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Effect of Vinasse, a Sugar Factory Waste, on Biomethane Production under Industrial-scale and Mesophilic Conditions

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Abstract
In this study, the potential for biomethane production from vinasse, a waste by-product of sugar factories, was evaluated in a biogas unit under mesophilic conditions. The organic raw materials used in the biomethane potential (BMP) experiment were mixed with fermenter liquid (inoculum) at defined rates after laboratory determination of dry matter (%) and volatile solids (%). The facility was then simulated in a gas mesophilic environment for 30 days to monitor the gas output.
Industrial challenges associated with the use of vinasse as a sugar factory waste in biomethane production, and the impurity values such as possible contamination during the supply of vinasse, can be evaluated as limiting factors. The biogas produced in the reactor contained CH_4, CO_2 and H_2S gases. The ratio of inoculum to solid content in the organic matter was used to calculate the biomethane yield by means of the BMP device of the organic additives used in the study. When the biogas production from sugar factory waste was examined under one-year storage conditions, it was observed that optimisation of the stored waste would enable production under industrial conditions. According to the findings of this study, vinasse was used to produce biomethane, demonstrating its potential for industrial-scale waste management aligned with circular economy principles.

Keywords
Starch, vinasse, inoculum, volatile solids, mesophilic conditions, biomethane production potential

1 Introduction

1.1 Global energy needs and biofuels

The final stage of anaerobic digestion involves the introduction of methane-producing bacterial groups. While some of the methane bacteria use hydrogen and carbon dioxide to generate methane and water, others use acetic acid to form methane and carbon dioxide. Bacteria that release methane gas break down acetic acid and convert them into biogas by synthesising hydrogen and carbon dioxide. Around 70 % of the methane produced under anaerobic conditions is formed by the breakdown of acetic acid, while the remainder is formed by carbon dioxide and hydrogen. Not all soluble volatile organic acids and compounds are converted into biogas; some organic substances may be removed from the system without purification. Methane-forming bacteria utilise a limited range of nutrients – primarily hydrogen, acetic acid, and single-carbon compounds.[1]

1.2 The role of biomethane and anaerobic digestion

The formation stage of methane gas occurs much slower than the formation of acetic acid. Therefore, the methane-formation stage controls the overall speed of anaerobic degradation and determines the retention time in the reactor. Since methanogenic bacteria use the products from the acetic acid-formation stage as raw materials, both steps must proceed in balance.[2] Provided that H_2 and CO_2 are sufficiently available and the partial pressure of H_2 is optimal, CH_4 production proceeds via hydrogenotrophic methanogens. However, the methane-production step is not always the rate-limiting step; the hydrolysis stage may, in some cases, be more critical.[3,4]

1.3 The problem of vinasse waste in sugar production

In anaerobic environments, many factors, such as C/N ratio, dry matter content (DM), volatile solids (VS), hydraulic retention time (HRT), organic loading rate (OLR), toxic substances, temperature, pH, and alkalinity, affect biogas yield.[5] Microbiological balance and stability are critical for the successful operation and efficiency of anaerobic systems. To ensure this balance and stability, an appropriate inoculum must be used, and parameters such as dry matter content, pH, organic acid formation must be measured regularly.

Molasses is a brown by-product produced during the processing of plants such as sugarcane and sugar beet. Vinasse is a dark-coloured, strong-smelling liquid waste generated in bioethanol facilities that ferment molasses.[6]

During the distillation process, approximately 10–15 l of vinasse are produced for every 1 l of ethyl alcohol.[7,8] The chemical composition of vinasse varies depending on the starting material used in the process. Vinasse derived from sugarcane, grapes, sugar beet, and sorghum is typically acidic, and contains high levels of organic matter, as indicated by its COD and BOD values.

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1.4 Potential of vinasse as biomethane feedstock

Due to its high organic matter content, direct discharge of vinasse into aquatic environments reduces both the dissolved oxygen levels and pH.[9] Consequently, several methods have been adopted for vinasse disposal, including its use as fertiliser, concentration through evaporation, conversion to animal feed, and utilization in biogas production.[10]

Using vinasse as a fertiliser, however, can result in soil and groundwater pollution, soil salinisation, reduced buffering capacity of soil, and decreased agricultural yield, mainly due to its organic load.[11,12,13]

1.5 Gaps in current research

The use of vinasse as sugar factory waste in biomethane production due to its organic content is an important alternative in terms of meeting the energy needs of the producer. Evaluating the biomethane production potential of vinasse together with starch as a comparison scale will be a guide for a possible large-scale biogas energy production facility.

1.6 Aim of the present study

In order to determine whether sugar factory waste could serve as an alternative energy source for the producer, this study examined the impact of vinasse, which has a dry matter content of 14 %, on the capacity to produce biogas and biomethane, by comparing it to starch that has a known biomethane content. This comparison supports the concept of a circular economy from a sustainable energy perspective. Unlike most studies reported in the literature, which focus on total biogas yield, this study evaluates only the methane content, independent of CO_2 and H_2S. In addition, the study includes a calculation of the electricity generation potential based on the methane yield.

The use of starch in biogas production has been the subject of various research studies due to its high organic matter content. Its commercial evaluation as a raw material has driven interest in alternative feedstocks.[14] However, the use of vinasse for biogas production in the waste utilisation process, depending on its dry matter content, offers an important initiative in terms of providing alternatives to the producer.

The most important aspect of this study is its evaluation of vinasse – an industrial-scale waste – in biomethane production. It explores contamination risks during production, their effect on energy yield, compares outcomes with high-organic-content materials such as starch, and presents a model to the producer. The study ran for 39 days in terms of experimental process, and as a result of microorganism activities, biogas production was achieved at an industrial scale using approximately 9,000 m^3 ton biogas production reactors, without requiring additional investments, independent of the shape of the reactors.

2 Experimental

2.1 Instrumentation

To assess the biomethane potential of the organic chemicals used in the biomethane production subject to this study, a biomethane potential test was conducted in "batch" mode using the AMPTS-II Light™ model from BPC Instruments.

2.2 Material and methods

No special chemical preparation was implemented for waste homogenisation at an industrial scale, based on the assumption that such preparation could reduce efficiency in energy production due to contamination risks. Ambient temperature and pH were monitored throughout the experiment.

For the measurement mechanism with the BMP device, different organic solutions such as starch and vinasse, whose methane production potential was to be analysed, were prepared at volumes of 1,800 ml to ensure sufficient gas production within the 2,500 ml reactor. The volatile solids content determined the type of organic material to be added. The amounts of inoculum and substrate (either starch or vinasse) required to achieve a total volume of 1,800 ml were calculated for the experimental settings where the inoculum to substrate ratio was found to be 2. The results are shown in Table 3. Table 4 summarises the amounts of organic solutions, such as vinasse and starch that were utilised to determine the inoculum solution and the potential for biomethane generation.

However, to determine biomethane potential, the amount of volatile solids in the specified amounts of starch and vinasse mixed with the inoculum solution was calculated using expression (1).

$$S_{vs} \cdot \%V_s \tag{1}$$

The amount of inoculum solution required to calculate the V_s content of BMP solutions, prepared by adding substrates, such as starch and vinasse, and the V_s value of this inoculum were calculated using expression (1).

The amount of substrate used in the experimental conditions is shown in Table 1, and the V_s value of inoculum solutions prepared with the addition of substrates, such as starch and vinasse, was calculated using expression (1).

The amount of biomethane created was determined using Eq. (2), even though the study's goal was to assess the potential for biomethane production of organic solutions, such as substrate and starch added to the inoculum solution.[15]

$$\mathrm{BMP} = \frac{V_S - V_B \dfrac{m_{I,S}}{m_{I,B}}}{m_{S,S}} \tag{2}$$

V_s is the amount of biogas released after the addition of the organic material whose biomethane potential needs to

Table 1 – Volatile solids (VS), organic matter (OM), and dry matter (DM) contents of different organic sources whose biomethane potential was measured during the test (first experiment: I/S : 2)

Chemical compound	CAS No.	Dry matter / %			Organic matter / %			Volatile solids / %		
		Amount	Standard deviation	Error	Amount	Standard deviation	Error	Amount	Standard deviation	Error
Inoculum	Irregular liquid animal manure – no CAS number	6.92	0.12	0.01	52.02	0.04	0.01	3.60	0.027	0.01
Starch	9005-84-9	98.00	0.05	0.01	97.96	0.13	0.01	96.00	1.21	0.01
Vinasse	91082-90-5	14.80	0.08	0.01	54.05	0.18	0.01	8.00	0.30	0.01

Table 2 – Volatile solids (VS), organic matter (OM), and dry matter (DM) contents of different organic sources whose biomethane potential was measured during the test (second experiment: I/S : 4)

Chemical compound	CAS No.	Dry matter / %			Organic matter / %			Volatile solids / %		
		Amount	Standard deviation	Error	Amount	Standard deviation	Error	Amount	Standard deviation	Error
Inoculum	Irregular liquid animal manure – no CAS number	8.32	0.22	0.01	52.28	1.10	0.01	4.35	0.07	0.01
Starch	9005-84-9	80	1.32	0.01	93.28	2.11	0.01	75.20	0.03	0.01
Vinasse	91082-90-5	17.10	1.05	0.01	73.10	0.48	0.01	12.50	0.11	0.01

be measured (Nml), V_B is the amount of biogas generated from the inoculum solution without the addition of organic substrate (Nml), $m_{I,S}$ is the amount of inoculum to which substrate is added (ml), $m_{I,B}$ is the amount of inoculum without the addition of organic substrate (ml), $m_{S,S}$ is the amount of volatile solids of the substrate whose biogas potential needs to be measured (g), and BMP is the amount of biomethane produced as a result of organic addition (Nml/gVS).

Table 1 lists the inoculum, starch, and vinasse's dry matter, organic matter, and volatile solid contents, which are the focus of this investigation and which affect the efficiency of biomethane generation.

The vinasse used for biogas production during the experimental study was provided as waste from the granulated sugar production process of Konya Sugar Factory dated June 2023.

Starch bears the same CAS number as starch listed in its IUPAC form (CAS registration number: 9005-25-8) because it serves as the positive control. The vinasse used as sugar factory waste in the biomethane production capacity method has chemical characteristics that are comparable to those of vinasse described in the literature, and its CAS number is 91082-90-5 (Table 2). It is also included into the inoculum solution by the inoculation method in the BMP device because it is not exposed to particular pretreatment for the synthesis of biomethane.

To determine whether mesophilic conditions were suitable for production, the reaction solution (inoculum) was prepared. Starch was introduced as a substrate into the reactor solution (inoculum) at 37 °C for five days. The ratio of inoculum to starch provided as substrate was found to be 2. The Inoculum/Substrate "I/S" ratio was therefore determined to be "2".

As shown in Tables 1 and 2, the standard deviation values obtained for the inoculum and starch solutions used in this study were believed to result from the high amount of matter present in the mixtures. In the statistical analysis, certain meaningful data deviated from the expected trend, resulting in a high standard deviation at the same error value, as expected.

Temperature was determined as 37 °C and pH 8.15 as a mesophilic environment for inoculation in biomethane production. The experiment was conducted by placing inoculum solution, inoculum and vinasse, and inoculum and starch mixtures in the biomethane potential measuring device. Gas evolution was monitored for 39 days. It was observed that the maximum rate of biomethane production in all three mixtures occurred during the first four days, after which the production rate gradually declined.

The Automatic Methane Potential Test System (BMP) instrument was used to produce biomethane without additional chemical preparation (Fig. 1). Three distinct solution settings were used to generate the organic solutions to be tested for biomethane: inoculum solution, inoculum and vinasse solution mixture, and inoculum and starch mixture (Tables 3 and 4). These organic mixtures were loaded into the BMP device, and their gas outputs were measured in a controlled, closed experimental environment. The gas

Table 3 – Organic substances and process parameter values used in the measurement of biomethane potential for I/S : 2 value

No	Compound	Inoculum / g	Amount of substrate / g	Final gas volume / Nml		Substrate (Vs) / g	BMP methane / Nml CH_4 g VS^{-1}		
				No			Amount	Standard deviation	Error
1	Inoculum	1800.00	–	3940.3	3931.60	–	–		
				3926.1					
				3928.4					
2	Starch	1766.53	33.47	15159.8	15273.00	31.80	358.95	25.12	0.01
				15439.8					
				15219.4					
3	Vinasse	1469.39	330.61	17523.4	17426.90	26.45	537.52	37.52	0.01
				14369.6					
				17387.7					

Table 4 – Organic substances and process parameter values used in the measurement of biomethane potential for I/S : 4 value

No	Compound	Inoculum / g	Amount of substrate / g	Final gas volume / Nml	Substrate (Vs) / g	BMP methane / Nml CH_4 g VS^{-1}		
						Amount	Standard deviation	Error
1	Inoculum	1800.00	–	6569.70	–	–		
2	Starch	1777.03	22.97	12381.10	17.14	343.39	30.12	0.01
3	Vinasse	1655.93	144.07	12573.90	18.01	362.58	41.25	0.01

sensors attached to the BMP device enabled the screen to monitor the amount of biomethane generated for each solution. The gas produced contained methane, as well as carbon dioxide and hydrogen sulphide. The BMP system removes carbon dioxide and hydrogen sulfide from the system through absorption and allows for the measurement of the amount of methane gas produced. Additionally, hydrogen sulphide in the produced gas could be removed from the reaction environment by washing with 3 M sodium hydroxide. Substrates were added slowly to the inoculum to ensure proper homogenisation in a single step.

In this study, gas volumes were calculated and normalised in Nml (normalised millilitres) according to the measurement range of the BMP device, as Nml is the accepted unit for quantifying methane production.[15] Since the amount of methane in the biogas produced with the BMP device was measured, methane concentrations were given as the produced biogas material. In order to control the chemical process, the relevant measurements were taken daily and were included in the calculation cumulatively.

To ensure consistency in gas output results for the Inoculum/Substrate (I/S) ratios 2 and 4, three measurements were taken, and their average was used due to the numerical closeness of the results.

All experimentally obtained data represent the average of the three repeated measurements. Variability was calculated based on the closeness of these repeated values, and the error value was determined accordingly. The error calculation involved quantifying the deviation between the errors and values in the revised article. To compare the results, the closeness of the repeatable measurement values of each condition was evaluated using statistical analysis.

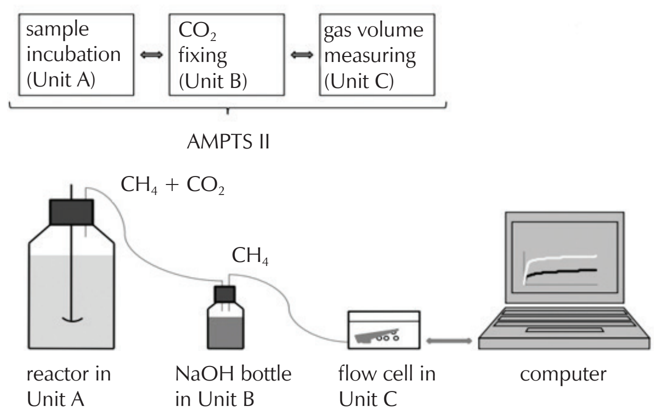

Fig. 1 – Schematic presentation of the automatic methane potential test system (AMPTS) II[15]

This study can be replicated using the BMP device by maintaining an Inoculum/Substrate ratio of 2. The fermentor liquid (inoculum) should be sourced from a biogas plant and diluted with water to adjust the dry matter content to the desired level. It is important to note that the fermentor liquid inoculum used in this study varied in chemical composition over time, which could inevitably impact biogas production efficiency under industrial conditions. In addition, an attempt was made to examine its behaviour under different feeding regimes by testing an I/S ratio of 4. This was the rationale for including a second trial at an I/S of 4.

3 Results and discussion

The Konya Sugar Factory, the subject of this experimental study, has a sugar production capacity of approximately 2000–2500 tons/day, from which approximately 800–1000 tons/day of 14–17 brix vinasse is obtained. The focus of this study was the use of this scale of vinasse in biogas production.

The fact that vinasse is included in the circular economy process as a waste chemical is an important problem on the energy production side. From this perspective, utilising vinasse for biogas production plays an important role in minimising the waste disposal problem of the sugar industry.

To guide the experimental setup, different Inoculum/Substrate ratios (2, 3, and 4) were tested. Ultimately, the Inoculum/Substrate (I/S) ratio of "2" was selected as optimal due to both economic and performance considerations. Under laboratory conditions using the BMP device, the highest gas output was achieved with an I/S ratio of 2.

The amount of methane gas produced was calculated using Eq. (2) by subtracting the methane released by the inoculum from the total methane output and dividing it by the weight of the volatile solids (V_S) supplied. This allowed for the determination of methane yield per gram of organic dry matter product in millilitres.[16]

Eq. 2 was used to determine the amount of biomethane generated in the BMP device of pure inoculum, starch-added inoculum, and vinasse-added inoculum solution. The resulting biomethane values are shown in Table 3.

In this context, V_S represents the total volume of gas derived from the substrate sample (substrate and inoculum), V_B is the volume from the blank sample (inoculum), $m_{I,S}$ is the amount of inoculum's organic matter in the substrate bottle, and $m_{I,B}$ is the amount of substrate's organic matter. The amount of organic matter in the substrate bottle is denoted by $m_{S,S}$, while the inoculum is in the empty bottle. The BMP device used in this experimental study measured daily biomethane output. Biomethane potential was tested using the BPC Instruments AMPTS-II Light™ model equipment. This system determined the maximum methane potential of raw materials by monitoring gas accumulation in the closed reactor containing inoculum, vinasse, or starch mixture at an anaerobic temperature of 37 °C and an ambient pH of 8.15. Plotting biogas volume against time in this case produced the biogas generation curve.[17]

To track the effects of the inoculum solution alone, as well as the additional organic components under investigation, starch and vinasse, on the biogas outputs, both negative and positive control procedures were employed. The experimental setup used for the negative control omits starch and vinasse, and measures only the biogas produced by the inoculum solution. The pH was regularly monitored to ensure a healthy reaction environment during the 39-day test period.

Positive control can be defined as the known biogas measurement value of starch in the reactor, where starch was employed as a reference material along with the vinasse used to test biomethane. Thus, the inoculum solution containing starch used in this investigation, and whose biomethane measurement value was determined in conjunction with the starch biomethane measurement value documented in the literature, can be characterised as a positive control.

Starch bears the same CAS number as starch in its IUPAC form (CAS registration number: 9005-25-8) since it is employed as a positive control. The vinasse used as sugar factory waste in the biomethane production capacity method has chemical characteristics comparable to those of vinasse described in the literature, and its CAS number is 91082-90-5. It is also included in the inoculum solution by the inoculation method in the BMP device as it is not exposed to any particular pretreatment for the synthesis of biomethane.

This study evaluated the biomethane potential of three different organic solutions: the reactor liquid without additives (inoculum), the inoculum and starch mixture, and the inoculum and vinasse mixture (Tables 3 and 4). The goal was to investigate the inoculum-containing solution, the impact of starch on the inoculum solution's biomethane content, and the influence of the substrate on the inoculum solution. Each measuring vessel had a reaction capacity of 1,800 ml, and biomethane measurements of the reactor liquids were performed in order to determine that 330 ml of the 1,800 ml solution medium was vinasse and 33.47 ml was starch. The daily amount of biogas produced in the BMP device over a period of 39 days is shown in Fig. 2.

Vinasse, which, like starch, was assessed as sugar factory waste with high organic content during the 39-day experimental study, demonstrated significant potential for biogas production. This can be observed in Fig. 2, which presents the biogas production potentials of the inoculum, starch-added inoculum, and 14 % dry matter inoculum solutions. Based on the biogas production amount obtained in the study, it can be concluded that vinasse represents both a valuable component for the circular economy and a cost-effective alternative to starch.

The experimental data indicate that the gas production peaked in the first four days of the 39-day biogas production period with the addition of starch and vinasse along with the inoculum solution (Fig. 3). The retention times of all three organic solutions, including the positive and negative controls, were evaluated over the same timeframe to ensure a valid comparison of the methane generation potentials of the substrates – such as vinasse and starch – under identical conditions.

Table 5 shows that the starch-added inoculum solution produced 358.92 Nml CH_4 g VS^{-1} of biomethane. In com-

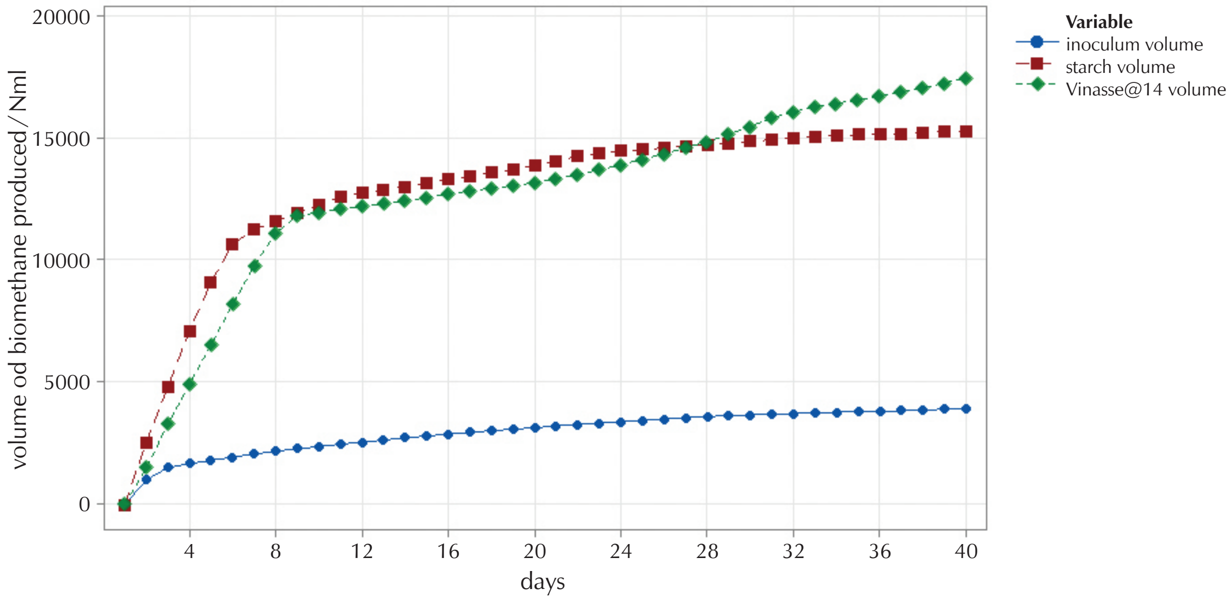

Fig. 2 – 39 days of biomethane production process of inoculum, starch added inoculum, and vinasse added inoculum solutions with 14 % dry matter content

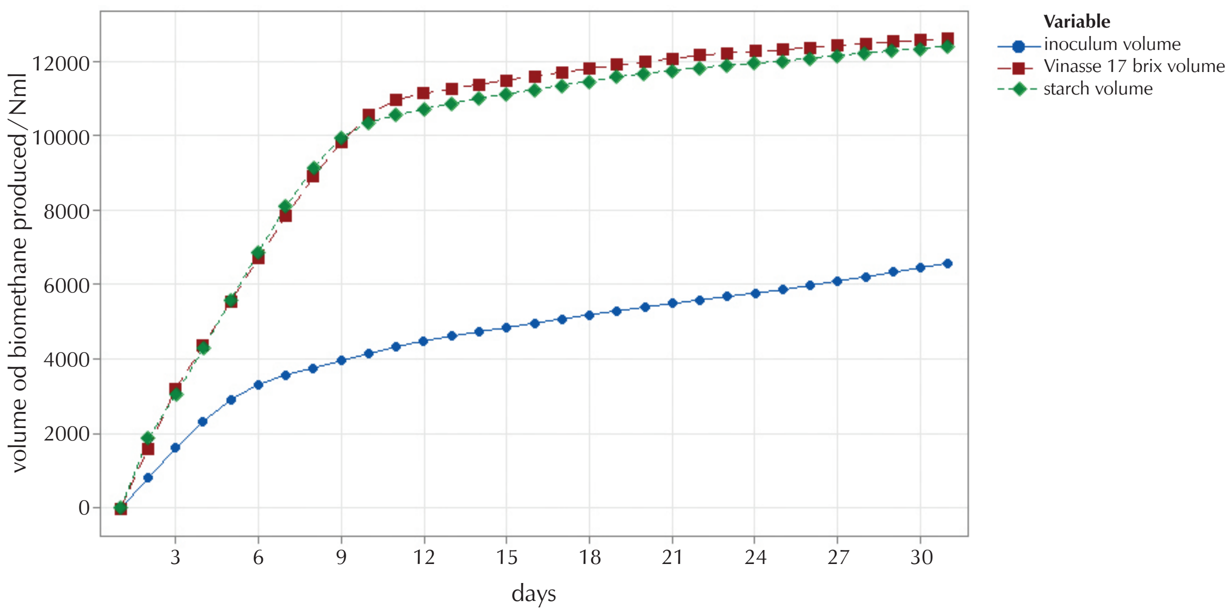

Fig. 3 – 30 days of biomethane production process of inoculum, starch added inoculum, and vinasse added inoculum solutions with 17 % dry matter content

Table 5 – Biomethane production, energy parameters, and characterisation of the produced gas

Organic compound	Dry matter / %	Organic matter / %	Volatile solids / %	Amount of methane produced / Nml CH_4 g VS^{-1}			Amount of energy obtained from 1-ton fresh waste / kWh		
				Amount	Standard deviation	Error	Amount	Standard deviation	Error
Inoculum	6.92	52.02	3.60	60.67	20.16	0.01	7.66	1.36	0.01
Inoculum + Vinasse	14.80	54.05	19.00	500.00	5.23	0.01	333.45	3.67	0.01
Inoculum + Starch	98.00	97.96	96.00	358.95	12.34	0.01	1209.52	23.56	0.01

Table 6 – Biomethane production, energy parameters, and characterisation of the produced gas (I/S : 4)

Organic compound	Dry matter / %	Organic matter / %)	Volatile solids / %	Amount of methane produced / Nml CH_4 g VS^{-1}			Amount of energy obtained from 1-ton fresh waste / kWh		
				Amount	Standard deviation	Error	Amount	Standard deviation	Error
Inoculum	8.32	52.28	4.35	70.12	5.65	0.01	10.19	2.18	0.01
Inoculum + Vinasse	17.10	73.10	12.50	362.58	23.12	0.01	168.12	12.21	0.01
Inoculum + Starch	80.00	92.28	75.20	343.39	34.78	0.01	1084.67	30.17	0.01

Table 7 – Organic contents of materials with BMP measurements and analysis methods

Chemical content	Unit	Analysis results, vinasse 14,80 Brix	Analysis results, vinasse 17 Brix	Starch	Analysis method (ref.)
organic matter	%	8	12.5	98	18
organic carbon	%	3.45	4.7	48.21	19
organic nitrogen	%	0.73	0.85	0.1	20
water soluble K_2O	%	1.69	1.7	0.02	21
pH	%	5.02	5.2	6.72	22
total solids	%	14.8	17.1	92.65	23
sulphur	%	0.39	0.46	0.01	24
COD	g l^{-1}	18.67	19.68	16.21	25

Table 8 – Comparison of BMP values obtained for I/S : 2 and I/S : 4

Variable	N	Mean	SE mean	Standard deviation	Minimum	Maximum
1st experiment BMP / Nml g VS^{-1}	3	500	21.6564	37.5100	462	537
2nd experiment BMP / Nml g VS^{-1}	3	362.58	7.47685	12.9503	348.9	374.65

parison to the amount of biomethane produced from pure starch, 415 Nml CH_4 g VS^{-1} of biomethane was created from pure starch when it was CH_4, and 86 % of biomethane was produced in an industrial setting. Therefore, in a biogas production facility, starch has a beneficial impact on biomethane production performances in methane gas generation.

The amount of energy generated from methane under current conditions and the conversion efficiency for biomethane production in Toros Agri Meram Renewable Energy facilities, which are the focus of this study, are displayed in Table 5. In contrast, methane gas generated from organic sources is burned off for energy production in the GTG (Gas Turbine Generator) unit in a biogas production facility.

Vinasse, a sugar industry byproduct with a dry matter percentage of 14 %, contributed more to the BMP device's methane production than starch, which had a higher organic content, as shown in Table 6. In comparison to the inoculum solution and starch mixture, its contribution to the synthesis of biomethane (500 Nml CH_4 g VS^{-1}) is at an acceptable level, despite having a lower organic matter content (54.05 %) than starch. Consequently, waste from sugar factories can be regarded as a significant substitute for energy generation.

The biomethane measuring (BMP) instrument yielded the values listed in Table 6, which are the results of data collected in the industrial facility where this study was conducted. The characterisation of the organic contents used in this study is shown in Table 7.

In this study, three BMP test runs were conducted for I/S : 2 and I/S : 4. The standard deviations along with the maximum and minimum values of the data obtained for each experiment are shown in Table 8.

In order to understand the contribution of vinasse to biomethane production, its comparison with starch, one of the organic materials with the highest volatile solids content, demonstrates that vinasse can be an important alternative in biomethane production.

Digester inoculum was sampled from an anaerobic digester in Toros Agri Meram, Konya. Its characteristics were as follows: pH 8.15 ± 0.01, total chemical oxygen demand (TCOD) of 18.0 ± 3.2 g l^{-1}, soluble chemical oxygen demand (SCOD) of 0.6 ± 0.03 g l^{-1}, $NH4^+$-N of 0.75 ± 0.03 g l^{-1}, total nitrogen (TN) of 0.95 ± 0.07 g l^{-1}, and alkalinity ($CaCO_3$) of 27405 ± 120 mg l^{-1}, and VFA(-FOS) 10607.1 ± 0.09 mg l^{-1}, and VFA/TAC(FOS/TAC) of 0.39.

In this experimental study, the batch method was used to determine the BMP potential. In the industrial-scale Toros Tarım Meram facilities, the cycle time, the time required for degassing and completion of the process was calculated at 28–30 days. Therefore, although 39 days is a sufficient period, it can even be considered excessive. Furthermore, when the methane gas outputs of the organic wastes under this study were monitored in the laboratory environment, it was determined that 90 % efficiency was achieved in methane gas output in the first 15 days. Since the methane gas output decreased to 0.5 % in the following period, it was decided to limit the study to 39 days.

A distinguishing feature of this study is the use of vinasse, a by-product of sugar production, as an energy source for biomethane production. Due to its organic content, vinasse's contribution to energy production was compared with starch as a reference material. However, working with the inoculum/substrate ratios of 2, 3, and 4 was important in terms of understanding its contribution to biomethane production. The gas output values obtained in the 39-day experimental period were aimed at understanding the nature of the gas output rather than the uncertainty of the repetitions.

Although the use of vinasse for biogas production, which is the subject of this study, is seen as an important alternative for the producer regarding waste disposal, the solid matter content of vinasse is the most important constraint in biogas production. If any change in the production conditions affects the solid matter content of vinasse, it will affect the amount of biogas produced from it. Therefore, regulating the solid matter content of the vinasse before biogas production will prevent irregularity in energy production. Nonetheless, the shift in the solid matter concentration for the production of biogas will serve as a reference for potential optimisation research.

As an important factor in biomethane production, the dry matter content of vinasse, which is a sugar factory waste, is higher than that of starch, which can be considered an indicator that organic matter does not directly affect the biomethane content. Therefore, despite its high organic content, the use of vinasse as an industrial waste in this study is presented to the producer as an important alternative in biomethane production. The study data suggest that vinasse's dry matter content is more effective than starch, which is also rich in organic matter.

4 Conclusion

This industrial-scale experimental study highlights the mesophilic anaerobic digestion process of vinasse from a circular economy perspective, emphasising its potential both for waste management and biogas production. Biomethane output was monitored for 39 days using a BMP device, and the results showed that vinasse with 14 % dry matter content outperformed starch, which is rich in organic content.

This study was carried out in the form of biogas production in waste material removal with the evaluation of vinasse with 14 % dry matter content as waste and the real industrial-scale Konya Sugar Factory (Turkey) sugar factory facility data. The results showed that the BMP device used in biogas production during the experimental period provided important alternative information for the evaluation of various organic wastes in biomethane production.

As vinasse typically accounts for at least 10% of the final sugar production volume, its evaluation as a biomethane source is both feasible and beneficial for producers.

The experiment found that vinasse with an inoculum/substrate (I/S) ratio of 2 and 14 % dry matter content yielded higher biomethane production efficiency than pure starch.

Using vinasse with 14 and 17 % brix or dry matter produced 333.45 and 168.12 kWh of energy from 1 t of total vinasse, respectively. Based on these results, it can be said that 1 t of vinasse can provide approximately 250 kWh of energy on average. In practical terms, about 1 MWh of energy can be produced from 4 t of fresh vinasse. These values may vary with the biogas company's inoculum (fermentation liquid) dry matter, pH, and other organic contents.

The decision to use a vinasse/starch ratio of 2 as the organic content in biomethane production, was made to evaluate the data obtained at the minimum value of substrate addition to the inoculum. Using a higher amount of organic matter would not be cost-effective for the producer.

Differences observed in biogas production at Inoculum/Substrate ratios of 2 and 4, may be attributed to excessive dry matter loading and microorganism changes in the reactors. In these two trials, the gas potential will decrease as the dry matter and organic load increase. This is a crucial matter for actual plants. Specifically, the ratio of "biogas yield/organic source" is directly impacted by pH variations.

The use of vinasse in biogas production serves as an important alternative within the framework of organic waste regulations. It helps mitigate environmental risks associated with waste disposal and, depending on the soot content, the evaluation of organic waste in biogas production can be considered an important step to guide technological development in the energy sector.

List of abbreviations

BMP	– biomethane potential
DM	– dry matter
VS	– volatile solids
HRT	– hydraulic retention time
OLR	– organic loading rate
COD	– chemical oxygen demand
BOD	– biochemical oxygen demand
OM	– organic matter
Nml	– normalised millilitre
I/S	– inoculum/substrate ratio
GTG	– gas turbine generator
TCOD	– total chemical oxygen demand
SCOD	– soluble chemical oxygen demand
NH_4^+-N	– ammonium nitrogen
TN	– total nitrogen
VFA(FOS)	– volatile fatty acids
TAC	– total alkalinity or total bicarbonate alkalinity

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SAŽETAK

Učinak vinase, otpada iz tvornice šećera, na proizvodnju biometana u industrijskim i mezofilnim uvjetima

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U ovom radu ispitan je potencijal proizvodnje biometana iz vinase, otpadnog nusproizvoda tvornica šećera, u bioplinskoj jedinici koja radi u mezofilnim uvjetima. U pokusu određivanja potencijala biometana (BMP) vinasa je, nakon analize udjela suhe tvari i hlapljivih krutih tvari, miješana s fermentacijskom tekućinom (inokulumom) u unaprijed definiranim omjerima. Proces je proveden tijekom 30 dana u mezofilnim uvjetima da bi se kontinuirano pratio nastanak bioplina.
Kao mogući ograničavajući čimbenici identificirani su industrijski izazovi primjene vinase u proizvodnji biometana, uključujući i rizik od onečišćenja tijekom prikupljanja i opskrbe vinase. Bioplin proizveden u reaktoru sadržavao je CH_4, CO_2 i H_2S, a iskorištenje biometana određeno je na temelju omjera inokuluma i udjela krute tvari u dodanom organskom materijalu upotrebom BMP uređaja.
Analiza proizvodnje bioplina iz otpada tvornice šećera pod uvjetima jednogodišnjeg skladištenja pokazala je da bi optimizacija načina skladištenja i rukovanja otpadom mogla omogućiti učinkovitu primjenu procesa na industrijskoj razini. Dobiveni rezultati potvrđuju da se vinasa može uspješno valorizirati za proizvodnju biometana te ima važan potencijal u sklopu održivog gospodarenja otpadom i kružnog gospodarstva.

Ključne riječi
Škrob, vinasa, inokulum, hlapljive tvari, mezofilni uvjeti, potencijal biometana

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