Co-digestion of Wastewater Treatment Plant Sludge and Plate Scrap to Increase Biogas Yield

W. Asrat[1], K. Purushottam Kolhe[2*]

1- Department of Mechanical Engineering, School of Mechanical, Chemical and Materials Engineering at Adama Science and Technology University, Adama, Ethiopia
2- Department of Mechanical Engineering, Sinhgad College of Engineering, Vadgaon (BK.), Pune-411041, Pune University, India
(*- Corresponding Author Email: kishorkolhe05@gmail.com)
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Abstract

This research seeks to determine the highest possible yield by integrating wastewater treatment plant sludge with food waste from plate scraps at Adama Science and Technology University (ASTU) in Ethiopia. Feedstock characterization and biogas co-generation were done on different Plate Scrap (PS), Wastewater Treatment Plant Sludge (WTPS), and 100 mL cow manure combination ratios. The feedstocks were evaluated for their TS and MC before combination, and TS, VS, TDS, COD, BOD, and pH after combination. This experiment was done in two rounds using three water baths and twenty-seven Batch Reactors (BR) with 2.5 L volume each. In the first round, eighteen reactors were used, and nine were used in the second experiment. Triplicate testing was used to evaluate the feedstock sample characteristics and to run the experiment. The reactors were operated for thirty-five days at a hydraulic retention time and a temperature of 50 °C. The daily biogas yield using the water displacement method, total biogas yield, and methane composition were measured and reported. Three sub-reactors were considered to find the average biogas yield of individual reactors. A notable increase in both daily and total biogas yield was observed with the reactor composition of 75% PS Injera (PSI) flat bread and 25% WTPS. The daily maximum and the average biogas yields were 220 mL and 810 mL, with the TS of 55,066 mg L^{-1} and the VS of 51,000 mg L^{-1}. The maximum methane inside the produced biogas was 68%, from PSI75% and WTPS25%. This combination also showed the highest biogas yield.

Key Words: Anaerobic Digestion (AD), Biogas yield, Co-generation, PS, WTPS

Lists of abbreviations and notations
TS: Total Solid
MC: Moisture Content
VS: Volatile Sold
TDS: Total Dissolved Solid
COD: Chemical Oxygen Demand
BOD: Biochemical Oxygen Demand

Introduction

Ethiopia has abundant renewable energy resources that meet the country's present energy demands. In this respect, research on renewable energy sources is at the beginning stage. Most people from the total population living in towns and rural regions rely on traditional energy sources, such as fuel wood, dry cow dung, and agricultural waste. The existing Ethiopian energy system shows a large gap between urban and rural usage. Almost all rural homes cook using traditional biomass-based energy, while over 90% of urban households utilize electricity for lighting. Cooking consumes the greatest energy, with petroleum and electricity accounting for only 7% of the overall energy demand (Benti *et al.*, 2021, Kolhe 2015).

Wastewater treatment facilities in Ethiopia are essentially non-existent, and those that do exist are badly managed. Even huge cities, like Addis Ababa, experience poor drainage and wastewater overflow from businesses, institutions, and residential areas (Haddis, de Geyter, Smets, & Van der Bruggen, 2014). Ethiopian cities lack domestic wastewater treatment facilities except for Addis Ababa. As part of the World Bank's strategic sanitation initiatives, donors plan to upgrade the existing treatment plant in Addis Ababa and build urban wastewater treatment facilities in all large Ethiopian cities (GIZ, 2020). Due to fast urbanization, increased population, and water shortage, the agricultural sector is nowadays facing a great challenge. To this end, wastewater is used for irrigation, which has positive and negative impacts on the agricultural production of vegetables. Farming with wastewater has a major role in income generation, producing irrigated vegetable crops in Ethiopia, and irrigating vegetable crops used as a food source and income generation for the urban community. Consuming wastewater from irrigated vegetable crops can cause diseases like cholera and typhoid (Gashaye, 2020, Kolhe *et al* 2024). Adama Science and Technology University (ASTU) has built a waste treatment plant to treat and recycle wastewater of compounds like grey water and black water. The wastewater plant setup is shown in Fig. 1. The treatment plant has two Imhoff tanks that separate solids from liquids. The aeration tanks stabilize wastewater by removing harmful pathogens, pollutants, and poisonous chemicals. Two Dortmund tanks were used to settle sludge produced by physical, chemical, and biological processes. Coarse and small solid materials are removed with fine and coarse metal mesh screens installed at the treatment plant's inlet. The plant can treat 18,750 cubic meters of wastewater and produce around 600 kg of sludge per day. The average wastewater flow to the treatment plant is 8 liters per second; also, the wastewater circulation of Adama Science Technology University is briefly elaborated on in Fig. 2.

Fig.1. Adama Science and Technology University (ASTU) wastewater treatment plant

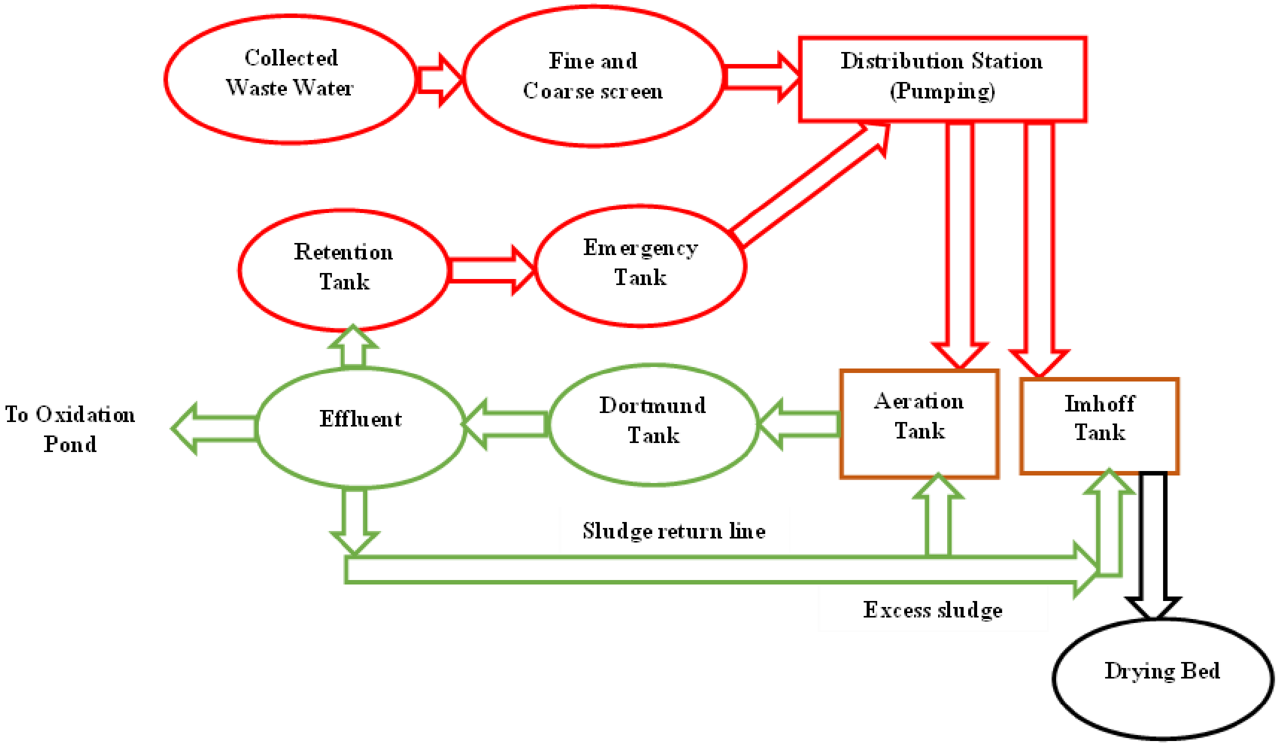


Fig.2. Adama Science and Technology University (ASTU) treatment plant wastewater circulation

Energy recovery from fossil fuels and other non-renewable resources is common. This generates harmful effects on the environment and living things. Production of energy using renewable energy sources can avoid drawbacks from non-renewable energy resources (Azadbakht, Safieddin Ardebili, & Rahmani, 2023; Safieddin Ardebili & Khademalrasoul, 2018).

Biogas is a substitute for traditional energy sources, which cause ecological and environmental issues while depleting faster. It is a clean, eco-friendly, and renewable source of energy (Deepanraj, Sivasubramanian, & Jayaraj, 2017). Biogas can be produced from feedstocks, which can be biodegraded with an anaerobic process. Food waste and wastewater treatment plant sludge are among them. Several operating parameters can influence the anaerobic digestion process, including feedstock composition, co-feedstock mixing ratio, reactor types, and environmental factors such as temperature, hydraulic retention time (HRT), organic loading rate (OLR), pH, and nutrients (Cheong *et al.*, 2022).

Anaerobic digestion is a widely known process for digesting varied organic matter into usable resources. Mono digestion has different issues, like volatile fatty acid accumulation and higher organic loading. However, the co-digestion of various raw materials can overcome those constraints. Co-digestion offers the advantage of boosting digestibility through the coactive effects of co-feedstocks, improving process stability, and increasing the nutrient content of the resulting feedstock. Anaerobic co-digestion can be advantageous because it balances compounds, supplements trace elements, dilutes toxic and inhibiting molecules, and fosters the diversity of bacteria. Anaerobic co-digestion enables the use of two or more varied feedstocks in the same processing system. The characteristics of the feedstocks shall be balanced to treat them collectively. Co-digestion of food waste can generate a higher biogas amount with a fast production rate (Prabhu & Mutnuri, 2016). Feedstocks with combined feedstocks have improved performance over mono digestion by reducing the harmful effects of toxic compounds through dilution and increasing organic loading (Ebner, Labatut, Lodge, Williamson, & Trabold, 2016). This research aims to find the best blends of biogas feedstock for co-digestion among the WTPS and PS.

This research aimed to recover energy by combining canteen leftovers (plate scrap) and wastewater treatment plant sludge in different mixing ratios. Like other countries, Ethiopia would produce abundant leftover food in universities, governmental organizations, and restaurants. In universities, wastewater treatment plants have been built in different areas of Ethiopia to manage wastewater from dormitories, canteens, and surface water. Uncontrolled waste can produce landfill gas and harm human health. The accumulation of landfill gas could lead to pathogenicity if it is not transformed into usable forms (Zaki Dizaji *et al.*, 2021). So, recovering energy from available waste would be the best solution to avoid landfill gas that harms living things and causes pathogenicity (Azadbakht & Safieddin Ardebili, 2024). This study used plate scrap and wastewater treatment plant sludge to generate biogas at different mixing ratios. The feedstocks were collected freshly from Adama Science and Technology University canteen and the wastewater treatment plant. Collection, sorting, packing, characterization, determination of water and sludge, digestion, and recording of biogas and methane were done appropriately and carefully following scientific procedures. Co-generation using Plate Scrap Injera (PSI) flatbread and Wastewater Treatment Plant Sludge (WTPS) at different mixing ratios showed a higher biogas yield and methane production than other co-generation combinations.

Materials and Methods

Materials

Plate scraps and wastewater treatment plant sludge are used as feedstock. A 2.5-liter plastic bottle reactor was used for the co-digestion process, and two series of one-liter plastic water bottles were used to collect the produced gas and displaced water. The reactors were batch-fed type and filled with two-liter diluted and homogenized co-feedstock and with half-liter gas space. The detailed compositions of the used materials for biogas generation are shown in Table 1.

Table 1- Detailed Composition of used materials for biogas generation

Injera, bread, or mixed plate scrap (%)	Sludge (%)	Cow manure (mL)
25	75	100
50	50	100
75	25	100

The pH, Total Solid (TS), Volatile Solid (VS), Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), Total Dissolved Solid (TDS), and Moisture Content (MC) were measured with the help of different scientific instruments as depicted in Fig 3 (a-d), such as a digital pH meter to measure the level of pH, hot air oven to measure TS, muffle furnace to measure VS, Filter photometer photoLab® S6 – WTW to measure COD, and BOD and MC were calculated analytically.

Muffle furnace (b) Hot air oven (c) Photo Meter (d) COD Digester

Fig. 3. Scientific instruments used for characterization and experimental study

Sample Preparation

The feedstock was taken from the Adama Science and Technology University canteen and the water treatment plant. In this experiment Completely Randomized Design (CRD) was used. The experimental feedstocks were assigned randomly to the treatment groups, which were taken from a garbage can. Three replications were considered for recording accurate results. Three one-liter samples were collected from each station. The size of a sample of sludge was 500 mL, and a total of 1.5 mL was collected for characterization, three for one 500g of Injera, Bread, and mixed PS from the ASTU canteen.

(a) PS Injera (b) PS Bread (c) PS Mixed

Fig. 4. Canteen samples showing plate scraps

Plate scrap sample

The total solid (TS) and Moisture Content (MC) of plate scraps collected from the ASTU canteen were analyzed. Four samples were collected from two places: Three samples were taken from the university student canteen, and the rest from the wastewater treatment plant ASTU. Sample feedstocks of foodstuffs like plate scraps of Injera, Bread, and mixed food items are collected from the student canteen of Adama Science and Technology University. The food items were collected freshly and carefully, then sorted, weighed, and packed for further feedstock characterization. The details of the prepared plate scrap sample are shown in Figure 4.

Wastewater treatment plant sludge sample

Samples from the wastewater treatment plant were collected from the university treatment plant, as shown in Figure 5. Methane bacteria always exist in sufficient amounts inside the Dortmund tank, so during sample preparation and digestion, the activated sludge is pumped into the Imhoff tank, and then the feedstock is collected.

Fig. 5. Wastewater treatment plant sludge sample

(a) PSI with WTPS (b) PSB with WTPS (c) PSM with WTPS

Fig. 6. Laboratory sample plate scrap mixed with sludge

Mixed feedstock (Plate scrap and Sludge) sample

The feedstock mixture was prepared for three types of plate scraps namely injera, bread, and mixed, with sludge in different ratios (25:75, 50:50, 75:25), as shown in Figure 6.

Methods

Figure 7 describes the methods and experimental investigation path used in this research, as discussed in the following steps:

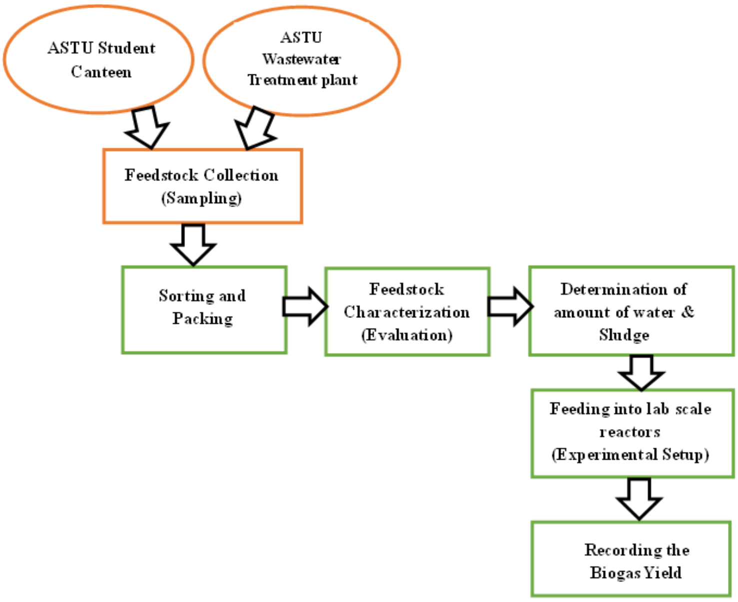


Fig. 7. General research methodology of co-generation of biogas

Sorting and packing

Plate scraps and wastewater treatment plant sludge were sorted carefully and packed in plastic bags after being collected from the student canteen and the wastewater treatment plant at ASTU.

Characterization of feedstock

Analyzing the feedstock characteristics for a biogas reactor input is essential to determine biogas yield, the organic matter that is converted into biogas, and the amount of water to be added to the feedstocks. The sample characterization is carried out in two steps, as discussed below.

Characterization of plate scraps and wastewater treatment plant sludge

Adding water dissolves the total solids within the biogas digester feedstocks. The amount of water to be added to the feedstock is determined by the feedstock's total solid content. The advantage of dissolving the feedstock's total solids is that it creates favorable conditions for pathogens (Wang, Hu, Wang, Wu, & Zhan, 2023; Mrosso, Mecha, & Kiplagat, 2023). In this characterization, samples of each separate feedstock were evaluated for TS and moisture levels. Samples of food stock, such as plate scraps, Injera, bread, mixed meal items, wastewater treatment plant sludge, and 100 mL of cow manure, were examined to determine total solids and moisture content.

Co-digestion feedstock characterization

Co-digestion feedstocks were analyzed for pH, TS, VS, TDS, COD, BOD, and MC. Twenty-seven samples were taken to the Adama Science and Technology University Wastewater Treatment Plant laboratory. The samples were homogenized, each a mixture of foodstuff and wastewater treatment plant sludge in various ratios. Plate scraps and WTPS used in the anaerobic digestion process were analyzed for moisture content, total solids, and volatile solids as per the guidelines of the American Public Health Association (APHA, 2005). TS was determined by placing the feedstocks in a hot air oven (Make: Nabertherm, GmbH, Bahnhofstr. 20, 28865 Lilienthal / Bremen, Deutschland) at 105 °C for 24 h. The moisture content of the feedstocks was determined analytically based on the TS value obtained. VS was determined using a muffle furnace (Make: Nabertherm Compact Muffle Furnace LE 6/11/B150 LE060K1BN, Deutschland) at 550± 2°C for 2 h.

Determination of water to be added to the feedstocks and sludge to be added to the reactor

The required quantity of water to be added in various feedstock like PS Injera, PS Bread, PS Mixed, and Sludge, and 100 mL cow manure for a fixed water temperature of 50 °C, with 35 days of Hydraulic Retention Time and at 10% concentration of total solid (Indren, Birzer, Kidd, & Medwell, 2020) was determined using Equation (1).

$$Water\ Required = 100 \times \frac{TS}{10} \qquad (1)$$

Determination of the amount of sludge to be added to the reactor

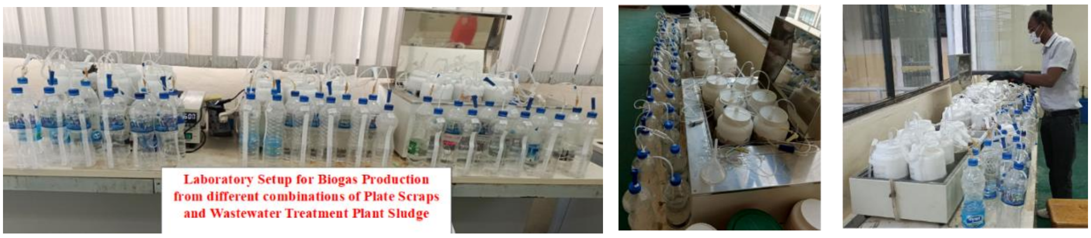
The required quantity of sludge in different mixing ratios was determined based on the following conditions: TS of the feedstock and the sludge, water to be added inside the feedstock, given the ratio of mixing, and the total volume of the reactor by Equation (2).

$$\text{Amount of sludge} = Solution\ of\ the\ substrate(Ratio) \times Mixing\ ratio\ of\ the\ sludge \qquad (2)$$

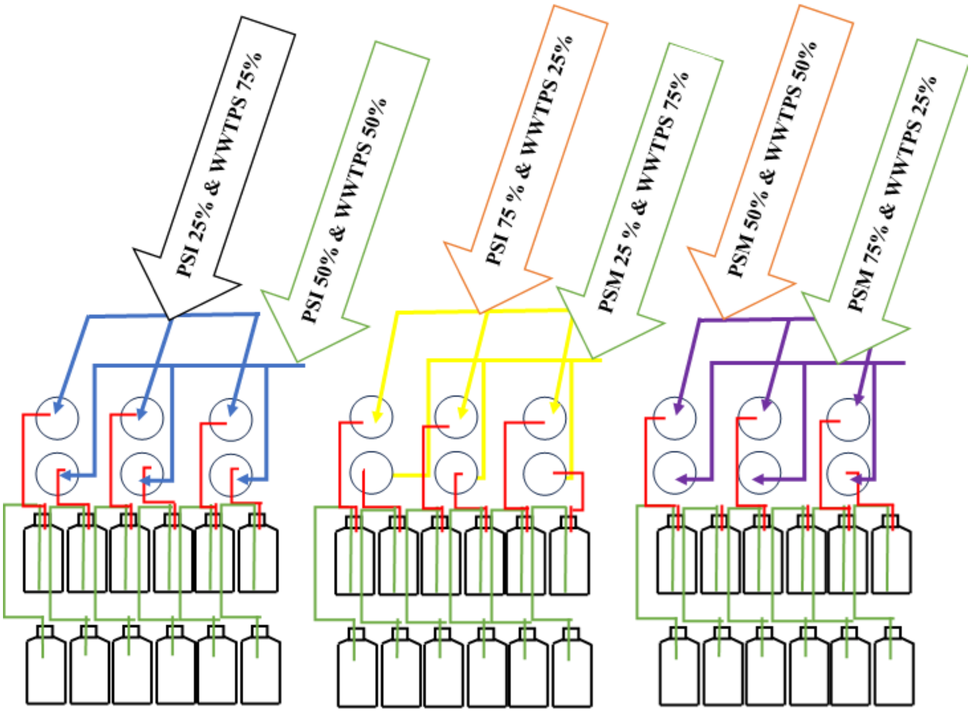
Experimental procedure

The laboratory setup for biogas production was established at the Department of Chemical Engineering, Environmental Engineering Laboratory of ASTU, as shown in Figure 8. Three water baths were used for the experiment; two had a capacity of eight liters of water, and the third one was twenty liters, and all were equipped with automatic thermostats with digital temperature adjustment. Each water bath holds six 2.5-liter reactors and operates for 35 days continuously. The baths were filled with water once in 24 hours at a set temperature of 50 °C (thermophilic). Eighteen reactors were used for the first-round experiment, and nine were used for the second-round experiment, filled with two-liter feedstock mixed with different mixing ratios. Plate Scrap Injera (PSI) and Plate Scrap Mixed (PSM) with varying ratios of composition, along with Wastewater Treatment Plant Sludge (WTPS) and 100 mL of cow manure, were used to produce biogas in the first round. Plate Scrap Bread (PSB), composed of Wastewater Treatment Plant Sludge (WTPS) and 100 mL of cow manure in different ratios, was used in the second-round experiment. To mix the feedstock in the reactor thoroughly, a hand-shaking method was implemented every 24 hours throughout the experiment session. The details of the composition of the feedstock are shown in

Table 2. The biogas yield was recorded twice a day from 26 Nov 2024 to 31 Dec 2024 for the first-round experiment and from 2 Jan 2025 to 05 Feb 2025 at 8:30 AM and 4:00 PM. The methane gas in each reactor was recorded after the biogas production process was completed.



(a) Laboratory setup



(b) Experimental setup

Fig. 8. Experimental set-up for Co-generation

Recording the biogas yield

The daily biogas yield was measured using the water displacement method, and total biogas yield and methane composition were measured and reported.

Recording the methane amount

Methane was measured indirectly using an Infralyt Smart gas analyzer. This gas analyzer measures the amount of carbon dioxide in the produced biogas. A flame test was executed to confirm the presence of methane in the produced biogas. Figure 9 depicts the recording of carbon dioxide to determine the percentage of methane with an indirect recording mechanism

Fig. 9. Photograph showing a recording of methane with an indirect mechanism

Results and Discussion

Results

The results of this study to find TS and MC, from the sample of the feedstock collected freshly, are presented in Table 2. The amount of water required to dissolve the total solids of feedstock and sludge required for biogas production is presented in this section. The experimental recorded results of COD, TS, VS, TDS, and pH and their impact on biogas yield are discussed below. The biogas yield and amount of methane inside the produced biogas are measured. Table 3 depicts the recorded quantity of water required to dissolve the total solids of the feedstock. Table 4 presents the Sludge Required for the PSI, PSB, and PSM.

Table 2- TS and MC of biogas reactor feedstock before blending for co-digestion

Feedstock sample	TS	MC (%)
PSI	43.11%	56.89
PSB	36.05%	64.05
PSM	28.51%	71.45
WTPS	86,800 mg L^{-1}	

Table 3- Water required to dissolve the total solids of the feedstock

Feedstock sample	TS of the sample (%)	Total feedstock in 10% concentration of TS (kg)	Water required (L)
PSI	43.11	4.311	3.311
PSB	36.05	3.605	2.605
PSM	28.51	2.851	1.851

Table 4- Sludge to be added to a biogas reactor

Feedstock	Composition	Sludge required (mL)
PSI	PSI 25% & 75% sludge	860
	PSI 50 % & 50% sludge	690
	PSI 75% & 25% sludge	431
PSB	PSB 25% & 75% sludge	851
	PSB 50% & 50% sludge	721
	PSB 75% & 25% sludge	451
PSM	PSM 25% & 75% sludge	754
	PSM 50% & 50% sludge	398
	PSM 75% & 25% sludge	220

Table 5 shows the produced biogas, using the water displacement method and the amount of methane using the Infralyt Smart gas analyzer.

Table 5- Test result of recorded biogas and methane

Feedstock	Average biogas yield (mL)	Average CO_2 (%)	Average CH_4 (%)
PSI25% & WTPS75%	330	42	58
PSI50% & WTPS50%	520	39	61
PSI75% & WTPS25%	810	32	68
PSB25% & WTPS75%	250	48	52
PSB50% & WTPS50%	480	48	52
PSB75% & WTPS25%	680	47	53
PSM25% & WTPS75%	280	45	55
PSM50% & WTPS50%	580	43	57
PSM75% & WTPS25%	710	40	60

Discussions

As shown in Table 5, when the amount of plate scrap increases from 25% to 75%, the biogas yield showed significant differences and slight differences were observed in the methane amount. An increase in the plate scrap amount means an increase in total solids. Therefore, the total solid feedstock has a greater direct impact on biogas yield than on methane production. Plate scrap injera showed maximum biogas yield and maximum methane from the other combinations, which were 810mL and 68% respectively. Plate scrap bread showed a slight difference in the amount of methane, while the total solids of the feedstock increased (Wang *et al.*, 2020).

Fig. 10 depicts the total and volatile solids of a mixture of plate scrap injera and wastewater treatment plant sludge at different ratios of PSI and WTPS. The increase in the feedstock ratio increases PS and VS. The feedstock combination, PSI 75 % and WTPS 25 %, has the maximum TS and VS compared to others. The total solids of a mixture of plate scrap and wastewater treatment plant sludge increases as the amount of plate scrap mixed increases accordingly (Zhao *et al.*, 2021). The volatile solid of the feedstock increases as the amount of PSM increases, but not in the same fashion as the total solids.

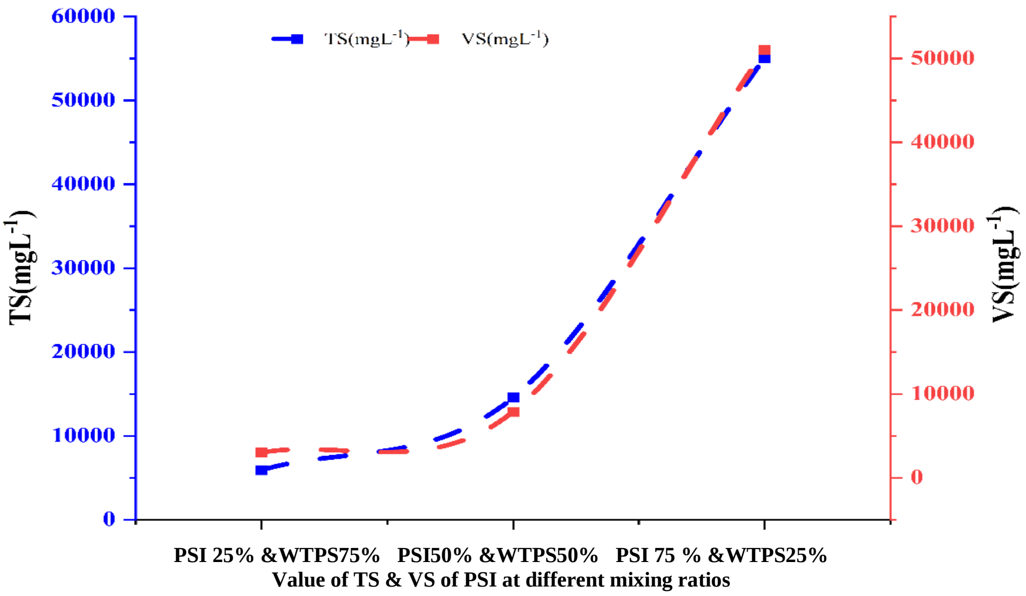


Fig. 10. TS and VS of PSI at different mixing ratios with WTPS

Fig. 11 shows that the feedstock PSM 75% & WTPS 25% has shown the maximum TS and VS compared to the others.

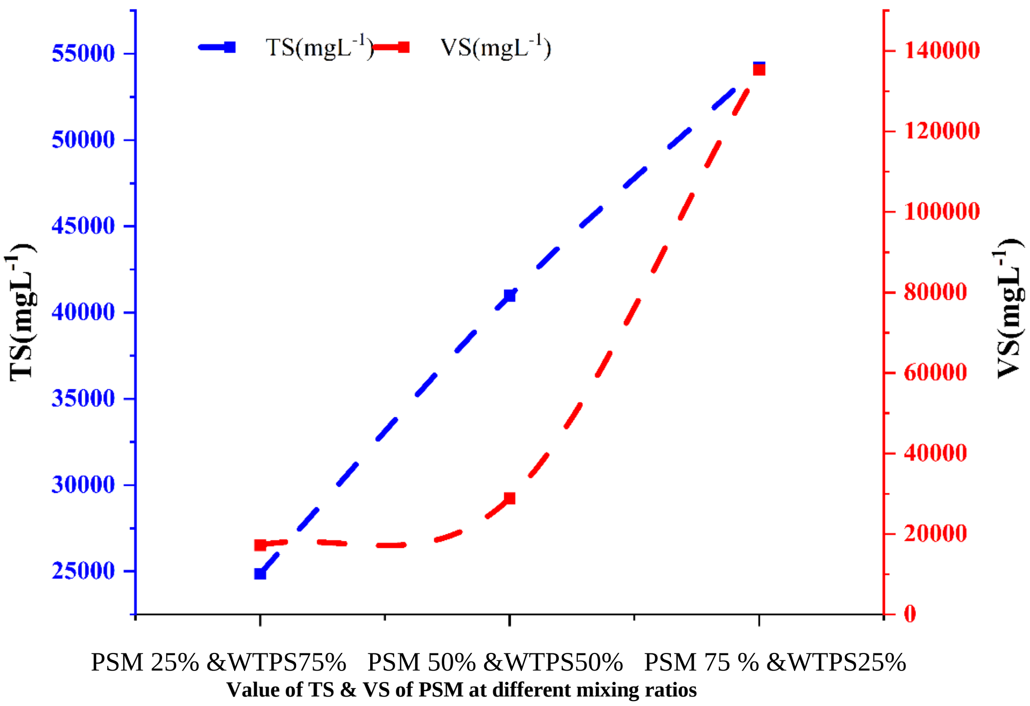


Fig. 11. TS and VS of PSM at different mixing ratios with WTPS

The total solids of a mixture of plate scrap bread and wastewater treatment plant sludge increase as the amount of plate scrap bread increases accordingly. The volatile solid of the feedstock increases as the amount of PSB increases. Fig. 12 shows that the feedstock PSB 75% & WTPS 25% has shown the maximum TS and VS than the others.

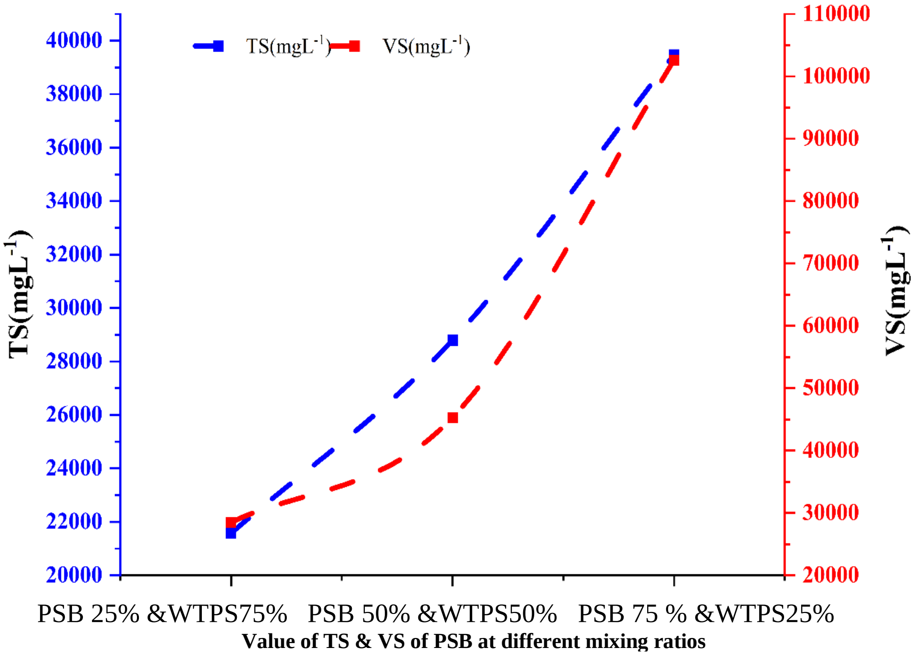


Fig. 12. TS and VS of PSB at different mixing ratios with WTPS

Fig. 13 depicts the chemical oxygen demand of PSI, decreasing as TS and VS increase. The more COD, the more susceptible the process is to acid conditions during digestion. This inhibits a normal biogas production process and results in more carbon dioxide than methane. The pH is between 6.95 and 7.04, showing that the digester is in favorable condition for producing biogas.

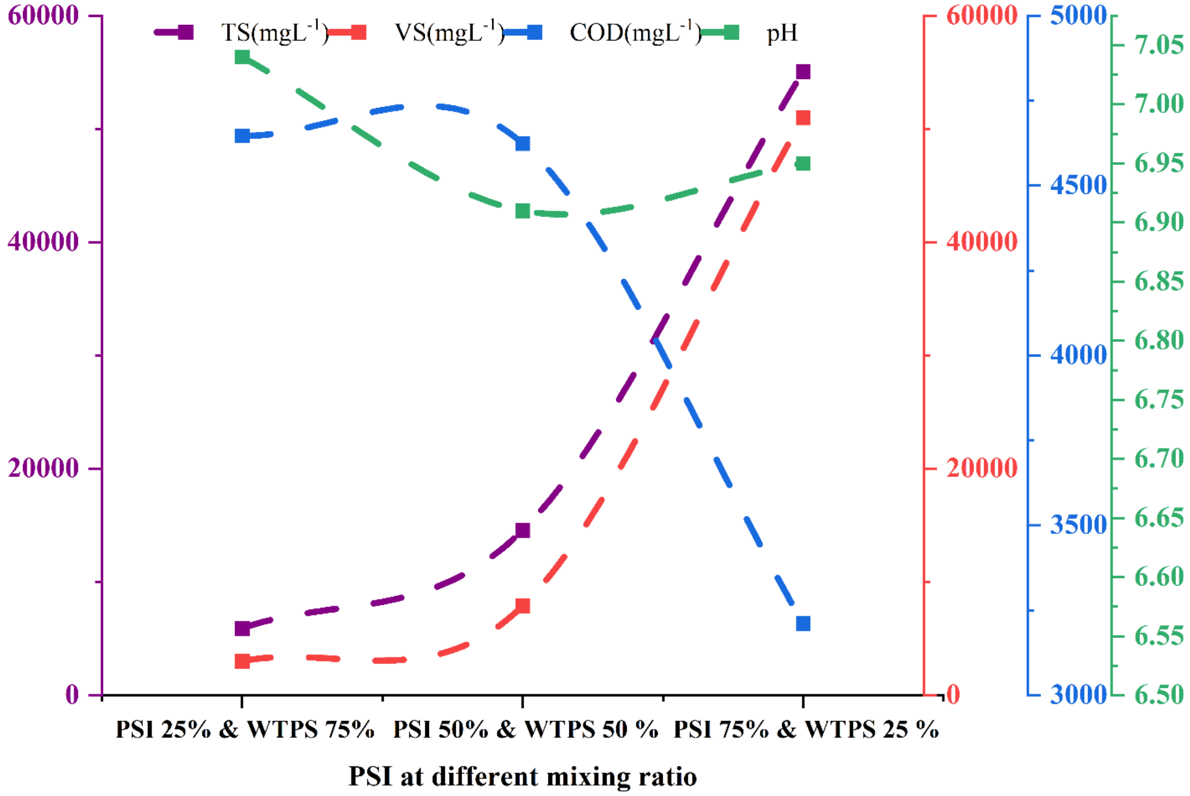


Fig. 13. The Influence of PSI mixing ratio on TS, VS, COD, and pH

Fig. 14 depicts the chemical oxygen demand of PSM decreasing as TS and VS increase. The more COD, the more susceptible the process is to acid conditions during digestion (Srisowmeya, Chakravarthy, & Nandhini Devi, 2020). This inhibits a normal biogas production process and results in more carbon dioxide than methane. The pH is between 6.83 and 7.03, showing that the digester is in favorable condition for producing biogas.

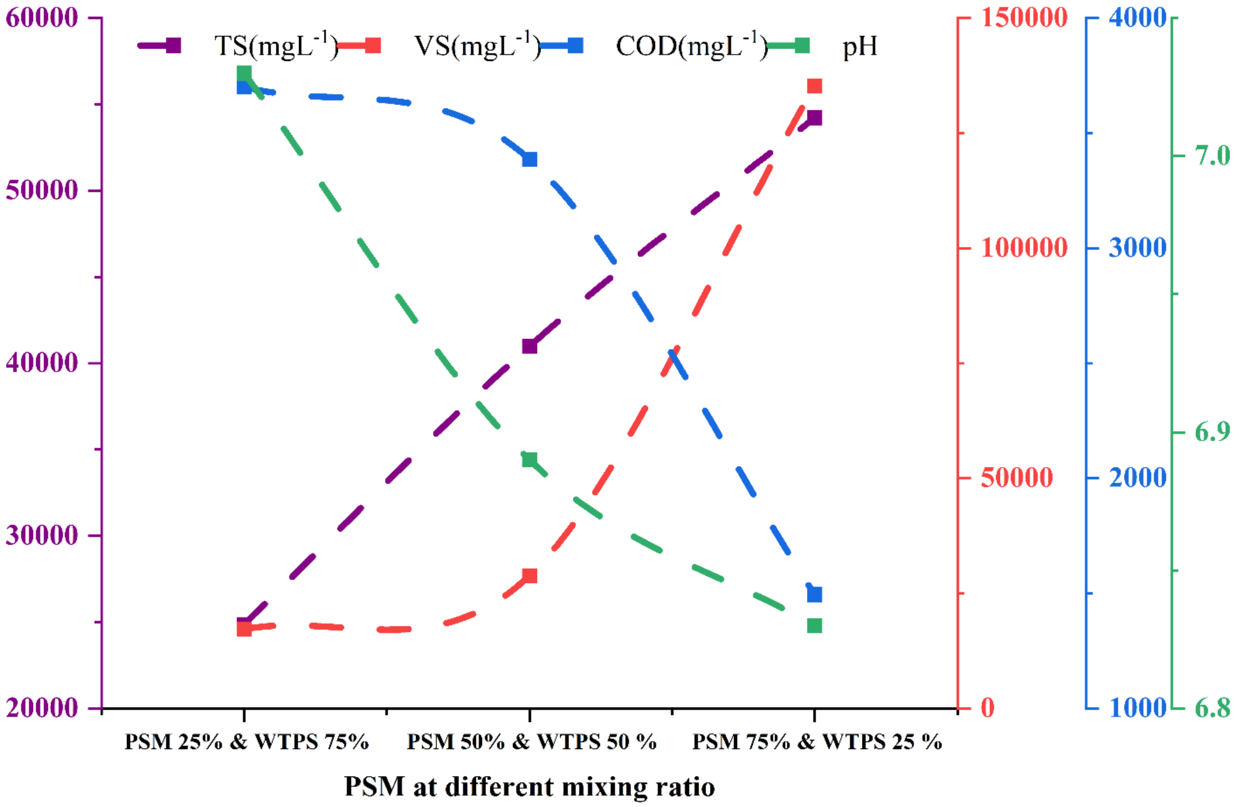


Fig. 14. The Influence of PSM mixing ratio on TS, VS, COD, and pH

Fig. 15 depicts chemical oxygen demand of PSB decreasing as TS and VS increase. The more COD, the more susceptible to acid conditions during digestion. This inhibits a normal biogas production process and produces more carbon dioxide than methane. The pH is between 6.51 and 6.99, showing that the digester is under favorable conditions for producing biogas.

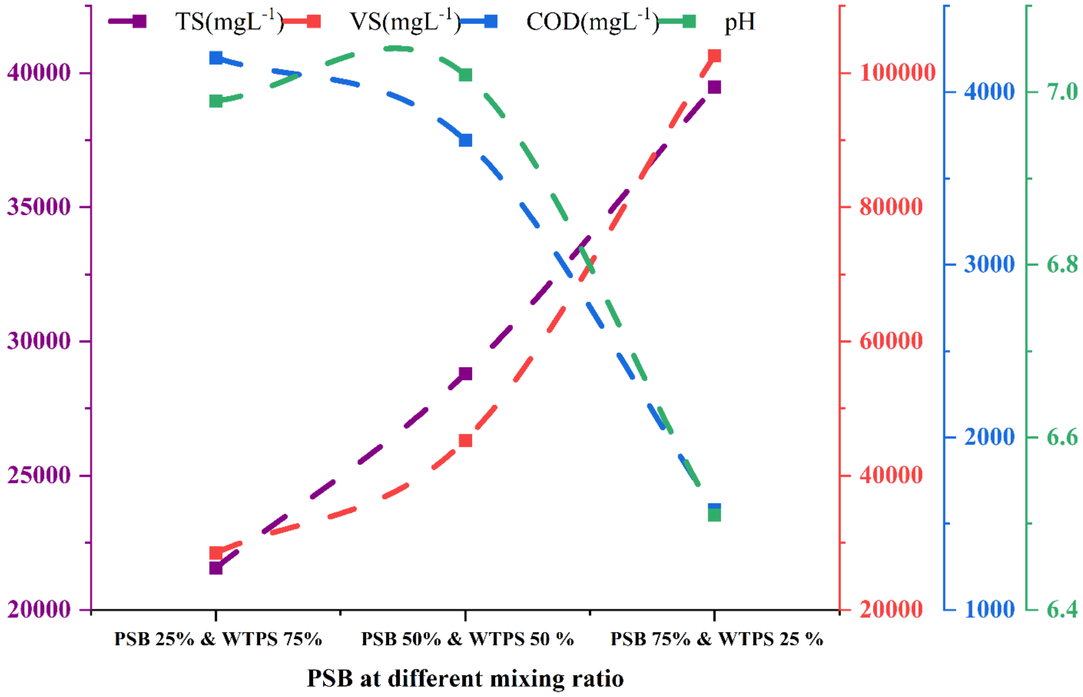


Fig. 15. The Influence of PSB mixing ratio on TS, VS, COD, and pH

The produced biogas from all feedstocks is increasing as the percentage of plate scraps increases from 25% to 75%, and the rate of wastewater treatment plant sludge decreases from 75% to 25%, as shown in Fig. 16.

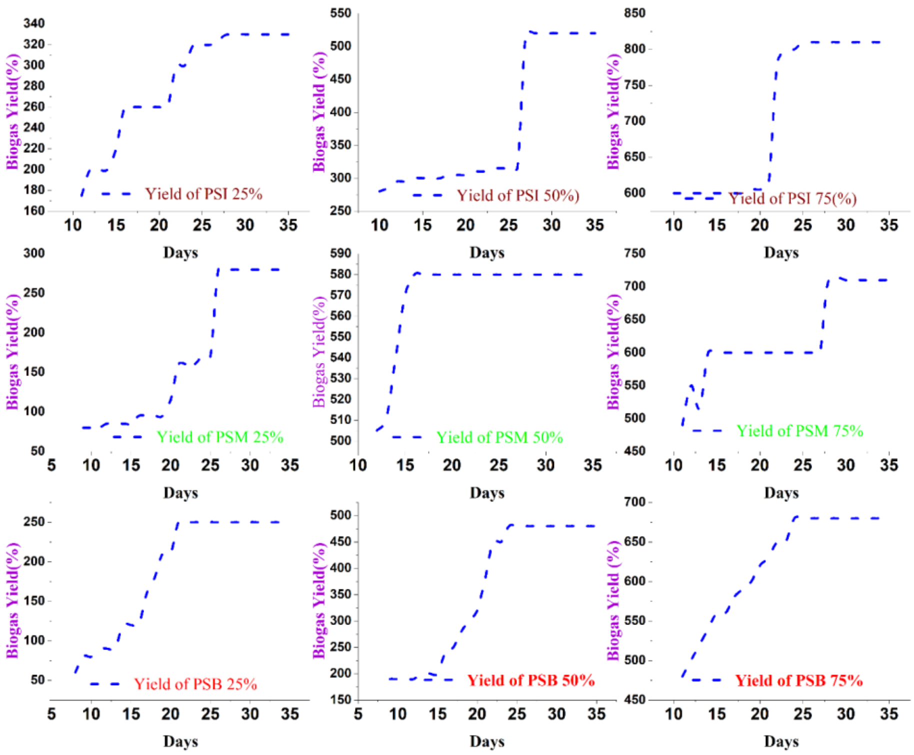


Fig. 16. Biogas yield of different combinations

The combination of PSI 75% and WTPS 25% has shown the highest biogas production, but PSI 25% and WTPS 75% have the lowest biogas production from the Plate Scrap Injera group biogas production process, as shown in Fig. 17.

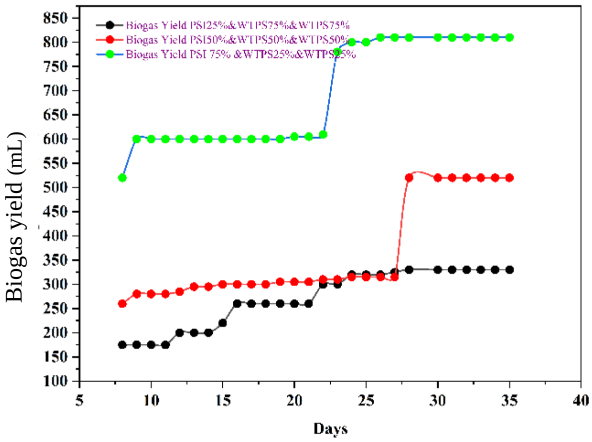


Fig. 17. Biogas yield of PSI at different mixing ratios with WTPS

A combination of PSM 75 % & WTPS 25 % has shown the highest biogas production, but PSM 25 % & WTPS 75 % have the lowest biogas production from the Plate Scrap Mixed group biogas production process. A combination of PSM 50% & WTPS 50% has shown the highest biogas production than PSI 50% & WTPS 50% as shown in Fig. 18.

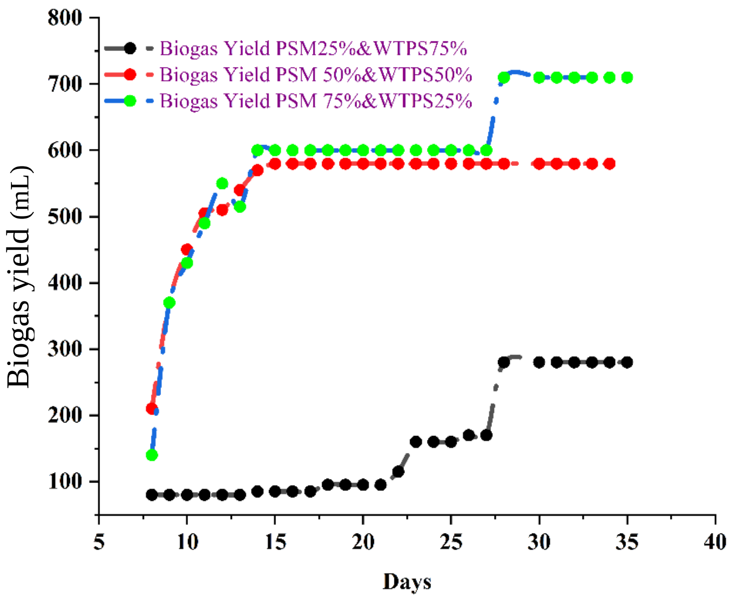


Fig. 18. Biogas yield of PSM at different mixing ratios with WTPS

A combination of PSB 75% & WTPS 25% has shown the highest biogas production, but PSB 25% & WTPS 75% has shown the lowest biogas production from the Plate Scrap Bread group biogas production process, as shown in Fig. 19.

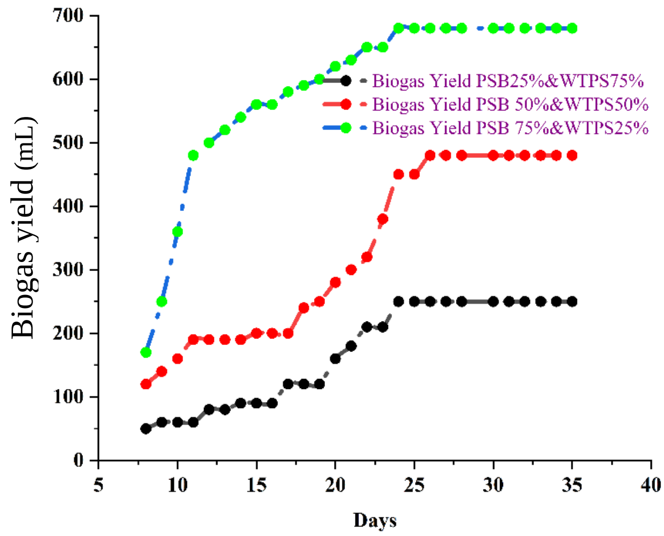
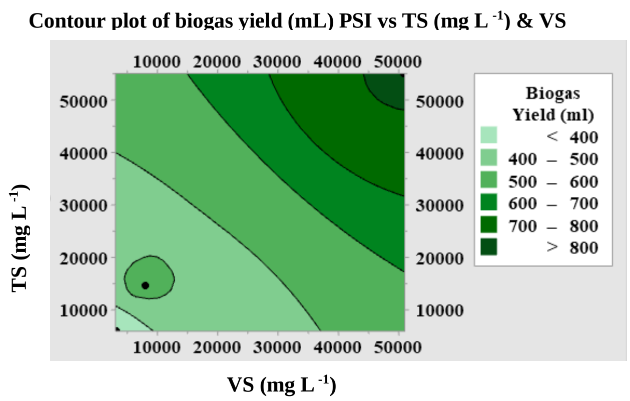
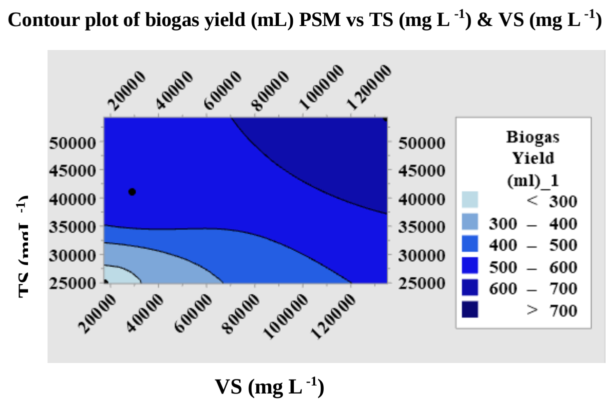


Fig. 19. Biogas yield of PSB at different mixing ratios with WTPS

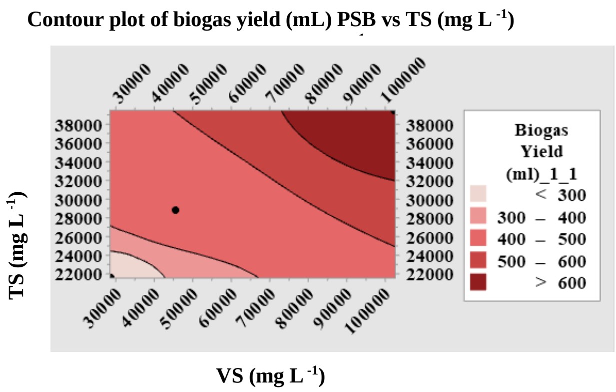
Fig. 20 shows the impact of total and volatile solids on biogas yields. The higher the total and volatile solids, the higher the biogas yield.



(a) Biogas yield of PSI vs TS



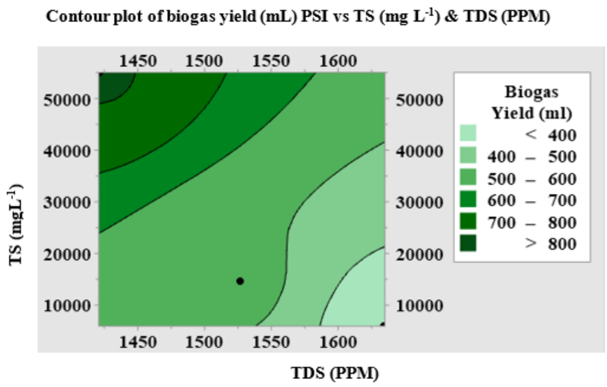
(b) Biogas yield of PSM vs TS



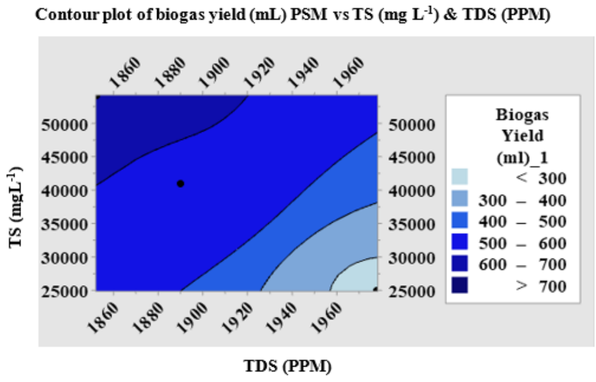
(c) Biogas yield of PSB vs TS

Fig. 20. Biogas yield vs TS and VS

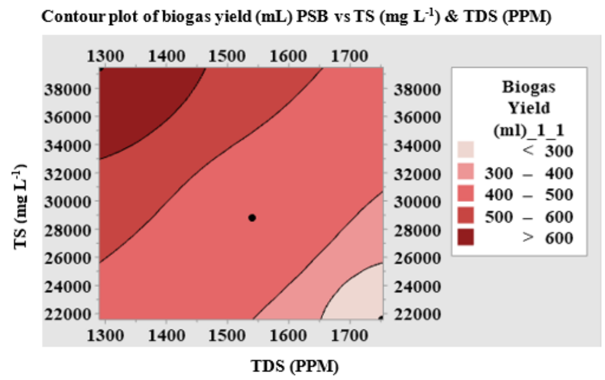
Fig. 21 shows the impact of total and total dissolved solids on biogas yields. The higher the total and total dissolved solids, the higher the biogas yield. The effects of TS and TDS on the biogas yield of PSB is less than the rest (PSI and PSM).



(a) Biogas yield of PSI vs TS and TDS



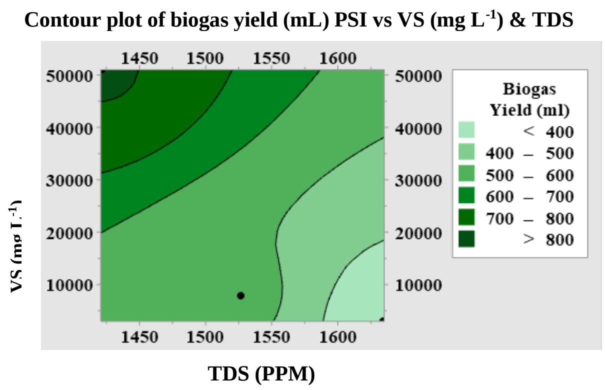
(b) Biogas yield of PSM vs TS and TDS



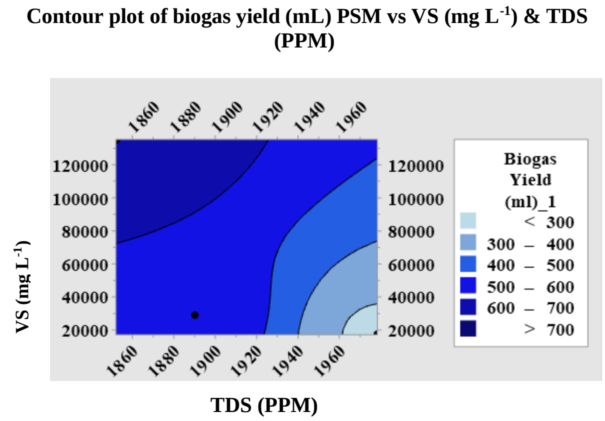
(c) Biogas yield of PSB vs TS and TDS

Fig. 21. Biogas yield vs TS and TDS

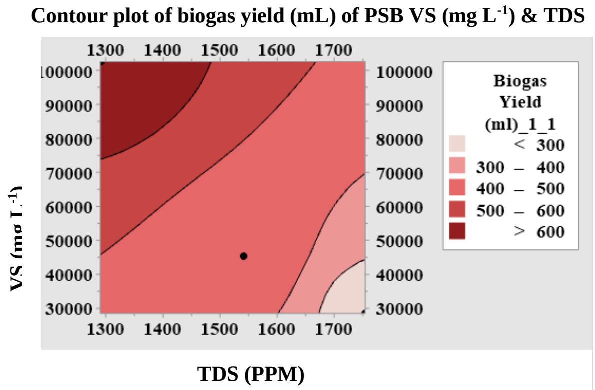
Fig. 22 shows the impact of Volatile and total dissolved solids on biogas yields. The higher the volatile and total dissolved solids, the higher the biogas yield.



(a) Biogas yield of PSI vs VS and TDS



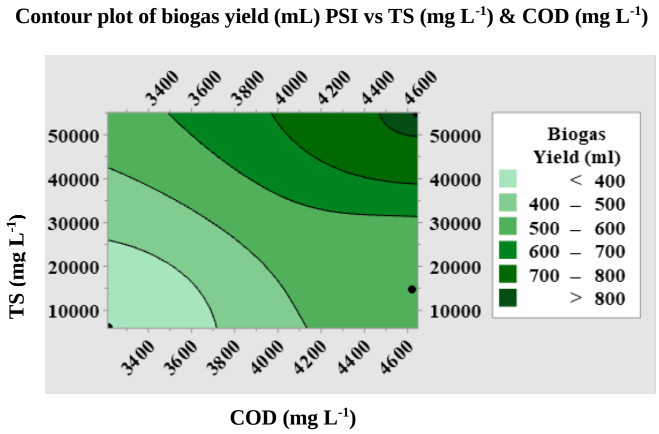
(b) Biogas yield of PSM vs VS and TDS



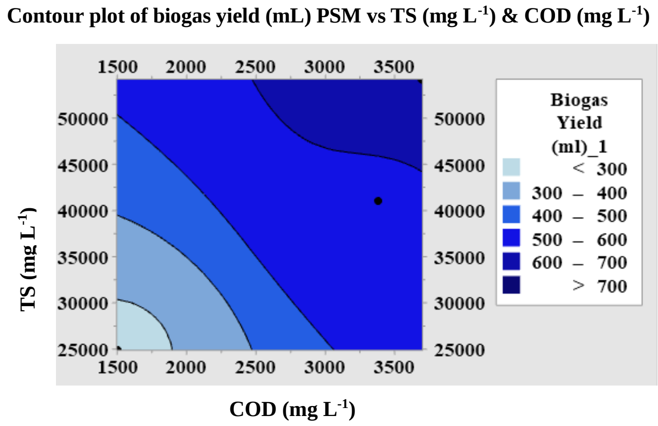
(c) Biogas yield of PSB vs VS and TDS

Fig. 22. Biogas yield vs and TDS

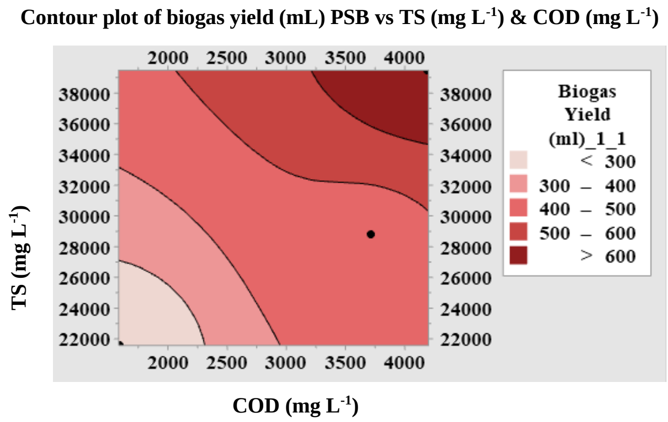
Fig. 23 shows the impact of total solid and Chemical oxygen demand on biogas yields. The higher the total solid and the lower the chemical oxygen demand, the higher the biogas yield.



(a) Biogas yield of PSI vs TS and COD



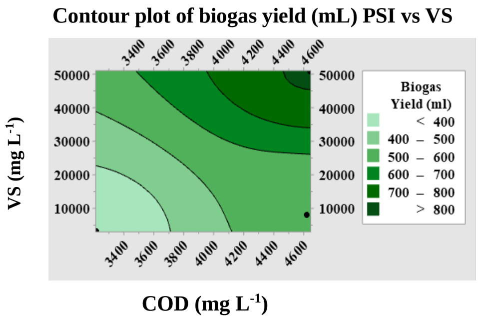
(b) Biogas yield of PSM vs TS and COD



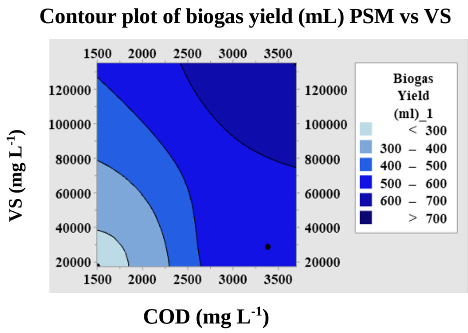
(c) Biogas yield of PSB vs TS and COD

Fig. 23. Biogas Yield vs TS and COD

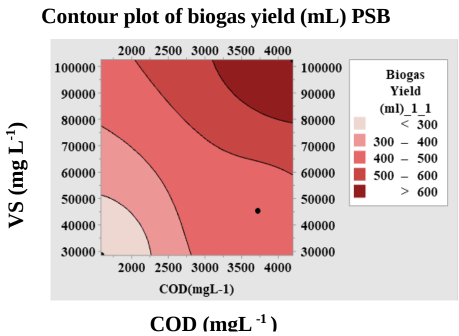
Fig. 24 shows the impact of volatile solids and Chemical oxygen demand on biogas yields. The higher the volatile solids and the lower the chemical oxygen demand, the higher the biogas yield.



(a) Biogas yield of PSI vs VS



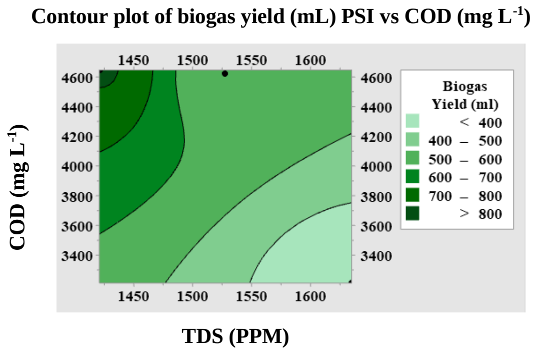
(b) Biogas yield of PSM vs VS



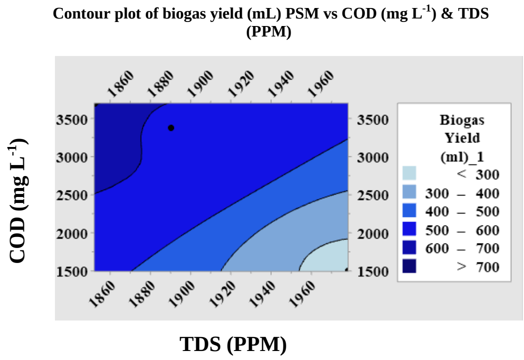
(c) Biogas yield of PSB vs

Fig. 24. Biogas Yield VS and COD

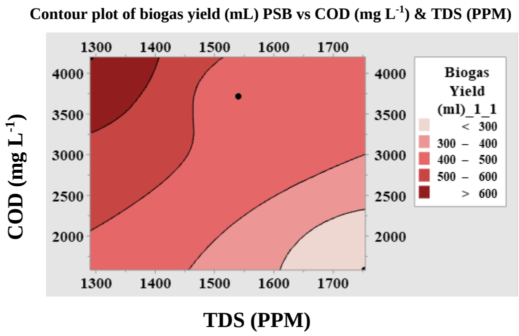
Fig. 25 shows the impact of volatile solid and Chemical oxygen demand on biogas yields. The higher the volatile solid and the lower the chemical oxygen demand will result in the higher biogas yield.



(a) Biogas yield of PSI vs TDS and



(b) Biogas yield of PSM vs TDS



(c) Biogas yield of PSB vs TDS and

Fig. 25. Biogas Yield vs TDS and COD

Measured methane

The measurement is conducted by indirectly assessing the amount of carbon dioxide produced with a gas analyzer. The maximum amount of methane from the produced biogas yield is 68% and similar research on food wastes of different combinations was 56.7, 58.6, 60.8, 60.1, and 59.4% (v/v) (Jayaraj, Deepanraj, & Velmurugan, 2014). To confirm the presence of methane in the produced gas, flame tests were conducted on sample reactors that had an adequate amount and pressure.

Statistical analysis on the biogas yield of different compositions (treatments)

The statistical analysis was done with IBM SPSS 26, and the results are presented in the tables below. In the statistical analysis, the compositions in the three treatments and with respective reactors were compared (R1, R2, and R3 in 25:75, 50:50, and 75:25).

Table 6 depicts which composition (treatments) showed the correlation coefficient of the two variances that indicate the direction and strength of the linear relationship (R) and the coefficient of determination (R square) among them. The results in column R showed that all the variances in different feedstocks and compositions had a positive linear relationship. The biogas yield (dependent variable) increased as the amount of food waste in the feedstocks increased. PSIR2,25,50,75 showed the maximum yield among the others, and PSBR2,25,50,75 was the lowest. Again, PSBR2,25,50,75 showed a strong relationship among the variance in a regression model.

Table 6- Summarized results from the model summary of the statistical analysis

No.	Combination	R	R square
1	PSIR1,25,50,75 (Plate Scrap Injera Reactor 1 at 25%, 50%, and 75% of Injera composition)	.849 ns	0.72

2	PSIR2,25,50,75 (Plate Scrap Injera Reactor 2 at 25%, 50%, and 75% of Injera composition)	.875 ns	0.765
3	PSIR3,25,50,75 (Plate Scrap Injera Reactor 3 at 25%, 50%, and 75% of Injera composition)	.676 ns	0.457
4	PSMR1,25,50,75 (Plate Scrap Mixed Reactor 1 at 25%, 50%, and 75% of Injera composition)	.679 ns	0.46
5	PSMR2,25,50,75 (Plate Scrap Mixed Reactor 2 at 25%, 50%, and 75% of Injera composition)	.700 ns	0.49
6	PSMR3,25,50,75 (Plate Scrap Mixed Reactor 3 at 25%, 50%, and 75% of Injera composition)	.719 ns	0.517
7	PSBR1,25,50,75 (Plate Scrap Bread Reactor 1 at 25%, 50%, and 75% of Injera composition)	.768 ns	0.590
8	PSBR2,25,50,75 (Plate Scrap Bread Reactor 2 at 25%, 50%, and 75% of Injera composition)	.598 ns	0.358
9	PSBR3,25,50,75 (Plate Scrap Bread Reactor 3 at 25%, 50%, and 75% of Injera composition)	.822 ns	0.676

ns: no statistically significant difference between those treatments at that significance level

Tables 7, 8, and 9 depict the significance of the experiments on biogas yield from PSI in different combinations. The significance level indicates that all combinations were significant, and there was a significant difference between the means.

Table 7- ANOVA table of biogas yield of PS Injera R1,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	824180.000	1	824180.000	72.020	.000
	Residual	320424.167	28	11443.720		
	Total	1144604.167	29			

Dependent Variable: Biogas Yield R1,25,50,75%; Predictors: (Constant), PS Injera

Table 8- ANOVA table of biogas yield of PS Injera R2,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	1113920.000	1	1113920.000	91.357	.000
	Residual	341404.167	28	12193.006		
	Total	1455324.167	29			

Dependent Variable: Biogas Yield R2,25,50,75%; Predictors: (Constant), PS Injera

Table 9- ANOVA table of biogas yield of PS Injera R3,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	258781.250	1	258781.250	23.553	.000
	Residual	307642.917	28	10987.247		
	Total	566424.167	29			

Dependent Variable: Biogas Yield R3,25,50,75%; Predictors: (Constant), PS Injera

Tables 10, 11, and 12 illustrate the significance of the experiments on biogas yield from PSM in various combinations. The significance level indicates that all combinations were significant, and there was a substantial difference between the means.

Table 10- ANOVA table of biogas yield of PS Mixed R1,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	589961.250	1	589961.250	23.888	.000
	Residual	691505.417	28	24696.622		
	Total	1281466.667	29			

Dependent Variable: Biogas Yield R1,25,50,75%; Predictors: (Constant), PS Mixed

Table 11- ANOVA table of biogas yield of PS Mixed R2,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	569531.250	1	569531.250	26.930	.000
	Residual	592165.417	28	21148.765		
	Total	1161696.667	29			

Dependent Variable: Biogas Yield R2, 25, 50, 75%; Predictors: (Constant), PS Mixed

Table 12- ANOVA table of biogas yield of PS Mixed R3,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	556111.250	1	556111.250	29.954	.000
	Residual	519835.417	28	18565.551		
	Total	1075946.667	29			

Dependent Variable: Biogas Yield R3,25,50,75%; Predictors: (Constant), PS Mixed

Tables 13, 14, and 15 depict the significance of the experiments on biogas yield from PSB in different combinations. The significance level indicates that all combinations were significant, and there was a significant difference between the means.

Table 13- ANOVA table of biogas yield of PS Bread R1,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	521645.000	1	521645.000	40.351	.000
	Residual	361971.667	28	12927.560		
	Total	883616.667	29			

Dependent Variable: Biogas Yield R1,25,50,75%; Predictors: (Constant), PS Bread

Table 14- ANOVA table of biogas yield of PS Bread R2,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	245311.250	1	245311.250	15.585	.000
	Residual	440726.250	28	15740.223		
	Total	686037.500	29			

Dependent Variable: Biogas Yield R2, 25, 50, 75%; Predictors: (Constant), PS Bread

Table 15- ANOVA table of biogas yield of PS Bread R3,25,50,75%

	Model	Sum of Squares	df	Mean Square	F	Sig.
1	Regression	768320.000	1	768320.000	58.526	.000
	Residual	367576.667	28	13127.738		
	Total	1135896.667	29			

Dependent Variable: Biogas Yield R3,25,50,75%; Predictors: (Constant), PS Bread

Conclusion

From this study, the following conclusions were made:

Co-digestion is helping to convert two or more biodegradable waste feedstocks into a usable form of energy. On one hand, it creates an opportunity to manage wastes that emit harmful gases, and on the other hand, it can be a source of energy and organic fertilizer.

This research measured the biogas produced and the amount of methane in the produced biogas. To confirm the presence of methane in the produced gas, flame tests were conducted on sample reactors that had an adequate amount and pressure. The combination of 75% PSI and 25% WTPS yielded the highest average biogas, with total solids recorded at 55,066 mg L^{-1} and volatile solids at 51,000 mg L^{-1}, producing 810 mL of biogas with a methane content of 68%.

Canteen waste cannot produce biogas unless combined with other feedstocks that have methane bacteria, so mixing it with wastewater treatment sludge and cow manure can be a solution to produce biogas. Therefore, the co-digestion of plate scraps blended with wastewater treatment sludge has raised the biogas yield.

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Conflict of interest statement

On behalf of all authors, the corresponding author declares that there are no conflicts of interest.

Data access statement

The data presented in this article originate from an unpublished PhD dissertation. Supporting data are available from the authors upon reasonable request.

Authors' declaration statement

This manuscript is the authors' original work and has not been published elsewhere. All authors have reviewed and approved its submission.

Authors Contribution

W. Asrat: Led the conceptualization, experimental design, and execution, data analysis, and resource provision. Drafted the manuscript and conducted reviewing, editing, and proofreading.

K. Purushottam Kolhe: Contributed to conceptualization, research analysis, and resource allocation. Assisted in drafting, reviewing, editing, and visualization.

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هضم هم‌زمان لجن تصفیه‌خانه فاضلاب و ضایعات نان برای افزایش بازده بیوگاز

وویشت اسرات[1]، کیشور پوروشوتام کوله[2]*

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چکیده

این تحقیق به دنبال تعیین بالاترین بازده ممکن با ادغام لجن تصفیه‌خانه فاضلاب با پسماند غذایی در دانشگاه علوم و فناوری آداما (ASTU) در اتیوپی است. مشخصات خوراک و تولید همزمان بیوگاز بر روی نسبت‌های مختلف ترکیبی از ضایعات غذایی (PS)، لجن تصفیه‌خانه فاضلاب (WTPS) و ۱۰۰ میلی‌لیتر کود گاوی انجام شد. میزان جامدات کل (TS) و محتوای رطوبت (MC) خوراک‌ها قبل از ترکیب و میزان TS، VS، TDS، COD، BOD و pH پس از ترکیب ارزیابی شدند. این آزمایش در دو مرحله با استفاده از سه حمام آب و بیست و هفت راکتور ناپیوسته (BR) که حجم هر کدام ۲/۵ لیتر بود انجام شد. در مرحله اول، از هجده راکتور و در مرحله دوم آزمایش از نه راکتور استفاده شد. برای ارزیابی ویژگی‌های نمونه خوراک و اجرای آزمایش، از آزمایش با سه تکرار استفاده شد. راکتورها به مدت سی و پنج روز در زمان ماند هیدرولیکی و دمای ۵۰ درجه سانتی‌گراد کار کردند. بازده روزانه بیوگاز با استفاده از روش جابه‌جایی آب، بازده کل بیوگاز و ترکیب متان اندازه‌گیری و گزارش شد. سه راکتور فرعی برای یافتن میانگین بازده بیوگاز هر راکتور در نظر گرفته شده است. افزایش قابل‌توجهی در بازده روزانه و کل بیوگاز در راکتور با ترکیب ۷۵ درصد PS نان اینجرا و ۲۵ درصد WTPS مشاهده شد. حداکثر و میانگین بازده روزانه بیوگاز ۲۲۰ میلی‌لیتر و ۸۱۰ میلی‌لیتر به‌دست آمد، با TS ۵۵۰۶۶ میلی‌گرم در لیتر و VS ۵۱۰۰۰ میلی‌گرم در لیتر. حداکثر متان درون بیوگاز تولیدی ۶۸٪ بود که با تیمار ۷۵٪ ضایعات نان اینجرا (PSI) و ۲۵٪ WTPS حاصل شد. این ترکیب همچنین بالاترین بازده بیوگاز را داشت.

واژه‌های کلیدی: بازده بیوگاز، تولید همزمان، هضم بی‌هوازی (AD)، PS، WTPS

۱- گروه مهندسی مکانیک، دانشکده مهندسی مکانیک، شیمی و مواد، دانشگاه علوم و فناوری آداما، آداما، اتیوپی
۲- گروه مهندسی مکانیک، کالج مهندسی سینگهد، وادگان (ب.ک.)، پونه-۴۱۱۰۴۱، دانشگاه پونه، هند
(*- نویسنده مسئول: Email: kishorkolhe05@gmail.com)

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