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Effect of mixing ratio on biomethane potential of anaerobic co-digestion of fruit and vegetable waste and food waste

Akanksha Vijay Agrawal[1] · Parmesh Kumar Chaudhari[1] · Prabir Ghosh[1]

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Abstract

Anaerobic digestion (AD) is a mature technology for treating organic fraction of municipal solid waste. In the present study, an attempt has been made to evaluate the optimum mixing ratio for co-digestion of two main streams of organic fraction of municipal solid waste (OFMSW) i.e., fruit and vegetable waste (FVW) with food waste (FW) and its effect on biogas yield using single-stage anaerobic digester. The different ratios selected for the study were (FVW:FW) (1:1, 1:2, 2:1). The results indicated that (FVW:FW) in the ratio (1:2) gave the highest cumulative biogas yield (510.96 mL/g VS) in comparison to (1:1) (472.2 mL/g VS) and (2:1) (420.5 mL/g VS) ratio, whereas monodigestion of FVW and FW gave cumulative biogas yield of 429.16 mL/g VS and 393 mL/g VS, respectively. The co-digestion of FVW and FW contributed to the digester's stability, which improved operation of AD and increased biogas production. The methane content in the digesters was increased from 35 to 67% with the time. The co-digestion of FVW and FW at optimal mix ratio yields 21% higher methane content as compared to monodigestion of FVW. Performance analysis indicated a volatile solid reduction of 72% at the optimum mix ratio.

Keywords Anaerobic digestion · Biogas · Food waste · Fruit and vegetable waste · Mixing ratio

1 Introduction

Population explosion coupled with urbanization led to a rise in the global generation of municipal solid waste. At present, the global municipal solid waste (MSW) generation accounts for 1.3 billion metric tonnes annually and it is anticipated to surge multifold to 2.2 billion metric tonnes per annum by 2025 [1]. More than half of the solid waste generated worldwide is consist of the organic fraction of the MSW, known as biogenic municipal solid waste [2]. Fruit and vegetable waste (FVW) and food waste (FW) are major components of the OFMSW and according to the Food and Agricultural Organization [3], up to 15% of fruit and 25% of vegetables are wasted at the end of the supply chain. This results in an annual global contribution of 1748 million tonnes of FVW [4]. India is the world's second-largest producer of FVW; 30–40% of total production is lost at the end of the supply chain each year, costing 1622 million USD. The disposal of the highly biodegradable organic matter into landfill poses serious threat to the environment. On the other hand, anaerobic digestion (AD) appears to be the promising technology for effective management of this huge quantum of waste with generation of the bioenergy and nutrient recovery. Therefore, this huge quantum of the waste can be utilized to combat the global energy crisis owing to its rich composition of carbohydrates, protein, and lipids [5]. AD is a series of biochemical reactions that breaks down the complex organic matter in an anaerobic environment and produces biogas and digestate that can be utilized as fertilizer. In the last decade, various researchers have tried to explore the challenges and process optimization for the smooth functioning of AD. AD is carried out in the four subsequent phases such as hydrolysis, acidogenesis, acetogenesis, and methanogenesis. However, separating the different microbial communities at different phases and providing them the optimal conditions can boost AD performance and reduce the limitations associated with the anaerobic digestion of organic waste [6]. Monodigestion of FVW is challenging due to the presence of simple sugar that often results in quick acidification of the biomass resulting in inhibition of the activity of methanogenic microorganism [7, 8]. Furthermore, a high carbon to nitrogen ratio of FVW leads to depletion of the nitrogen content in AD which necessitates the addition of the co-substrate such as

✉ Akanksha Vijay Agrawal
ava310387@gmail.com

1 Department of Chemical Engineering, National Institute of Technology, G.E. Road, Raipur, India

kitchen waste, anaerobic sludge, and agricultural waste [9]. This will also reduce the impact of the excess volatile fatty acid formation and enhance the process stability. A few advantages of the co-digestion technique include cost savings by digestion of several waste streams simultaneously in a single facility, thus enabling efficient use of equipment [10]. The co-digestion of FVW along with anaerobic sludge has improved biogas yield and facilitated the use of high organic loading rate (OLR), thereby improving the process economy [11–13]. FW can be an ideal substrate for anaerobic co-digestion owing to its higher moisture content, high nutrient availability, and high biodegradability [14]. Furthermore, FW is available in abundant quantity as approximately 40% of the food that is produced ends up in municipal waste [15]. Previous studies showed that when compared to other organic waste, such as yard waste, paper, and mechanically sorted MSW, FVW has a higher methane production [16]. Lin et al. [17] reported a higher methane production (0.49 m^3 CH_4/kg VS) for co-digestion of FVW along with FW for a mixing ratio of 1:1. According to Pavi et al. [5], co-digestion of the FVW with the organic fraction of municipal solid waste resulted in higher methane production as compared to monodigestion of OFMSW and FVW. Callaghan et al. [18] demonstrated co-digestion of FVW with cattle slurry and chicken manure, and they pointed out cattle slurry as a more suitable feedstock compared to chicken manure. This enhanced the methane yield from 0.23 to 0.45 m^3 CH_4 kg^{-1} VS. The exploration of the ideal conditions for the anaerobic co-digestion of FVW and FW has received very little interest. Hence, the present study aims to evaluate the impact of the mixing ratio on the anaerobic co-digestion of FVW and FW for methane generation as optimizing the process parameters is very essential for increasing biogas production. The amount of methane produced by the co-digestion of FW and FVW was also compared to that produced by the monodigestion of FW and FVW in our present investigation.

2 Materials and methods

2.1 Materials

2.1.1 Fruit and vegetable waste

Fruit and vegetable waste (FVW) was procured from the local vegetable market which mainly consists of vegetable and fruit waste in the proportion of banana (20%), apple (10%), sapodilla (10%), spinach (10%), cabbage leaves (10%), cauliflower leaves (10%), eggplant (10%), potato (10%), bottle gourd (5%), and ridged gourd (5%). The ratio depicts the quantity of waste anticipated to be generated in the local market. Physical segregation of the waste was done to remove the inert materials such as plastic bags and pebbles. The vegetable and fruit waste were washed repeatedly to remove any dirt particles present. The waste was homogenized into a smooth paste using a kitchen mixer grinder. The substrate was used immediately; however, when not used immediately, it was stored at 4 °C in the refrigerator for its future use [17]. Various physicochemical parameters of the FVW are depicted in Table 1. The mixture of FVW contains a higher concentration of carbohydrate as compared to protein and also the presence of high moisture content of the FVW makes it a potent substrate for biomethanation.

2.1.2 Food waste

Food waste was collected from the Indian Coffee House (ICH) which is located at the premises of the National Institute of Technology, Raipur, India. FW mainly constitutes of rice, chapatti, cooked vegetables, pulses, and salad along with a trace quantity of other miscellaneous food items. The procured food waste was homogenized into a smooth paste using a domestic mixer grinder. Later, the physicochemical characteristics of the FW were determined in a laboratory, represented in Table 1. Proximate and ultimate analyses of the FW were done to evaluate the alkalinity, pH, moisture content, total solids, and volatile solids. Ultimate analysis was done to determine carbon (C) and nitrogen (N).

2.1.3 Inoculums

The anaerobic sludge to be used as inoculum was procured from a pilot-scale anaerobic digester that used a mesophilic regime to process dairy waste at Kharora, district Raipur, Chhattisgarh, India. Degasification of inoculum was done at the laboratory prior to its use in the anaerobic digester to deplete residual biodegradable organic matter and decrease endogenous methane production [19]. The schematic diagram of the digester is represented in Fig. 1. It has an inlet and outlet arrangement for the measurement of the biogas. The digesters were placed in a water bath to maintain the

Table 1 Characteristic of inoculum and substrates (FVW, FW)

Parameter	Units	Inoculum	FVW	FW
pH		7.2	4.85	5.3
Moisture content	%	90	92	85
Total solids (TS)	%	6.56	4.56	13.5
Volatile solids (VS)	% of TS	72	92	89
Alkalinity	mg/L of $CaCO_3$	4100	3700	4000
Total VFA	mg/L	105	80	96
VFA/alkalinity ratio		0.015	0.021	0.024
Carbon	%	32	44	41.23
Nitrogen	%	2.1	2.23	4
C/N ratio		15.23	19.73	10.3

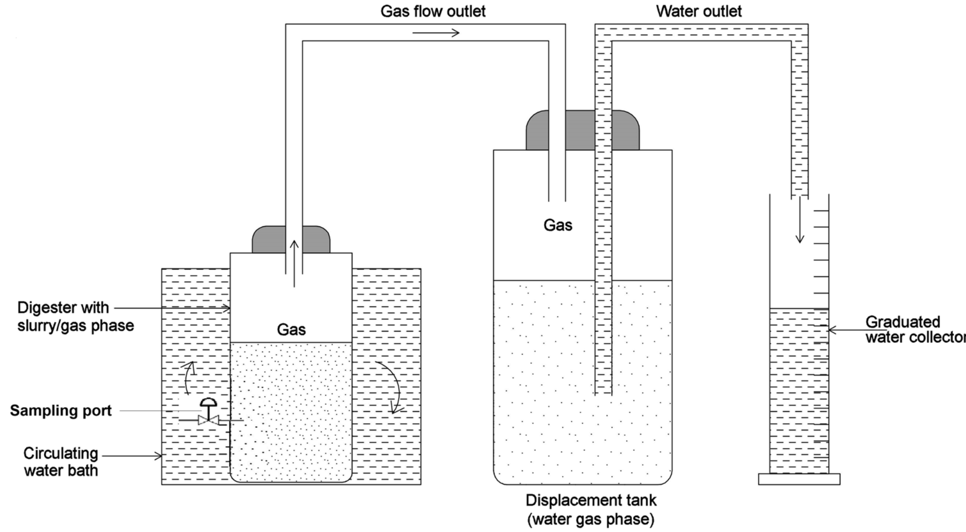

Fig. 1 Experimental setup for anaerobic digestion

uniform temperature of 37 °C throughout the process. Digesters were loaded with the required amount of FVW, FW, and inoculums. The percentage of inoculums was fixed as 20% for all the digesters. To assure anaerobic conditions in the digesters, nitrogen gas was flushed through each digester. Substrates (FVW and FW) were mixed at different ratios (FVW:FW) 2:1, 1:1, and 1:2. Daily biogas yield was measured using the water displacement method until the biogas recorded was less than 1% of the cumulative biogas. All the digesters were operated for hydraulic retention duration of 41 days. About 0.5 g of sodium bicarbonate was added to each reactor as a buffering agent for correcting pH and alkalinity to prevent suppression of the biogas production due to quick acidification, which may occur due to the high biodegradability of the waste [20]. Figure 1 depicts the experimental setup used for the experiment. Gas chromatography (Nucon 5700) with a Porapak Q column and hydrogen gas (H_2) as the carrier gas at a flow rate of 30 mL was used to analyze the methane content of the biogas.

2.2 Analytical methods

The sample was withdrawn from the outlet port for analyzing pH, alkalinity, and VFA as per APHA standard methods (2012).

2.2.1 Proximate analysis

Moisture content, total solids (TS), and volatile solids (VS) were determined according to APHA standard methods (2012).

2.2.2 Ultimate analysis

A CHNS analyzer was used to analyze the percentage of carbon and nitrogen (Thermo Finnigan-Flash EA-1112, USA). It operates on the tenet of the "Dumas method," which involves flash combustion to completely and instantly oxidize the material. After being separated by a chromatographic column, the combustion products like CO_2, SO_2, NO_2, and H_2O are then measured using a thermal conductivity detector (TCD). The TCD output signal is proportionate to the concentration of the different components of the mixture because the instrument has been calibrated with standard gases.

3 Result and discussion

3.1 Daily biogas production

The variation of the daily biogas yield for monodigestion of FVW, FW, and co-digestion of FVW and FW at different mixing ratios for a retention time of 41 days are depicted in Fig. 2. It was observed that the rate of biogas production was not constant for any of the mix ratio, and it varied from high to low for all the ratios. Since the temperature was maintained constant during the entire period of anaerobic digestion, it may be the pH of the digester which triggered the microbial activity. This affects the biogas production as anaerobic digestion is a series of biochemical reaction which involves unique microbes in each phase. Control experiments were performed to assess the biogas potential of the inoculums (without addition of the substrate). The results revealed that maximum daily biogas production from control experiment was 9.13 mL/g VS on day 18 after which it began to decline due to transformation of the easily biodegradable organic waste to biogas. On the other hand, monodigestion of the FVW and FW yielded maximum daily biogas output as 20.56 mL/g VS on day 20 and nearly 79% of biogas was produced in 28 days of HRT. Maximum biogas yield for the monodigestion of FW was recorded as 17.43 mL/g VS on

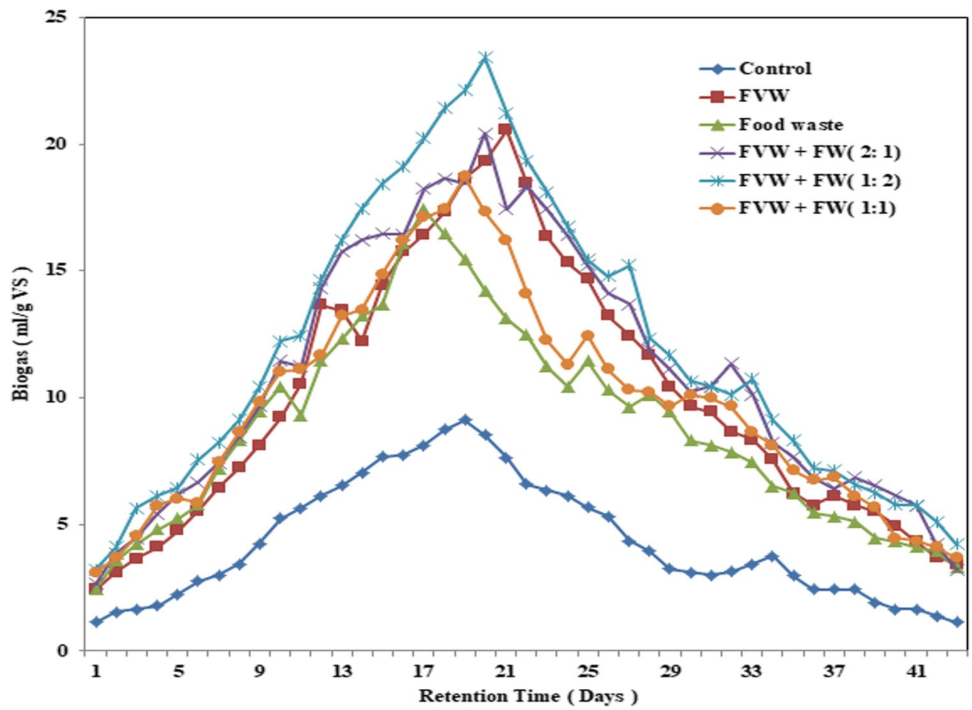

Fig. 2 Daily biogas variation for co-digestion of FVW and FW at different mixing ratios

day 17 and approximately 71% of degradation was achieved during 25 days of anaerobic digestion. Co-digestion of FVW and FW yields maximum daily biogas as 20.43 mL/g VS for (2:1) ratio, 23.43 mL/g VS for (1:2) ratio, and 18.72 mL/g VS for (1:1) ratio, and nearly 74% of bioconversion was achieved during the initial 26 days of operation for all the replicates of the co-digestion. This confirms that the co-digestion of FVW and FW shows a higher yield of biogas as compared to the monodigestion of FVW and FW which is attributed to the balance of the nutrients and increased buffering capacity inside the digester [21–23]. On the contrary, monodigestion of FVW had lower biogas yield than the optimal ratio of co-digestion of FVW and FW. This is due to the presence of high simple sugar which promotes quick acidification and later on inhibits the methanogenic activity of the microbes [7, 8]. To prevent the effect of acidification, FW appeared to be suitable candidate for co-digestion which improved the process stability and maximized biomethane production [5, 17]. Moreover, the effect of severe acidification can also be reduced by using a well-balanced mixture of FVW as some fruits contain low sugars [7, 17, 24, 25].

3.2 Cumulative biogas production

Cumulative biogas production for monodigestion of the FVW and FW and co-digestion of FVW and FW at different mix ratios are depicted in Fig. 3. Cumulative biogas yield for the control experiment was obtained as 186.14 mL/g VS. However, monodigestion of FVW and FW demonstrated a cumulative biogas yield of 429.16 mL/g VS and 393 mL/g VS respectively which is higher than those reported by Pavi et al. [5] and is in accordance with the results reported by Lin et al. [17]. Monodigestion of FVW displayed 9% higher biogas production as compared to FW. The low biogas generation from monodigestion of FW was majorly due to the low C/N ratio, which is a critical parameter for the effective digestion of the substrate [7, 26]. Also, the VFA inhibition and formation of long chain fatty acid are major issues associated with the monodigestion of FW which hindered the methanogenic activity [27]. The C/N value of the FW was found to be lower than the optimum which indicates the presence of a higher concentration of nitrogen in organic form which is mainly due to the higher % of the protein in FW [17]. The impact of the C/N ratio on anaerobic digestion has been studied in the past by various researchers and the optimal C/N ratio was suggested between 20 and 30 [28]. When FVW was co-digested with FW, it enhanced the C/N ratio of the substrates and buffering capacity of digester. This in turn reduced the risk of VFA inhibition, thus enhancing the biogas yield of the feedstock. In the present study, the effect of the different mixing ratios of (FVW:FW) for maximizing biogas production was evaluated. The results indicated that (FVW:FW) in the ratio (1:2) gave the highest biogas yield (510.96 mL/g VS) in comparison to (1:1) (472.2 mL/g VS) and (2:1) (420.5 mL/g VS) ratio. Co-digestion of FVW and FW in (1:2) ratio yield 16% and 23% higher biogas as compared to monodigestion of FVW and FW, respectively. This may be attributed to the presence of higher quantity of the food waste concentration in the feedstock that increases the volatile solid content. Thus, this increases the biodegradable

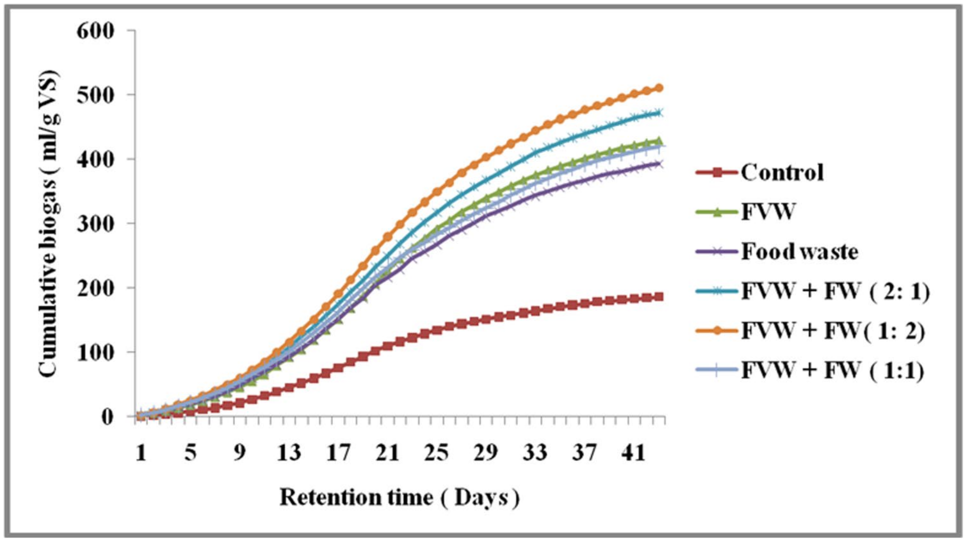

Fig. 3 Cumulative biogas production for co-digestion of FVW and FW at a different mixing ratio

organic matter available for substrate utilization and balanced C/N ratio. FVW and FW in (1:1) ratio yield 9% and 17% higher biogas as compared to monodigestion of FVW and FW, respectively. Pavi et al. [5] reported cumulative biogas yield for anaerobic digestion of FVW and FW in (1:1) ratio as 433.9 N mL/g VS. Our result indicated 8% enhancement in biogas production as compared to Pavi et al. [5]. These results indicate positive synergy between different co-substrate, enhance the internal environment of digesters, and reduce the risk of VFA inhibition, which enhances the biogas yield.

3.3 Methane content

The percentage of methane in the biogas samples of the different mix ratios of FVW and FW was evaluated at an interval of 3 days throughout the digestion period. To determine the composition of the biogas, 100 μl of biogas was taken in a Hamilton gas-tight syringe via septum, which was injected inside the gas chromatograph (Nucon 5700, India). The gas chromatograph is fitted with a Porapak Q column and thermal conductivity detector (TCD). The injector temperature was kept at 40 °C, the oven temperature at 40 °C, and the detector temperature was kept at 60 °C. Hydrogen gas was used as carrier gas. The flow rate of the carrier gas was maintained at 30 mL/min. Biogas is mainly composed of methane and carbon dioxide along with some impurities [1]. Variation of the methane and CO_2 at different mix ratios is depicted in Fig. 4a-e. From the graph, it can be seen that as the digestion period progresses, the percentage of methane in the biogas increases, whereas the CO_2 percentage decreases. For (FVW:FW = 1:2, 1:1, 2:1), the maximum methane production was 64.3%, 57.66%, and 54.32%, respectively (Fig. 4c-e). Therefore, it can be concluded that methane yield is enhanced with the increase in the concentration of FW. Moreover, with the decrease in the concentration of FW in the feedstock, incomplete utilization of the acetic acid takes place which caused low methane production [17]. On the other hand, the mono digestion of FVW and FW recorded the maximum methane yield of 52% and 53.4%, respectively (Fig. 4a and b). Therefore, it can be concluded that the co-digestion of FVW and FW achieved higher methane content as compared to the monodigestion of FVW and FW. Low methane yield for monodigestion is attributed to VFA inhibition which reduces microbial activity of the methanomers, thus reducing the biomethane potential of the waste. Among all the ratios, methane content was highest for the feed mixture of (1:2) ratio which is attributed to higher percentage of the biodegradable organics and balanced C/N ratio. These findings are in accordance with Lin et al. [17] and Browski et al. [29]. They also reported methane yield from 55 to 60% for the monodigestion of OFMSW, whereas for co-digestion of OFMSW and sewage sludge, the methane content varied from 58 to 66%. Lowest methane yield was obtained from the monodigestion of FVW and FW due to the rapid conversion of the organic matter to intermediate products such as VFA. This points to that co-digestion can produce positive synergy between co-substrate and improves the conversion of the VFA into methane production [5]. Lin et al. [17] displayed average methane content between 53.7 and 63.8% for the different mix ratios of co-digestion of FVW and OFMSW.

3.4 VFA concentration during the anaerobic co-digestion of FVW and FW

The performance of the AD system can be measured by VFA. It indicates a correlation between the methanomers and the conversion of the organic matter. VFA analysis gives an understanding of the digester's stability by maintaining

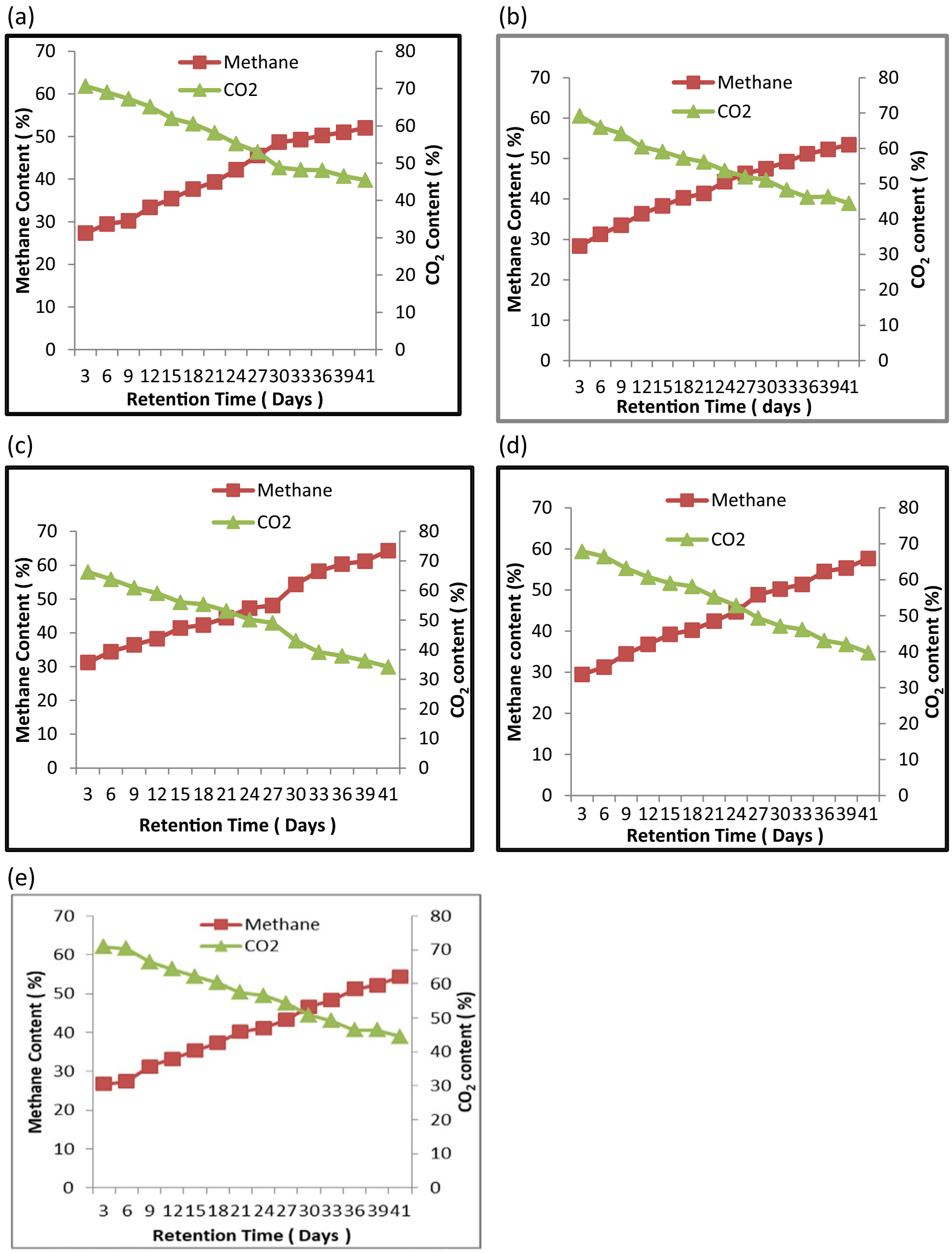

Fig. 4 Composition of biogas obtained from **a** monodigestion of FVW, **b** monodigestion of FW, **c** co-digestion of FVW:FW (1:2), **d** co-digestion of FVW:FW (1:1), and **e** co-digestion of FVW:FW (2:1)

the balance between its production and consumption [19]. However, the substrate characteristics play a vital role in the generation of the VFA. The concentration of VFA in the digester should be in the range of 0.4–0.8 g/L equivalent to acetic acid [30]. Excess production of the VFA reduces the pH of the digester which hampers the methanogenic activity of the microbes. The VFA concentration was increased dramatically with the increase in the FW proportion, which is attributed to the presence of high amount of fat and carbohydrates in the food waste (FW). The total VFA concentration was increased from 0.05 to 8.5 g/L as depicted in Fig. 5.

From the graph, it can be seen that during the initial stage of operation, the VFA concentration goes on increasing rapidly, and this may be due to the rapid conversion of the easily biodegradable matter to the intermediate compounds. Maximum VFA concentration was recorded as 8.5 g/L on day 24, 5.8 g/L on day 16, and 6.5 g/L on day 19 for FVW:FW (1:2), (1:1), and (2:1) ratios, respectively. After attaining the maximum concentration, the VFA production begins to decline, and this may be due to the shortage of the easily biodegradable organic matter. When the VFA concentration is too high, methanogens are unable to eliminate hydrogen and VFAs as rapidly as they are produced by the fermentative bacteria. The average total VFAs were significantly lower for the two ratios i.e., FVW:FW (2:1) and FVW:FW (1:1), due to low concentration of FW in the

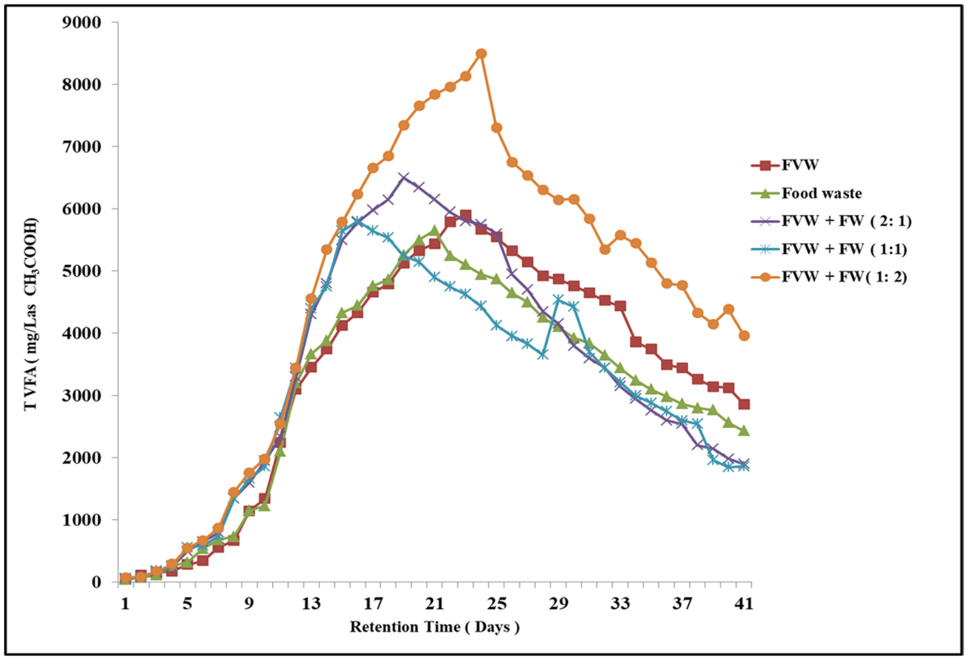

Fig. 5 VFA variation for co-digestion of FVW and FW at a different mixing ratio

influent feedstock. These concentrations were lower than the past studies [26, 31]. This may be possibly due to the change in the type of substrate utilized, although high non-dissociated VFA concentrations may result in very strong VFA inhibition, and stop methanogenesis [32]. During the initial stage of digester operation, the low pH of the reactor also contributed to the inhibition of methanogenesis. Moreover, as the process continues, buffering capacity of the digester gets exhausted. This promotes the pH drop, and ultimately ceases the methanogenic activity of the microbes and thus diminishing the amount of biogas produced.

3.5 Evaluation of digester stability during anaerobic digestion

3.5.1 pH and alkalinity variation in the reactor

The digester's pH is a crucial indicator of the process stability. Variation of pH values for different mix ratios and monodigestion of FVW and FW at the end of the AD are presented in Table 2. The pH of the anaerobic digestion should be maintained between 6.8 and 7.3 for best methanogenic activity [33]. Despite the low pH of the feed (4.5–5.5), the pH in the digester was maintained well between 6.8 and 7.5, which is in optimal range for the methanogenic microbes. This indicates the stability of the digester. However, the presence of bicarbonate and carbon dioxide in the digester also enhances the buffering capacity of the digester [1]. The values of alkalinity should be between 2400 and 5000 mg $CaCO_3$/L for the stable digester [26, 33]. The pH of different mix ratios of FVW and FW was higher as compared to single substrate, and this is mainly due to the presence of food waste in the mix. Since, food waste is characterized by the presence of highly nitrogenous matter such as protein, and when these matters are degraded, ammonia will be released into the solution and form ammonium bicarbonate. This contributes to the additional buffering capacity of the digester [34]. On the contrary, monodigestion of FVW and FW results in rapid acidification and hinders the methanogenic activity of the microbes. This is mainly due to biodegradation of cellulose poor waste such as FVW and FW, which contains less amount of cellulose and hemicellulose is limited by methanogenesis rather than acidogenesis [25, 35]. A major inhibition to methanogenesis is caused by rapid decrease in pH due to severe acidification, which will result in VFA accumulation and cease biogas production [25, 31]. Therefore, to overcome this shortcoming, anaerobic co-digestion of FVW and FW appears to be more feasible

Table 2 Summary of performance parameters for different mix ratios at the end of anaerobic digestion

Operational parameter	FVW	FW	FVW:FW (1:2)	FVW:FW (1:1)	FVW:FW (2:1)
pH	6.84	7.12	7.23	7.43	7.6
NH_4^+-N (mg/L)	2550	2340	2354	1945	2446
VFA (mg/L)	4500	6000	5800	6500	8500

Table 3 Performance analysis of various mix ratios of FVW and FW

Parameter	FVW	FW	FVW:FW (1:2)	FVW:FW (1:1)	FVW:FW (2:1)
Initial VS (%)	4.19	12.015	9.43	8.10	6.77
Final VS (%)	1.63	4.3	2.64	2.673	4.43
VS removal efficiency (%)	61.09	64.21	72	67	65.5

solution. FVW and FW are mainly composed of nitrogen-rich organic matter, which is mainly in the form of phospholipids, nitrogenous lipids, and nucleic acids [36]. Anaerobic degradation of this waste releases ammonia which increases the buffering capacity, required by the microorganism for growth and reproduction [17]. However, ammonia concentration should be present in optimal range. Higher concentration of ammonia results in the pH drop which will retard the methanogenic activity of the microbes and thus diminishes the biogas production [17]. Hence, it is recommended to have an optimal C/N ratio for smooth operation of AD. The significance of the C/N ratio has been investigated by researchers and the optimal C/N ratio for AD is suggested between 20 and 30 [28, 37]. A high C/N ratio will retard the growth of the anaerobic microorganism due to the nutrient deficiency. On the other hand, lower C/N ratio results in high concentration of ammonia in the digester, ultimately inhibition to the methanogenesis [1, 9, 38]. The average ammonia concentration at the end of the anaerobic digestion is presented in Table 2. The ammonia concentration of the effluent for different mix ratios lies between 1940 and 2550 mg/L. Results revealed that as the concentration of the FW increases in the influent feedstock, the concentration of the ammonia increases, and the highest amount of ammonia was recorded for FVW:FW (1:2) ratio as 2354 (mg/L). This is attributed to the well-established fact that FW increases the nitrogen content in the feedstock which releases ammonia in the solution [34]. On the other hand, in the monodigestion of FVW and FW, the ammonia concentration was recorded as 2550 and 2340 mg/L, respectively.

3.6 Volatile solid reduction at a different mix ratio of FVW:FW

The initial volatile solid content in FVW and FW was 4.19% and 12.015%, respectively (Table 3). The amount of the volatile solids in the feedstock increases with the increase in the concentration of the FW. It is noteworthy that for the monodigestion of the FW, the VS degradation was higher as compared to the monodigestion of FVW. The effluent VS concentration was 4.3% for monodigestion of FW. From Table 3, it can be concluded that VS removal efficiencies were affected by the change of influent FW ratio. The VS removal efficiency for different mix ratios of FVW:FW was increased from 65.5 to 72% with the increase in the concentration of FW in the influent feedstock. Lin et al. [17] reported that the VS reductions were increased from 71.7 to 79.3% with the increase in influent FW concentration.

4 Conclusions

Co-digestion of FVW and FW enhances the biomethane yield as compared to monodigestion of the FVW and FW. FVW:FW (1:2) was found as the optimal ratio for anaerobic co-digestion of FVW and FW. This is mainly due to the increase in the alkalinity of the digester which enhanced the process stability, thus preventing possible acidification and maximizing biomethane yield. Moreover, the availability of the balanced nutrients provided optimal environmental conditions for the survival of the microbes; this also leads to enhanced biogas yield. Pavi et al. conducted co-digestion of FVW and FW and they found that (FVW:FW) (1:3) ratio was optimal with higher biogas yield as 0.49 m^3 CH_4/kg VS and methane yield as 0.396 m^3 CH_4/kg VS. However, 3% more biogas yield was obtained in our study at FVW:FW (1:2). Lin et al. [17] displayed 0.49 m^3 CH_4/kg VS for co-digestion of FVW along with FW for a mixing ratio of 1:1, whereas in our investigation, 0.51 m^3 CH_4/kg VS was obtained for FVW:FW (1:2) ratio. Callaghan et al. [18] demonstrated co-digestion of FVW with cattle slurry and chicken manure, and they pointed out cattle slurry as a more suitable feedstock compared to chicken manure. This enhanced methane yield from 0.23 to 0.45 m^3 CH_4 kg^{-1} VS. However, in comparison to previous studies, the better result was obtained using food waste as co-substrate and methane content in our experiment also increased from 35 to 67% for different ratios of co-digestion.

Author contribution All authors contributed to the study conception and design. Material preparation, data collection, and experimental analysis were performed by Akanksha Agrawal. The first draft of the manuscript was written by Akanksha Agrawal. Data validation was done by Dr. P.K. Chaudhari and Dr. Prabir Ghosh. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability Not applicable.

Declarations

Ethical approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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