Comparative potential of biogas production from the distillery, fruit and vegetable waste and their mixtures (digestion).

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Heliyon 11 (2025) e42068

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Comparative potential of biogas production from the distillery, fruit and vegetable waste and their mixtures (digestion)

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ARTICLE INFO

Keywords:
Co-digestion
Distillery waste
Fruit-vegetable waste and methane yield

ABSTRACT

Biogas is becoming increasingly important as a renewable energy source in the face of global warming and declining fossil fuel reserves. Biogas is produced by anaerobic digestion of organic materials which can be available from various wastes such as agro-industrial, human, fruit waste, distillery, animal waste and aquatic plants. This study deals particularly with the comparative potential of biogas production from distillery, fruit and vegetable waste and their mixtures (digestion). The materials used as feed in this research were distillery waste which is dark-colored liquid waste from Desta Alcohol and Liquor Factory Private Limited Company. Fruit and vegetable waste such as banana peels, papaya, mango, tomato, avocado, cabbage leaves, watermelon skin, and orange skin were collected from juice houses and fruit and vegetable wholesale markets in Mekelle City, and Cow manure used as a buffer solution, collected from Desta Alcohol and Liquor Factory PLC. Waste samples were characterized for total solids, volatile solids, pH, biochemical oxygen demand, and chemical oxygen demand according to established standards. Biogas was analyzed using a biogas analyzer, an ORSAT apparatus for CO_2, and a TUTWILER apparatus for H_2S. Finally, the %CH4 was calculated from 100 % by ignoring other gases. The maximum biogas production from all wastes was observed at 37 °C. Mixture (co-digestion) produced high biogas in litter (L): 6.95, 9.47 and 9.54 at 20 °C, 37 °C and 50 °C respectively. The maximum methane composition was observed from the co-digestion (M) in (%) 67, 70 and 70.3 at 20 °C, 37 °C and 50 °C respectively. Methane yield was calculated at both temperature and substrates (waste). Comparatively, maximum methane yield was observed at 37 °C for distillery waste, fruit vegetable waste and mixture(digestion); 0.032, 0.061 and 0.079 L per gram volatile solids digestion (LCH_4/gVS) respectively.

1. Introduction

Renewable and sustainable energy development is vital for meeting global energy needs. Ideally, these sources should have minimal negative impacts on the environment [1,2]. Producing renewable energy from locally sourced materials offers significant advantages, including reduced production costs. Municipal waste management systems often use organic waste to generate energy by

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https://doi.org/10.1016/j.heliyon.2025.e42068
Received 21 August 2024; Received in revised form 28 December 2024; Accepted 16 January 2025
Available online 17 January 2025

burning it in waste-to-energy plants or collecting methane from decomposing landfills. However, although these systems use energy from various waste sources, they typically do not directly benefit waste generators and may even lead to extra collection expenses for them [3]. Biogas is a biofuel produced through the naturally occurring anaerobic digestion of biodegradable materials and wastes [4]. It results from the fermentation of organic matter under anaerobic conditions by bacteria that occur naturally in environments like marshes, sediments, wetlands, and certain insect species [5]. It is a mixture of gases, primarily composed of carbon dioxide, methane, and hydrogen sulfide, which are produced and collected [6].

Different technologies are available to treat waste from fruits, vegetables, and distilleries. These include biological methods like anaerobic and aerobic digestion, as well as physico-chemical processes such as adsorption, coagulation, flocculation, oxidation, membrane treatment, and evaporation/combustion. Anaerobic digestion is the best treatment for fruit, vegetable, and distillery waste due to its effectiveness as a biological option [7]. Anaerobic digestion (AD) is a promising technology that breaks down organic materials using microorganisms in an oxygen-deprived environment, resulting in energy recovery from municipal solid waste [6,8]. This process breaks down organic waste into simpler, stable end products. As a result, anaerobic digestion has become the primary method for managing large-scale organic waste, demonstrating a significant 30 % annual growth rate over the past decade [4]. Digesting biomass to produce biogas involves four key chemical stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [9]. Anaerobic digestion, the process that creates biogas, involves a series of interconnected steps where the starting material is progressively broken down into smaller components. Each step is facilitated by specific groups of microorganisms that successively decompose the products of the previous step [10]. The amount of methane produced from biomass during decomposition is a key factor determining the rate of organic material breakdown. However, the more readily a substance decomposes (its "putrescibility"), the greater the methane yield, leading to a faster biodegradation process. Multiple factors impact biogas production efficiency, such as volatile solids, loading rate, temperature, retention time, pH, moisture content, carbon-nitrogen ratio, and more [1]. Distillery industries in developing nations are major contributors to water pollution. A staggering 88 % of their raw materials become waste, which is often discharged directly into waterways, contaminating the water supply. The disposal of large quantities of biodegradable waste without proper treatment results in significant environmental pollution, making it a primary source of aquatic and soil contamination [11].

One main challenge of anaerobic digestion of fruit-vegetable and distillery wastes is the fast acidification caused by their low pH and higher volatile fatty acids (VFAs) production. This acidification hinders methane production in the digester [12]. However, fruit and vegetable wastes, with their high biodegradable nature, rich organic matter content, and high moisture content, make them ideal feedstock materials for biogas digesters [13]. Therefore, fruit and vegetable waste can be ideal feedstock materials for biogas production when co-digested with other biomass to enhance methanogenic activity. Converting distillery and fruit-vegetable wastes provides several long-term benefits: reduces greenhouse gas emissions (CO2 and methane), eliminates odors, produces nutrient-rich liquid for algal cultivation and plant irrigation, maximizes waste recycling, reduces reliance on imported fossil fuels, saves money, and decreases greenhouse gas emissions into the atmosphere [14]. The amount and type of organic material added to the system affect the production of biogas and methane in anaerobic digestion of biodegradable matter [3]. Therefore, distillery, fruit and vegetable wastes, and their mixtures can be subjected to anaerobic digestion for energy production in various ways. Biogas stands out among other renewable energies due to its unique characteristics, including utilization and control of organic waste, production of fertilizer and recycling water for agricultural irrigation. Furthermore, biogas production is not geographically limited, does not require advanced technology, and is simple to implement and utilize. It has a positive environmental impact, generating less carbon dioxide during combustion than is used for photosynthesis by the plants from which it is produced [15].

The experimental study aimed to compare and optimize biogas and methane production from anaerobic digesters using pure distillery waste, fruit and vegetable waste, and a mixture of distillery waste with fruit and vegetable waste. Distillery and fruit vegetable wastes were mixed at different ratios to optimize the production potential of distillery and fruit vegetable wastes under anaerobic degradation. The digester was operated with 100 % Distillery waste, and 100 % Fruit vegetable waste and the mixture of the distillery and fruit vegetable wastes were mixed with 50 % DW and 50 % FVW, 75 % DW and 25 % FVW and 25 % DW and 75 % FVW.

2. Materials and methods

2.1. Feedstock's (inputs)

The feedstock materials used for biogas and methane production in this laboratory study were, samples of pure distillery waste (DW), samples of pure fruit and vegetable waste (FVW), mixtures of DW and FVW at the following ratios, 50 % DW and 50 % FVW, 75 % DW and 25 % FVW, 25 % DW and 75 % FVW, 1 % v/v cow manure added to all of the above materials.

Distillery waste was collected from Desta Alcohol and Liquor Factory PLC, while fruit and vegetable waste were collected from juice houses in Mekelle city. Distillery waste was collected using plastic bottles, and fruit and vegetable waste was collected using plastic bags. The fruit and vegetable feedstock were manually shredded into small pieces, ground using a juicer to reduce particle size, and then mixed with distillery waste (if applicable) to ensure homogeneity in the digester.

2.2. Chemicals

To initiate the digestion process, 1 % v/v animal manure digestate from the anaerobic digester at Desta Alcohol and Liquor Factory PLC was used as an inoculum. The following chemicals were utilized during the anaerobic digestion experimental analysis: Buffer solution (EDS-OM-11001), Distilled water, Starch solution (maize starch (USP/BP)), Iodine (sesame oil USP/BP/ip), COD reagent

($HgSO_4$, $K_2Cr_2O_7$, 1.1-phenanthroline monohydrate, $FeSO_4{\cdot}7H_2O$), Tap water, Nitrification inhibitor B (Allyl Thiourea or ATH) and KOH (1310-58-3).

2.3. Methods

2.3.1. Sample collection and preparation

The collected FVW had a water content of 67.25 % and a total solid (TS) content of 32.75 %. Juicers and crushers were used to adjust the pH and TS values of the FVW. To prepare FVW samples for the experiment, raw materials were mixed with tap water to achieve an 8 % TS concentration [13].

The adjustment in Fig. 1 simplified pH measurement of fruit-vegetable waste by adding 3–4 L of tap water per kg of FVW for an 8 % total solid solution.

2.3.2. Physico-chemical analyses and sample characterization

2.3.2.1. pH. The sample's pH was measured using a CP-505 laboratory pH meter calibrated at neutral pH. The pH meter's electrode was placed in the prepared solution containing distillery, fruit and vegetable wastes, and their mixtures. A reading was then recorded from the aqueous sample.

2.3.2.2. Total solid (TS). The total solid measurement represents the total dry matter in the sample preparation. It includes both organic and inorganic matter [3]. To measure the total solid in the sample, clean crucibles were dried in an oven and weighed using a digital balance. The sample was then added to the crucible and reweighed, following a standard procedure. The oven was set to 105 °C and allowed to reach this temperature [13,16]. Each sample type was placed in a crucible and dried in an oven for 24 h until a constant weight was reached. The dried sample was then weighed promptly to prevent moisture absorption. The overall calculation of the total solids was:

$$\%TS = \frac{W_{DS}}{W_{WS}} * 100\% \quad \text{Eq (1)}$$

$$W_{WS} = (W_{DC} + W_{WS}) - W_{DC} \quad \text{Eq (2)}$$

$$W_{DS} = (W_{DC} + W_{DS}) - W_{DC} \quad \text{Eq (3)}$$

Where.

%TS Percentage of total solids.
W_{DS} Weight of dry sample in grams
W_{WS} Weight of wet sample in grams
W_{DC} Weight of dry crucible in grams

2.3.2.3. Volatile solids (VS). The sample dried at 105 °C in an oven needed additional heating in a muffle furnace at 550 °C for 1 h at a constant temperature [3,16]. The crucible was cooled in the desiccator and weighed again. The volatile solids were determined by the following calculation:

$$\%VS = \frac{W_{VS}}{W_{DS}} * 100 \quad \text{Eq (4)}$$

$$W_{VS} = W_{DS} - Ash \quad \text{Eq (5)}$$

Where.

%VS Percentage of volatile solids.
W_{VS} Weight of volatile solids
W_{DS} Weight of dry sample at 105 °C

2.3.2.4. Chemical oxygen demand (COD). Chemical oxygen demand (COD) is a measure of the organic matter content of feedstock, which can indicate its potential for biogas production [17]. To measure COD, samples of distillery, fruit-vegetable, and a mixture waste

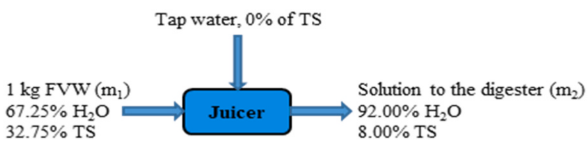

Fig. 1. Mass balance of fruit-vegetable waste in juicer.

were neutralized to the desired pH by adding buffer solution and inoculum. Specific volumes of the samples were used: 45.299 ml of distillery waste, 40.276 ml of fruit-vegetable waste, and 46.011 ml of the mixture waste. Measurements were recorded at 20 °C, 37 °C, and 50 °C. The COD analysis was conducted using a standard test tube. 0.05g $HgSO_4$ and 1.5 ml of 0.25N $K_2Cr_2O_7$ were added to the test tube, followed by the addition of the sample. The test tube was securely capped, placed in a safety bottle, and shaken vigorously. The tubes were then incubated in a COD digester at 148 °C for 2 h. After cooling to room temperature on a pipette stand, 2–3 drops of ferroin indicator solution (prepared by dissolving 1.485 g of 1,10-phenanthroline monohydrate and 695 mg of $FeSO_4 \cdot {}_7H_2O$ in 100 ml of distilled water) were added to each tube. Finally, the test tube was cleaned, and the COD reading was measured in mgO_2/l using a COD reading hatch.

2.3.2.5. Biochemical oxygen demand (BOD). Biochemical oxygen demand (BOD) measures the dissolved oxygen needed by microorganisms to break down organic matter in a water sample at 20 °C over five days [17]. For laboratory analysis of BOD, the pH of the sample was first adjusted to neutral, similar to the procedure for chemical oxygen demand (COD). After pH adjustment, 157 ml of DW, FVW, and M were poured into BOD vials. Each vial received four to five drops of nitrification inhibitor B (Allyl Thiourea or ATH) and four drops of 45 % KOH solution. The vials were tightly sealed with caps having a CO2-absorbing gasket, then incubated in a BOD chamber for five days. The BOD incubator provides readings in mgO_2/l.

2.4. Experimental set up

Before conducting the experiment, it was important to consider the key factors influencing anaerobic digestion. Several factors impact anaerobic digestion, with temperature, retention time, and substrate type being crucial for the process. This experiment was conducted at three different temperature ranges, each with a corresponding retention time. From the psychrophilic temperature (20 °C), mesophilic (37 °C) and thermophilic (50 °C) with their retention time (8, 10, 12, 14, 16, 18, 20, 22 and 24 days) for each temperature range conducted. The substrates used were distillery, fruit and vegetable and their co-digestion (mixture). Co-digestion experiments were conducted to select the best composition for biogas production with 50 % DW-50 % FVW, 75 % DW-25 % FVW and 25 % DW-75 % FVW samples at three different temperatures (20 °C, 37 °C and 50 °C). Next, the co-digestion with maximum biogas production of (75 % DW-25 % FVW) along with 100 % DW and 100 % FVW samples were investigated.

Two-liter capacity plastic bottles served as both digesters and collectors for the distillery waste (DW), fruit-vegetable waste (FVW), and their mixtures as shown in Fig. 2. A 1 % v/v of yeast, distilled water and potato agar (inoculum) was added to each sample. The mixture sample was prepared using a 75 % DW and 25 % FVW ratio. Water baths were used to maintain operating temperatures of 37 °C and 50 °C. For each temperature, 1.5 L of each sample were mixed with 15 ml of 1 % v/v inoculum then put into 2-L plastic bottles. Bottles were sealed anaerobically with mastic and plaster. Glass tubes were tightly attached to the digester's airtight fittings, extending with stretchable tubes to a urea bag. During digestion, the biogas produced was collected in the urea bag and analyzed using an analyzer to determine its composition (%CO_2, %H_2S). The percentage of methane (%CH4) was calculated by subtracting the percentages of other gases from 100 %.

Valves regulated gas flow from digester to either airbag or syringe. During digestion, the valve opened for biogas collection in the airbag, later analyzed for %CH4, %CO2, and %H2S composition. For analysis, the flow line was closed from digester to airbag and opened from airbag to syringe.

2.5. Product characterization

After setting up the anaerobic digestion experiment, a period of time was needed for biogas production and subsequent composition analysis. Due to the need to collect sufficient biogas for analysis, a time gap was maintained between successive measurements. The biogas composition was analyzed using a gas analyzer. The ORSAT apparatus was used to determine the percentage of carbon dioxide (%CO_2), using 125g of KOH. The TUTWILER apparatus was used to determine the percentage of hydrogen sulfide (%H_2S), employing a 2 % starch solution and 0.01N iodine. ORSAT indicated the total composition of carbon dioxide from the total biogas production and

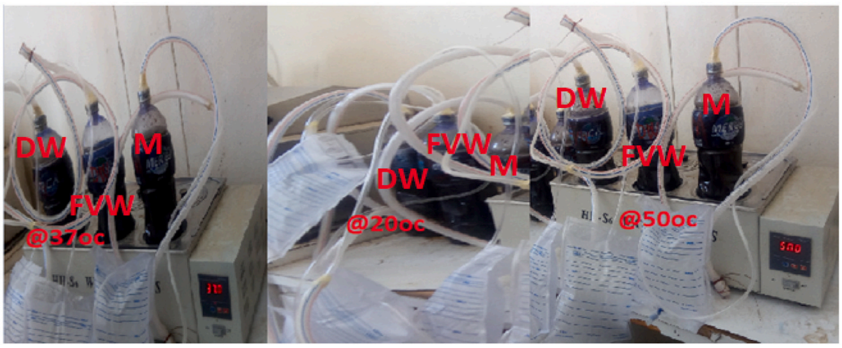

Fig. 2. Experimental set up in the laboratory.

TUTWILER indicated the total composition of hydrogen sulfide from the total biogas production. The percentage of methane (%CH_4) was calculated by subtracting the percentages of CO_2 and H_2S from 100 % by ignoring other gases in the biogas composition.

2.6. Methane yield

The biogas produced in the airbag was measured using a 2000 ml syringe. Methane yield for each substrate was calculated based on the volatile solids consumed by microorganisms during digestion, using the following equation (6).

$$CH_4 \text{ Yield} \left(\frac{l}{g} VS\right) = \frac{sum\ of\ biogas(l) * CH_{4\ Porduced(\%)}}{VS_{[g]}\ fed} \qquad \text{Eq (6)}$$

$$g\ VS = \text{total solid in the digester (g)* change in } \%VS = TS*(VS_I - VS_F)$$

$$CH_4 \text{ Yield} \left(\frac{l}{g} VS\right) = \frac{\sum_{8}^{24} Bg_{i*\%CH_{4_i}}}{TS*(VS_i - Vs_f)} \qquad \text{Eq (7)}$$

Where.

VS_i = % volatile solid of fed

VS_F = % volatile solid of digestate

Bg_i = biogases in litters each run of the digester

% CH_{4i} = percent methane each run of the digester

3. Results and discussion

3.1. Physico-chemical characterization waste sample

Different standard producers were used to characterize distillery, fruit-vegetable wastes, and their co-digestion for each parameter. Samples were collected and prepared, followed by pH measurement using a pH meter before mixing with buffer solution and inoculum. The pH of raw samples of FVW, DW and mixtures (M) are 3.687, 4.07, and 3.8, respectively. The pH of raw distillery is in the range of 3–4.5 and lower pH values for fruit and vegetable wastes are <5 [18,19]. However, the pH analysis for the experiment was conducted after the samples were mixed with buffer solutions and inoculum. The pH values of the diluted solutions were 6.735 for FVW, 6.535 for DW, and 7.033 for the mixtures (M). The general summary of pH value before and after dilution is given in Fig. 3.

The pH value is one of most important parameters for waste characteristics [20]. As indicated in Table 1, distillery waste has a relatively low pH value after it is treated (diluted) with buffer solution and tap water. Pedro Cerqueira [21], states that when distillery wastes are diluted with different dilutions, it change from neutral to alkaline. It shows that pH increases with dilution. Fruit vegetable waste is observed in Table 1 alkali (basic) compared with distillery waste. Mixing DW and FVW wastes can neutralize each other, allowing for co-digestion to prevent adverse conditions like low pH, excessive VFAs, and toxic substance build-up in the digestion environment [22]. The pH of the mixed wastes in each digester was between 6 and 7.2, ideal for biogas production. This suggests that the microorganisms in the anaerobic digesters were not harmed by the slurry's pH, as found in the investigation by Deressa [3].

Among the two wastes and their co-digested mixtures (as indicated in Table 1), distillery waste (DW) has a relatively high volatile solids (VS) content of 94.94 %. Volatile solids are the part of total solids that are likely to turn into biogas. This is in line with the typical approach in research to show CH_4 yield as volume of methane produced per gram of volatile solids digested. The volatile solid content of the fruit-vegetable waste (FVW) was 82.6 %, exceeding the typical range of 75%–80 % [23,24]. This result indicates that a significant portion of the FVW is biodegradable, making it a suitable feedstock for biogas production. While co-digestion (mixture) has a relatively lower volatile solid content compared to pure distillery waste and fruit-vegetable waste, this is attributed to the addition of tap water during dilution with buffer solution and inoculum.

High volatile solid concentrations, as found in pure distillery and fruit-vegetable wastes, can pose challenges. They can block gas

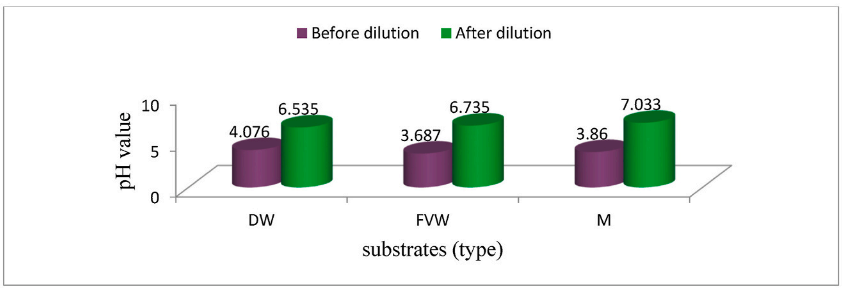

Fig. 3. pH values before and after dilution.

Table 1
Experimental sample analysis of (pH, VS, TS, COD and BOD).

Parameters	Waste type		
	Distillery waste (DW)	Fruit- vegetable waste (FVW)	Co-digestion(M)
pH	6.535	6.735	7.033
VS (%)	94.94	82.6	76.5
TS (%)	11.38515	8[a]	7.851
$COD_{(g/l)}$	23.3	10.65	14.62
$BOD_{5(g/l)}$	15.62	7.78	9.81

[a] Represent the ideal value biogas digester.

flow from the lower part of the digester, promote scum formation, and obstruct efficient circulation of the feed in the digester [25]. Conversely, excessive dilution, as observed in co-digested mixtures, leads to underutilization of the digester as water occupies a larger volume with less substrate available. Both scenarios can result in suboptimal gas production. Other critical biogas production factors like BOD and COD tended to decrease over the course of digestion. The average values of COD and BOD of treated distillery waste are 7–40 g/l and 5.5–20 g/l respectively [17]. The present study also agrees with the values reported by the researcher, which contain 23.3 g/l and 15.62 g/l for COD and BOD respectively. The general waste characterizations shown in Table 1.

3.2. Biogas production from anaerobic digesters

3.2.1. Effect of temperature, retention time and waste type on biogas production/process factors

The experimental results indicated that biogas production was lower at room temperature. At this temperature, maximum biogas production was observed after 18, 16, and 12 days of retention time for DW, FVW, and M, respectively, reaching 0.81, 0.88, and 1.08 L (as shown in Fig. 4). While all three substrates (DW, FVW, and M) showed an increase in biogas production after 14 days of retention time at room temperature, the biogas production from distillery waste (DW) decreased after 12 days. This decline is attributed to the acidic nature of distillery waste, which may not be optimal for bacterial biogas production. In contrast, both fruit-vegetable waste (FVW) and the mixture (M) showed an increase in biogas production between 8 and 12 days of retention time [17].

At 37 °C, maximum biogas production was achieved after 12 days for DW (1.27 L), 18 days for FVW (0.89 L), and 12 days for M (1.37 L) as shown in Fig. 5. Comparatively, at 50 °C, biogas production rates were higher. This is because increasing temperature can significantly enhance gas production. However, it is important to avoid sudden temperature increases to prevent a decrease in bio-methane production caused by the death of temperature-sensitive bacteria strains [26].

As shown in Fig. 6, at 50 °C, 1.25 L of biogas was produced from DW after 12 days of retention time, 1.25 L from FVW after 16 days, and 1.38 L from M after 14 days. The general trend of the graph lines at 20 °C, 37 °C, and 50 °C indicates a gradual decrease in biogas production, suggesting that the waste (substrate) in the digester is being consumed [27].

To compare biogas production from DW, FVW, and M at 20 °C, 37 °C, and 50 °C, biogas produced from nine individual anaerobic digesters (containing each substrate) over 24 days of retention time was collected for each temperature level as shown in Fig. 7. The cumulative biogas production increased with higher temperature, regardless of waste type. This matches the principle that anaerobic digestion rate rises with temperature, as explained by Mitchell [28]. Compared to pure distillery and fruit-vegetable wastes, the co-digested mixture (M) produced higher biogas yields: 6.95 L at 20 °C, 9.47 L at 37 °C, and 9.54 L at 50 °C, respectively, as shown in Fig. 7.

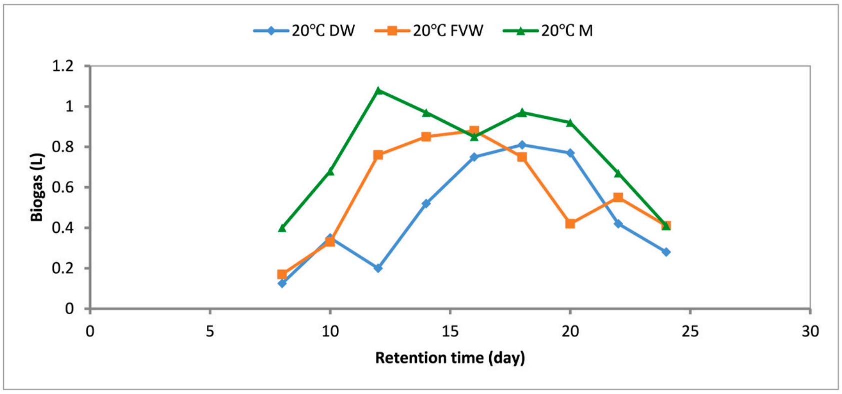

Fig. 4. Biogas produced at 20 °C.

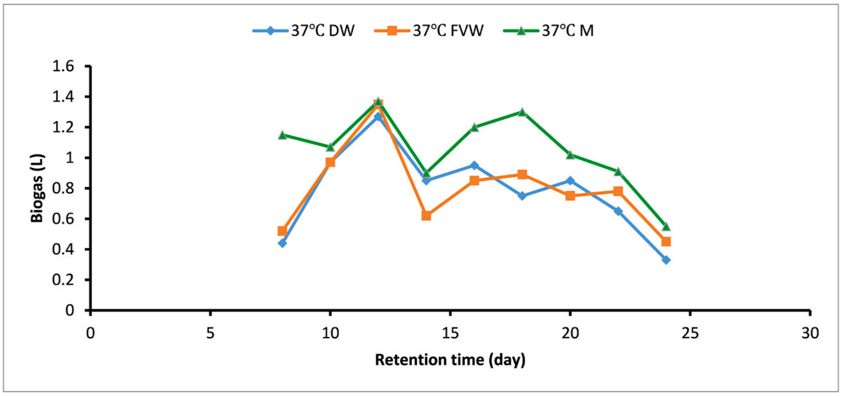

Fig. 5. Biogas produced at 37 °C.

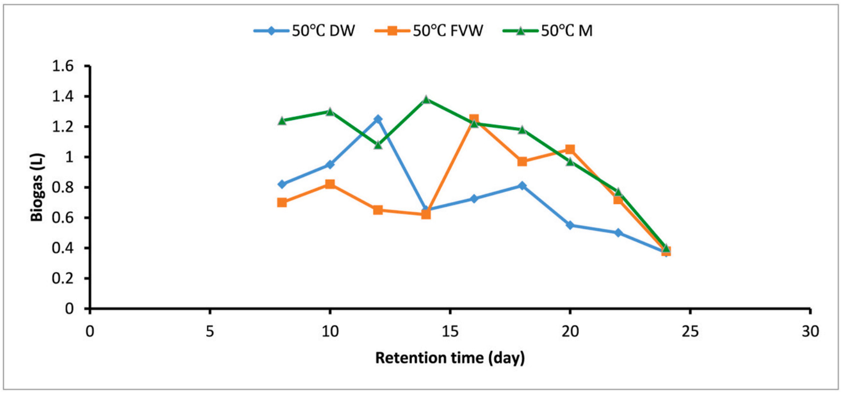

Fig. 6. Biogas produced at 50 °C.

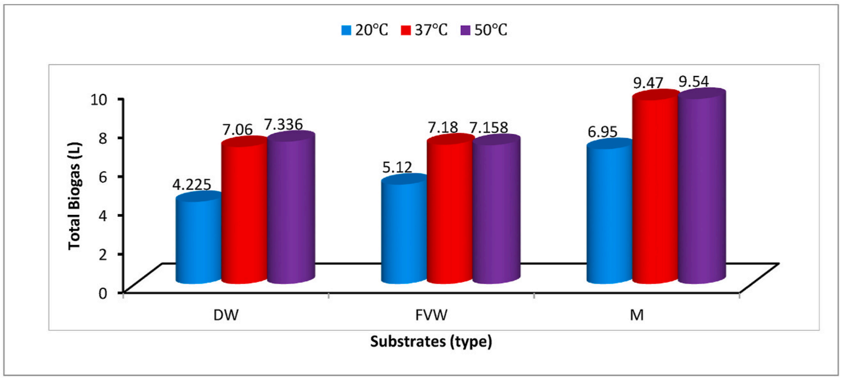

Fig. 7. Total biogas productions in liter of anaerobic digestion.

3.2.2. Effect of temperature, retention time and waste type on methane composition

Findings from the lab experiments showed that regardless of the waste types, the biogas had a higher percentage of methane at all three temperature levels [17]. At 20 °C, the maximum methane content (%CH4) was observed to be 58.5 % for DW after 20 days, 55.75 % for FVW after 18 days, and 70 % for the mixture (M) after 18 days of retention time as shown in Fig. 8. The mixture (M) produced biogas with the highest percentage of methane. Fruit-vegetable waste (FVW) was characterized by its low chemical oxygen demand (COD) value, likely due to the inhibition of ammonia accumulation (nitrogen), as expected.

As shown in Fig. 9, at 37 °C, the methane content in the anaerobic digester reached 65 % for DW after 18 days, 67.3 % for FVW after 18 days, and 70 % for the mixture (M) after 20 days of retention time, as illustrated in Fig. 9. Across all temperatures, the trend lines indicate an increase in methane production up to 20 days of retention time. However, after 20 days, the trend lines show a decrease,

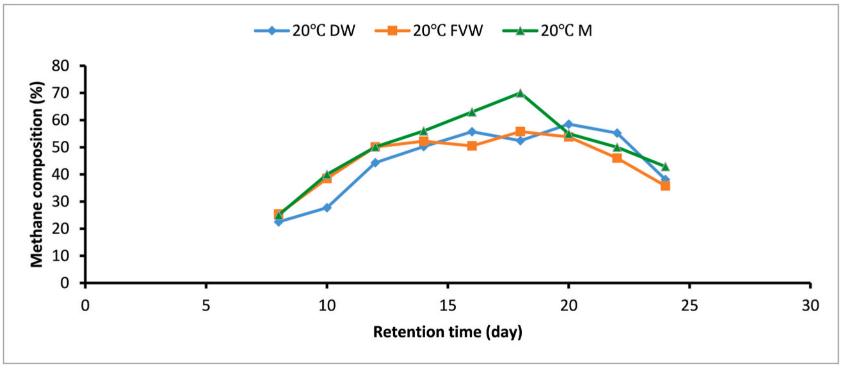

Fig. 8. Methane compositions in anaerobic digester at 20 °C.

suggesting that the substrate (waste) is no longer producing methane efficiently [27].

As illustrated in Fig. 10, methane production from the anaerobic digester increased until 20 days of retention time. After this point, a slight decrease was observed, likely due to a reduction in substrate accumulation (1). At 50 °C, the maximum methane content reached 70.2 % for DW, 64.8 % for FVW, and 70.3 % for M, all within 18 days of retention time.

To determine the maximum methane composition produced in each digester, the total methane produced over all days was summed. The mixture (M) consistently produced more methane than pure distillery waste (DW) and fruit-vegetable waste (FVW). The average methane percentages for the mixture were 50.21 % at 20 °C, 52.5 % at 37 °C, and 52.62 % at 50 °C as shown in Fig. 11. Both digesters containing distillery waste, fruit-vegetable waste, and the mixture produced the highest methane content at 37 °C. This demonstrates that methane production is optimized at moderate temperatures, often referred to as mesophilic temperatures in scientific contexts [28].

3.3. Methane yield

The initial volatile solid (VS) content of the distillery, fruit, and vegetable wastes, and their mixture was identical across all fermentation temperatures. However, at the end of the fermentation process, the VS content of the wastes differed due to variations in retention time and temperature. The methane (CH4) production was calculated by analyzing the changes in volatile solids (VS) during anaerobic digestion before disposing of the digestate, within a specified retention time [27]. The final value of VS is summarized in Table 2.

Methane yield was calculated using Equation (2.4). A full calculation summary of the CH_4 yield is given in Table 3 below.

$$\sum_{8}^{24} B_{gi} * \%CH_{4i}$$

Where B_{gi} biogas produced from each run of the digester

Methane yield provides a more accurate measure of anaerobic digestion performance than biogas yield, particularly when using precise CO_2 or H_2S detectors like the ORSAT or TUTWILER apparatus, respectively. The methane yield of distillery wastewater (DW) at 20 °C, 37 °C, and 50 °C was 0.024, 0.032, and 0.026 CH_4/gVS, respectively. Fruit and vegetable wastes (FVW) yielded 0.047, 0.061, and 0.044 CH_4/gVS at the same temperatures. The mixture (M) of these wastes yielded 0.063, 0.079, and 0.076 CH_4/gVS at 20 °C, 37 °C, and 50 °C, respectively.

The maximum methane yield was achieved at 37 °C, with values of 0.032, 0.061, and 0.079 CH_4/gVS for DW, FVW, and M, respectively. The lowest CH_4 yields were observed for DW and FVW, indicating that their digestion alone results in low biogas production despite their high pH value and high biodegradability, respectively. This is likely due to the inhibition of volatile fatty acids (VFAs) [29]. The summary of methane yield is shown in Fig. 12 for DW, FVW and M at (20 °C,37 °C and 50 °C) respectively.

4. Conclusion

This study investigated the biogas and methane production potential of distillery waste (DW), fruit-vegetable waste (FVW), and their co-digested mixture (M) using anaerobic digestion. Biogas production offers a renewable energy source and valuable organic fertilizer. This microbial process is influenced by retention time, temperature, volatile fatty acid content, and substrate type; controlling these factors optimizes biogas production. The wastes were characterized by their total solids (TS), volatile solids (VS), pH, biological oxygen demand (BOD), and chemical oxygen demand (COD). High VS content (94.94 % DW, 82.6 % FVW, 76.5 % M) indicated strong potential for biogas production. Total solids were also high (11.39 % DW, 8 % FVW, 7.85 % M), potentially hindering gas flow and causing scum formation in the digester.

Despite this, biogas production increased across all waste types, with the mixture (M) significantly outperforming DW and FVW alone in terms of biogas and methane yield. Maximum methane yield (0.079 lCH4/gVS) was achieved with the mixture at 37 °C, while the minimum (0.024 lCH4/gVS) was observed with DW at 20 °C. These results demonstrate that co-digestion of distillery and fruit-

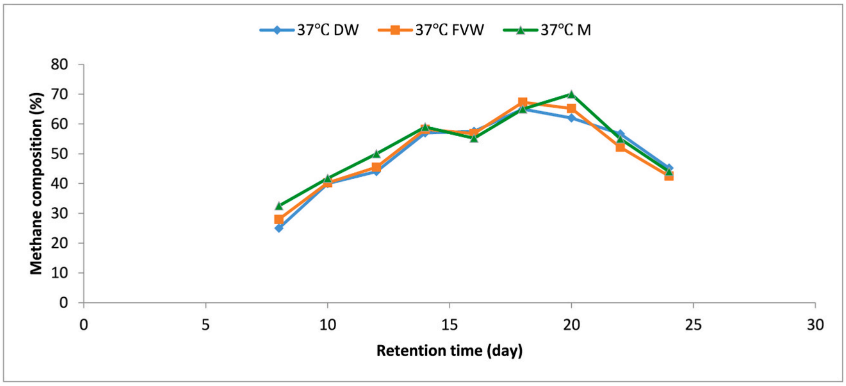

Fig. 9. Methane compositions in anaerobic digester at 37 °C.

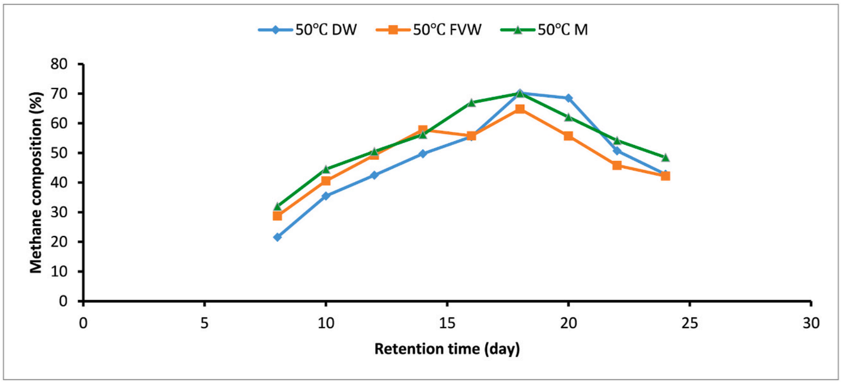

Fig. 10. Methane compositions in anaerobic digester at 50 °C.

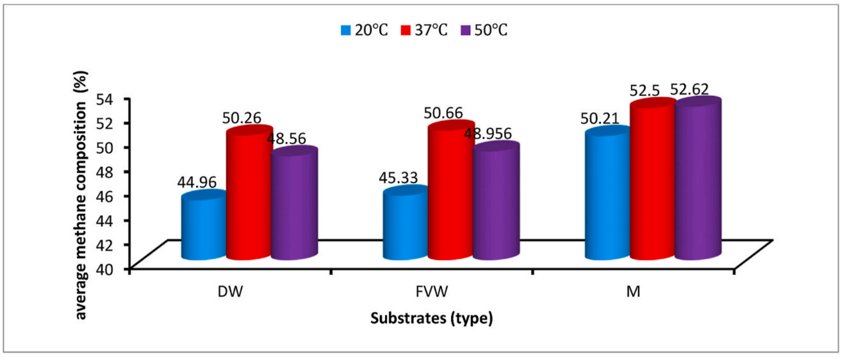

Fig. 11. Total average methane compositions in (%).

vegetable waste enhances biogas and methane production.

The study is limited by the small scale of the experiment, the use of a specific type of digester, the limited duration of the study, the use of specific type of factors affecting biogas production like temperature, retention time variation and substrate. Further research is required to address these limitations and optimize biogas production under different conditions.

Future research should focus on exploring the effects of different digester configurations, optimizing the ratio of waste mixtures, investigating the potential of using biogas for electricity generation, examining the long-term sustainability of biogas production and factors affecting pH, nature of digesters, C/N ratio, toxic materials, water content and others are very important concepts not covered in this research which needs further investigation. By expanding our understanding of these areas, we can work towards a more sustainable and efficient biogas production system.

In conclusion, utilizing distillery waste, fruit and vegetable waste, and their co-digested mixtures for biogas and methane

Table 2
Percent VS of digestate after 24 days of anaerobic digestion.

Waste type	%VS		
	Temperature		
	20°c	37°c	50°c
DW	44	28.8	21.7
FVW	38	31.87	14.7
M	26.4	22.8	18.7

Table 3
Methane yield calculation summary.

Waste type	Temperature	VS_f(as% TS)	%TS	VS_i	Change of $VS=VS_i-VS_f$	TS = 1500[a]% TS	gVS = TS[a]%VS change	CH_4 (l)[a]	Yield (lCH_4/gVS)
DW	20 °C	44	11.38515	94.94	50.94	170.777	86.99	2.106	0.024
	37 °C	28.8	11.38515	94.94	66.14	170.77	112.95	3.631	0.032
	50 °C	21.7	11.38515	94.94	73.24	170.777	125.077	3.282	0.026
FVW	20 °C	38	8	82.6	44.6	120	53.52	2.51	0.047
	37 °C	31.87	8	82.6	50.73	120	60.876	3.680	0.061
	50 °C	14.7	8	82.6	67.9	120	81.48	3.612	0.044
M	20 °C	26.4	7.851	76.5	50.1	117.765	59.00	3.688	0.063
	37 °C	22.8	7.851	76.5	53.7	117.765	63.24	5.004	0.079
	50 °C	18.7	7.851	76.5	57.8	117.765	68.06	5.154	0.076

[a] Represent thing sum of each biogas production from a digester in Litter multiplied by its corresponding %CH_4 composition.

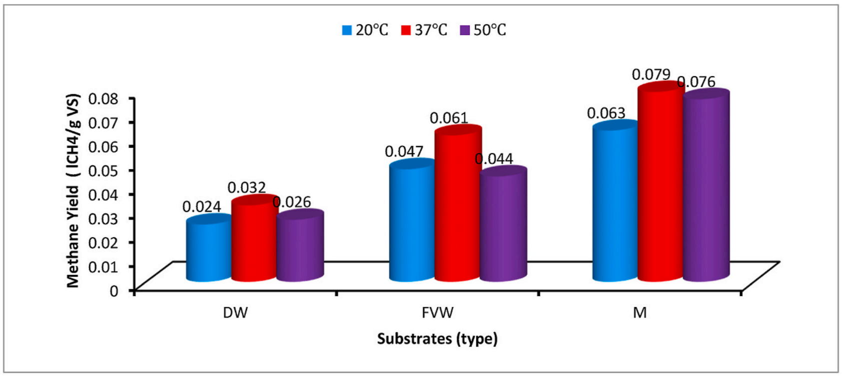

Fig. 12. Methane yield (CH_4*/gVS).

production not only address waste disposal challenges but also contributes to saving valuable foreign exchange by reducing the reliance on imported fuels, oils, and natural gas.

CRediT authorship contribution statement

Gebresilasie Gebremedhin Gebresilasie: Writing – original draft, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mulualem G. Gebreslassie:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mebrahtom Gebresemati:** Writing – review & editing, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Conceptualization.

Data availability statement

Data included in the article/supplementary material is referenced in the article.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors are grateful to Desta Alcohol and Liquor Factory PLC's quality control management office for allowing the use of their lab and equipment for this research. Special thanks to the technical labs for their support and assistance, as well as all wastewater treatment and quality control lab staff for their help. For the purpose of open access, the author has applied for a Creative Commons Attribution (CC BY) license to any Author Accepted Manuscript version of this paper arising from this submission.

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