_4 is 772 liters/m^3.

B. Effect of OLR on biogas generation.

Day wise biogas generation, and the concentrations of Methane (CH_4) and carbon dioxide (CO_2), and biogas produced from PFD under thermophilic conditions, are shown in Fig 3 (a, b). The results show that both OLR and daily biogas production increase linearly in the digester. The maximum biogas produced for each Run was 3112 liters/day for R_1, 6010 liters/day for R_2, 10534 liters/day for R_3, and 14837 liters/day R4, respectively. The CH4 and CO2 concentration for maximum value of biogas produced were 74.2%, 75.2%, 71.5%, 74.5% and 25.8%, 24.8%, 28.5%, 24.5% for Run R_1, R_2, R_3, and R_4 respectively.

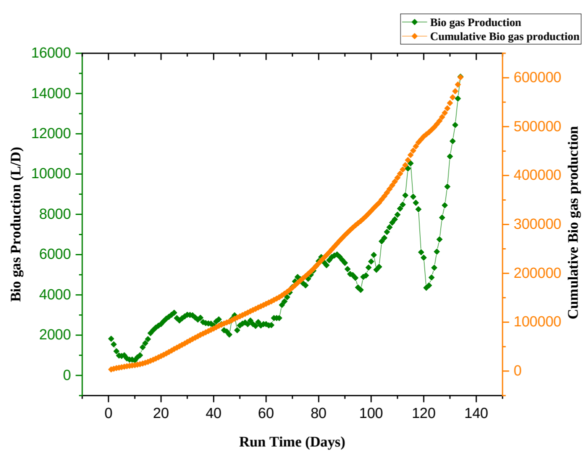

Fig 3(a). Day wise biogas production V/s OLR

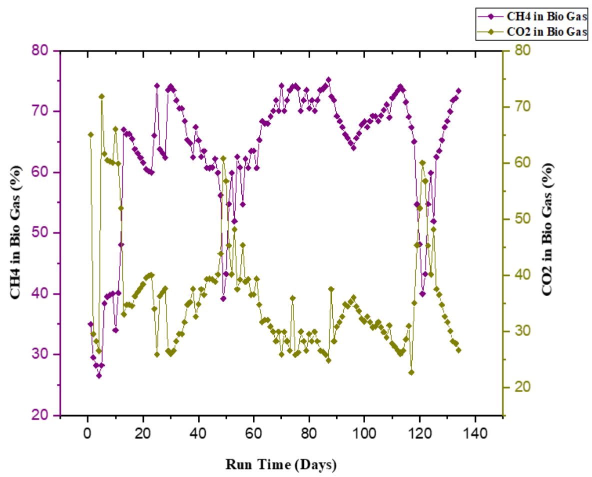

Fig 3(b). CH_4 and CO_2 Concentrations (%) V/s OLR

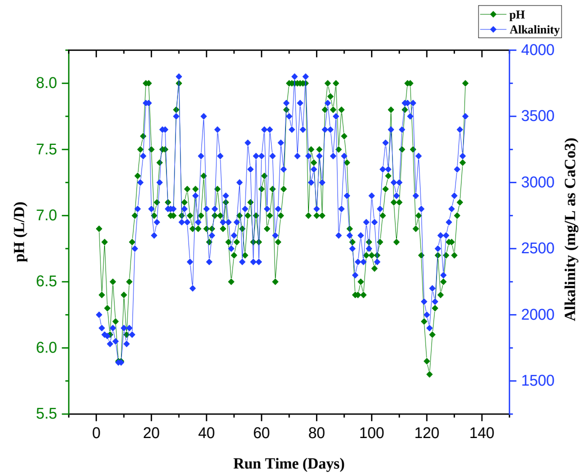

Fig 4. showing variations of Alkalinity and pH with OLR

The increase in CO2 concentration in the initial or any stage of anaerobic digestion shows an accumulation of Volatile fatty acids, which leads to excess acidification in anaerobic digestion of FW, which can be seen clearly in the run R_1. It is because the digester is under transition from a batch mode of operation to a continuous mode. Still, for the run R4, proper mixing is essential so that this problem can be resolved since the VS loading is well within the maximum design load. The CH_4 concentration in the biogas notably raised concerning an increase in OLR, which can be noticed from the average of CH_4 concentration Fig 3(b). The results show that the time required for the PFD to reach a steady-state for each Run was different. Higher the OLR requires more time for PDF to become stable as the anaerobic microbes' time to acclimatize to the transition from acidogenesis to methanogenesis is more.

C. Alkalinity and pH

Alkalinity is an absolute necessity for pH management and aides as a shield that averts a quick variation in pH. It resulted from the release of amines and the generation of ammonia as the proteinaceous wastes were fermented. Anaerobes, especially methanogens, are sensitive to the acid attentiveness inside PFD, and acidic conditions can inhibit their growth. The variations in pH and alkalinity are shown in fig 3.3. Due to Volatile fatty acids (VFA) formation, pH falls below 7.0 in the initial 10.0 days.

The alkalinity was also lower and reached a value of 1640 g/L as $CaCO_3$, the methanogenic microbial activities were slow, and CH4 concentration was found to be less than 50%. The pH of the digestate is enhanced by adding about 1.5kg Sodium hydroxide (commercial Soda, NaOH) on the 4^{th}, 6^{th}, 7^{th}, and 9^{th}day in total. From the 10^{th} day onwards, pH concentrations almost steady then, biogas production was found stable and produced a 3112 L/day value on the 25th day, shown in Fig 4.

As OLR increased from 2.4 kg VS/m^3day to 4.8 kg VS/m^3day, the concentration pH of AD decreases and attained a value of less than 7.0. However, it will remain in a neutral and favorable methanogenic phase and hence Methane concentration is found to be more than 50%. This also looks similar for the run R_3, whereas, for R_4, the pH value falls less than 6.0 and is regulated by volatile acid concentration. During the Run, if the pH falls less than 6.0, then the digester is immediately stopped, and it can be brought back to the stable conditions by adding an alkaline solution (NaOH).

IV. Conclusions

The PFD operated for continuous mode with stable biogas production using food waste as a substrate with a fixed TS concentration of 22.3% and a constant thermophilic temperature of 55°C successfully. Anaerobic digestion process investigated for the valorization of FW with OLR varying from 2.4 ± 0.88 to 12 ± 0.36 kg VS/m^3day and HRT of 64 to 16 days, increasing the OLR enhances the VS reduction. Dry Anaerobic digestion process was most significant during the run R_3 (OLR: 7.2 ± 0.62 kg VS/m^3day) than other runs at HRT of 22 days, and at pH 7.5, the maximum biogas 0.9144 m^3 was produced per kg VS removed with 93.26% reduction in VS, 74.5% CH_4 and 24.5% CO_2 concentrations.

Acknowledgments

The authors are grateful to Visvesvaraya Technological University Belagavi authorities for their support and encouragement for the smooth conduction of the project.

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