Anaerobic Digestion of Cow Manure for Biogas Production

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***Abstract*—Anaerobic Digestion (AD) has become a viable way to manage agricultural waste and produce renewable energy simultaneously. Cow dung is a particularly notable feedstock in this expanding field of study because of its high organic content, accessibility, and dual use as an energy source and animal waste. This study examines the effectiveness of using controlled anaerobic digestion to produce biogas from cow dung. The justification for using cow dung is due to it will assist the cattle industry developing a circular economy by lowering greenhouse gas emissions, enhancing waste management techniques, and promoting decentralised power systems. The performance of the AD process was assessed through the analysis of Total Solids (TS), Volatile Solids (VS), Chemical Oxygen Demand (COD), and Volatile Fatty Acids (VFA). Initially in the digestive process, a significant rise in VFA levels suggested that hydrolysis, acidogenesis, and acetogenesis were all actively proceeding. After 40 days of digestion, biogas tests showed a methane content of up to 60%, indicating that methane generation peaked during the methanogenesis period. Significant drops in TS and VS (between 92% and 99%) provided further verification of the high level of organic matter decomposition. Furthermore,** 96.4% **COD removal was achieved, highlighting the effective breakdown and conversion of organic material into CO_2 and CH_4, which are components of biogas. These results demonstrate the energy and environmental advantages of anaerobic digestion as a green waste-to-energy technology and support the feasibility of using cow dung as a feedstock for biogas generation.**

***Keywords*—anaerobic Digester, biogas, cow manure, total solids, volatile solids**

I. Introduction

Qatar's arid climate and limited cultivable land, combined with scarce freshwater resources, significantly constrain agricultural productivity, making the country heavily reliant on food imports to meet local demand [1]. Despite these limitations, agricultural operations such as greenhouse farming and livestock rearing have been expanding to enhance food security. However, these activities generate substantial organic waste, including crop residues, food processing byproducts, and animal manure, which, if not managed properly, pose serious environmental threats [2, 3]. According to the Ministry of Municipality and Environment (MME), Qatar produces an estimated 150,000 to 200,000 tons of agricultural waste annually, much of which is either dumped in landfills or openly burned, leading to severe environmental repercussions [4].

The above issue highlights the importance of identifying feasible and environmentally friendly waste management solutions in Qatar [5]. Anaerobic digestion, which converts organic waste into biogas a renewable energy offers a reliable solution. Particularly in hot, dry climates like Qatar's, anaerobic digestion is more effective than conventional decomposition, as it relies less on water and favorable weather conditions and in some cases can operate as a dry anaerobic digestion [6].

Improper disposal of organic waste contributes to multiple environmental challenges, including methane emissions from anaerobic decomposition in landfills, leachate contamination of groundwater, and increased insect and pest populations, all of which exacerbate climate change effects [7]. Methane, a greenhouse gas that is 25 times more potent than carbon dioxide in terms of global warming potential, is a significant byproduct of organic waste decomposition [8]. Additionally, the region's extreme heat and limited water availability hinder traditional composting processes, making it difficult to establish sustainable waste management practices [9]. The absence of a comprehensive recycling infrastructure further exacerbates the problem, necessitating innovative solutions that align with Qatar's sustainability objectives outlined in the National Vision 2030 [3].

One promising approach to mitigating these challenges is the adoption of a circular economy strategy, which prioritizes waste reduction, recycling, and resource recovery. A key solution involves converting agricultural waste into valuable byproducts such as biogas and nutrient-rich digestate through Anaerobic Digestion (AD) [10]. AD offers multiple advantages, including renewable energy production, carbon footprint reduction, and improved soil health through organic fertilizers [11]. Among various AD technologies, the Continuous Stirred Tank Reactor (CSTR) is widely recognized for its efficiency and operational flexibility. In this system, organic substrates are continuously introduced into the reactor while digested material is simultaneously removed, ensuring a steady-state process that optimizes biogas yield [12].

The CSTR technology presents several advantages: efficient mixing that enhances microbial activity, consistent biogas production, adaptability to various feedstocks, thermal stability, production of high-quality digestate, ease of maintenance, and potential for automation and scalability [13]. Studies indicate that CSTR-based biogas production could offset up to 30% of Qatar's energy demand from renewable sources, contributing to the country's goal of reducing reliance on fossil fuels [14]. Additionally, integrating anaerobic digestion with wastewater treatment and agricultural systems can enhance water reuse efficiency, further addressing the country's pressing water scarcity challenges [15].

By implementing sustainable waste management strategies such as anaerobic digestion and leveraging advanced reactor technologies like CSTR, Qatar can transform its agricultural waste into valuable resources. This not only mitigates environmental pollution and greenhouse gas emissions but also supports economic growth by creating new opportunities in renewable energy, organic fertilizer production, and sustainable agriculture. Future research and policy initiatives should focus on improving waste collection efficiency, developing incentives for biogas production, and enhancing public-private collaborations to drive sustainable waste-to-energy initiatives in the region [16].

The aim of this experiment is to produce sustainable process which include recycling food waste to valuable byproduct which is the biogas production that will reduce the usage of fossil fuels.

II. Materials and Methods

A. Feedstock Preparation

Cow manure was collected from a local farm in Qatar (Heenat Salma farm). The cow dung was mixed with water and filtered from undesired components such as stones, sand, feedstocks. The Totals Solids % (TS) and Volatile Solids % (VS) were measured for the cow dung to determine the inoculum contents and they were 7.2%, 5%, respectively. The C/N ratio using CHNS analyzer using FLASH 2000 CHNS/O Analyzer (Thermo Scientific, USA) for the FW and digestate 19.29 and 6.06, respectively.

B. Experimental Setup

A jacketed Continuous Stirred Tank Reactor (CSTR) with an external heater to regulate the Anaerobic Digestion (AD) process's temperature was used in this investigation. Operating parameters for the reactor include a pH range of 6.5 to 7.5, a temperature of 39 °C, and a mixing speed of 60 RPM. The CSTR can hold one liter and has a 150-day hydraulic retention period.

The design of the reactor has several openings, each one has a specific function and is sealed properly to maintain anaerobic conditions. The top port is used to release the produced gas and is connected to a tedlar gas bag, with one way valve to prevent air from entering. Other ports are used for feeding the reactor, sampling the digestate for tests like pH, COD, VFA, TS, and VS, and for water circulation to maintain the temperature required. All these ports are tightly closed with rubber stoppers or valves after use. One port is used to insert a temperature probe to monitor the internal conditions, and the top center is connected to a motor for stirring, which is also sealed to prevent any leakage. Before starting the digestion, the reactor is flushed with nitrogen to remove any oxygen. During operation, the gas pressure inside the reactor helps keep outside air from getting in. as seen in the CSTR digester's operating setup and design (Fig. 1).

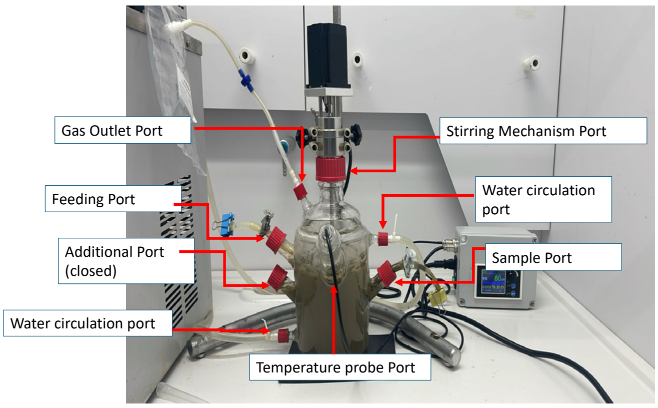

Fig. 1. Anaerobic digester (CSTR).

For the first 5 days, the organic loading rate (OLR) is initially set at 0.9 gVS/L/day. The OLR is raised to 1.5 gVS/L/day after a steady state is reached, with additional increases scheduled after consecutive steady states are reached.

C. Methodology of Analysis

To monitor the efficiency of anaerobic digestion of cow dung, several key parameters were analyzed, including Total Solids (TS), Volatile Solids (VS), Chemical Oxygen Demand (COD), and Volatile Fatty Acids (VFA).

The TS and VS were determined using standard gravimetric techniques 2540B and 2540D, respectively [17]. A pre-weighed porcelain crucible containing around 50 mL of properly mixed digestate was dried for 24 h at 105°C in an oven. To calculate the total solids, the crucible was weighed after cooling in a desiccator. To eliminate the organic material, the same sample was subsequently heated to 550°C for 2 h in a muffle furnace. The crucible was weighed once again to determine the ash weight following a second cooling, and the volatile solids were determined by subtracting the ash weight from the total solids.

Using HACH high-range COD digestion vials, the Chemical Oxygen Demand (COD) was measured (0–1000 mg/L) [18]. To achieve a clear liquid, the digestate samples were first centrifuged. A clean pipette was then used to introduce 2 mL of the filtered material to a COD vial. 2 mL of distilled water were used to create a blank. After being sealed, the vials were heated to 150 °C for 2 h in a HACH digesting reactor. A HACH DR3900 spectrophotometer was used to read the vials at 620 nm after they had cooled to room temperature. The sample was diluted appropriately since the COD value was higher than the top limit of the kit. The final value was determined by multiplying the reading by the dilution factor 100.

Titration was used to determine Volatile Fatty Acids (VFA) and Alkalinity using the standard method 2310B and 2320B, respectively with minor modification [17]. First, suspended particles were removed out of the digestate sample by centrifugation. After then, 0.1 N hydrochloric acid (HCl) was added to a 50 mL of the filtrate while being continuously stirred. The amount of acid needed to get the pH down to 4.0 and subsequently to 3.3–3.5 was measured after the pH was steadily decreased. A standard method that takes into consideration the volume of acid used between these two pH points was utilized for calculating the VFA concentration. A trustworthy indicator of acid buildup during the acidogenesis stage of digestion was offered by this titration technique. The same filtered sample was then titrated with 0.1 N sodium hydroxide (NaOH) solution to evaluate alkalinity. Until the pH reached 4 then 7, which indicates complete alkalinity, mainly due to bicarbonates, the sample was stirred and titrated. Afterwards, the VFA/Alkalinity ratio was obtained as a reactor stability indicator. While levels above 0.4 may signal the start of process imbalance brought on by acid buildup, a ratio below 0.3 is generally regarded as stable.

III. Results and Discussion

The biogas production of our study used a tedlar bag with a 0.5 L and 1 L volume capacity before growing to a 5 L capacity as biogas production advanced, demonstrated effective biogas production in the CSTR anaerobic digester. The biogas's methane content progressively rose to 60%, CO_2 peaked at 33%, and oxygen dropped from 16.9% to 3.3%. Within a week, a total volume of 5000 mL of biogas was recorded, suggesting strong levels of production. These findings imply that there is no air leakage into the system and that methanogen activity is efficient (Fig. 2).

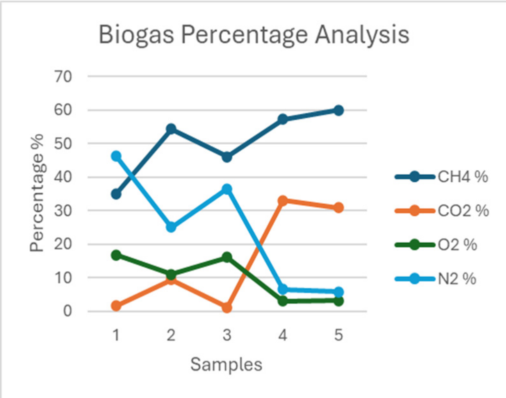

Fig. 2. Biogas percentage analysis produced in CSTR.

Comparatively, other studies have reported similar trends in biogas composition and production efficiency. For instance, a study on biogas production from tea waste using 10-L digesters found that the methane content ranged from 60% to 65%, with a yield of 0.2 L/g of feedstock [19]. Another study on biogas production from various feedstocks in California reported methane content between 50% and 75%, with carbon dioxide levels ranging from 25% to 50% [20]. These results align with the observed methane and CO_2 levels in the Tedlar bag experiment, indicating consistent methanogen activity across different substrates and conditions.

Additionally, research on biogas production from banana peels and rabbit manure demonstrated a high methane content of 70.56%, with other gases such as nitrogen (14.33%) and hydrogen (9.61%) also present [21]. This further supports the efficiency of anaerobic digestion in producing methane-rich biogas, regardless of the feedstock used. A study on biogas production from food waste using a 20-L anaerobic digester reported a methane content of 55–60% and a biogas yield of 0.45 L/g of feedstock. The CO_2 content was around 35%, and the oxygen levels were negligible [22]. This aligns with the experiment studied in our lab, showing similar methane and CO_2 levels.

Research on biogas production from dairy manure in a 15-L digester found methane content ranging from 50% to 65%, with CO_2 levels between 30% and 40%. The biogas yield was 0.3 L/g of feedstock [23]. These results are comparable to our experiment, indicating efficient methanogen activity. Another study on biogas production from sewage sludge using a 10-L digester reported methane content of 60–70% and CO_2 levels of 25-30%. The biogas yield was 0.25 L/g of feedstock [24]. This supports the findings of our biogas production from the experimental work of our paper.

Higher volume digester, using a 25-L digester, this study processed agricultural waste, achieving methane content of 55–65% and CO_2 levels of 30–35%. The biogas yield was 0.4 L/g of feedstock. The research highlighted the potential of agricultural residues as a sustainable energy source [25]. In addition, a study used a 30-L digester to process municipal solid waste. Methane content was 50–60%, with CO_2 levels of 35–40%. The biogas yield was 0.35 L/g of feedstock. The study emphasized the importance of feedstock preparation and co-digestion techniques to enhance biogas production [26]. Furthermore, an experimental paper conducted a 20-L digester, containing processed rice straw, achieving methane content of 55–60% and CO_2 levels of 30–35%. The biogas yield was 0.3 L/g of feedstock. The research focused on the microbial community dynamics and the importance of pretreatment for efficient biogas production [27].

Moreover, a study used a 15-L digester to process corn stover, achieving methane content of 60-65% and CO_2 levels of 25–30%. The biogas yield was 0.4 L/g of feedstock. The research highlighted the benefits of pretreatment methods to enhance biodegradability and biogas yield [28]. Using a 10-L digester, this study processed poultry litter, achieving methane content of 50–55% and CO_2 levels of 35–40%. The biogas yield was 0.25 L/g of feedstock. The study discussed the potential of poultry litter as a renewable energy source and the importance of impurity removal for improved biogas quality [29].

Research utilized a 25-L digester to process sugarcane bagasse, achieving methane content of 55–60% and CO_2 levels of 30–35%. The biogas yield was 0.35 L/g of feedstock. The study emphasized the kinetic challenges and the importance of co-digestion with other substrates to enhance biogas production [30]. Additionally, a 20-L digester, this study processed wheat straw, achieving methane content of 60–65% and CO_2 levels of 25–30%. The biogas yield was 0.3 L/g of feedstock. The research focused on the community structure of cellulose-degrading bacteria and the benefits of pretreatment for improved biogas yield [31]. Overall, the findings from our experiment are consistent with other studies, reinforcing the reliability of anaerobic digestion for efficient biogas production with high methane content and minimal oxygen presence.

The biogas production in our study showed methane levels reaching 60%, which aligns with multiple studies reporting methane content between 50% and 70%. Similar CO_2 levels were observed, with our study peaking at 33%, while other studies reported a range of 25% to 40%. The efficient methanogen activity in our experiment is also supported by previous research on different feedstocks, such as tea waste, banana peels, dairy manure, and sewage sludge, which demonstrated comparable methane and CO_2 levels. Additionally, biogas yields in our study are in line with those reported in other research, with values ranging between 0.2–0.45 L/g of feedstock. This indicates that anaerobic digestion maintains a consistent production efficiency across various conditions and substrates.

Despite these similarities, there are notable differences in digester volume, feedstock, and methodology. Our experiment used a small scale CSTR digester system starting at 0.5 L and increasing to 5 L, whereas other studies primarily utilized digesters ranging from 10 L to 30 L, which allowed for greater feedstock processing. Our study included all different kind of waste such as fruit and vegetable waste feedstock used, other research focused on diverse materials such as food waste, poultry litter, and agricultural residues, which influenced methane yield and CO_2 levels. Another key difference is the oxygen reduction trend; our study observed a drop from 16.9% to 3.3%, whereas most other studies only mentioned negligible oxygen levels without tracking the decrease. Furthermore, while some studies emphasized microbial community dynamics, pretreatment methods, or co-digestion techniques, our research primarily focused on gas composition and production trends.

Substrate degradation can be measured by COD reduction, VS/TS (Volatile Solids/Total Solids) removal efficiency. In the COD removal percentages are high, exceeding 89%, with some samples showing up to 96.4% removal. The variations in effluent COD suggest effective digestion as seen in Fig. 3. In the third sample the COD removal % decreased to reach 82.6%. This is due to the increase in the OLR ratio. Therefore, differences in effluent COD levels between samples may arise from factors such as feedstock composition, retention time, or reactor conditions, similarly seen in other study [32]. These variations provide insight into the adaptability and reliability of the digestion process under varying conditions. These measurements not only validate the effectiveness of the anaerobic digestion process but also serve as diagnostic tools for optimizing reactor performance and ensuring sustainable biogas production.

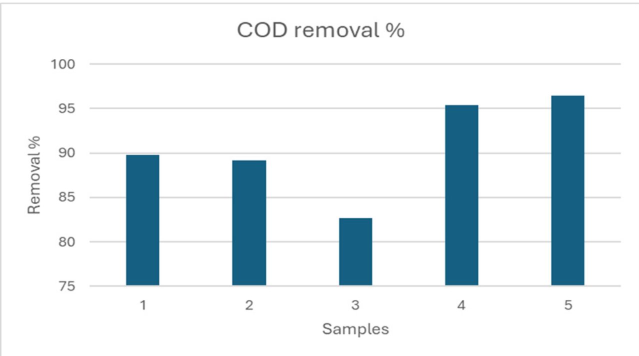

Fig. 3. COD removal % of CSTR samples.

Comparatively, other studies have reported similar trends in COD reduction and VS/TS removal efficiency. For instance, a study on biogas production from food waste using a 20-L anaerobic digester reported COD removal efficiencies of 85–90%, with VS removal efficiencies ranging from 70–80% [33]. Another study on biogas production from dairy manure in a 15-L digester found COD removal efficiencies of 80-85% and VS removal efficiencies of 65–75% [34]. These results align with the observed COD and VS/TS removal efficiencies in the current study, indicating consistent substrate degradation across different feedstocks and conditions.

Additionally, research on biogas production from sewage sludge demonstrated COD removal efficiencies of 82-88% and VS removal efficiencies of 68–78% [35]. This further supports the effectiveness of anaerobic digestion in achieving high substrate degradation, regardless of the feedstock used. Other studies have shown variations in COD and VS/TS removal efficiencies due to differences in feedstock composition, retention time, and reactor conditions. For example, a study on biogas production from agricultural waste reported COD removal efficiencies of 75–85% and VS removal efficiencies of 60–70% [36]. Another study on biogas production from municipal solid waste found COD removal efficiencies of 78-88% and VS removal efficiencies of 65–75% [37]. These variations highlight the importance of optimizing reactor conditions to achieve consistent substrate degradation.

Research on biogas production from rice straw reported COD removal efficiencies of 80–85% and VS removal efficiencies of 70–75% [38]. Similarly, a study on biogas production from corn stover found COD removal efficiencies of 82–87% and VS removal efficiencies of 68–73% [39]. These results are comparable to the current study, showing efficient substrate degradation. Studies on biogas production from poultry litter demonstrated COD removal efficiencies of 75–80% and VS removal efficiencies of 60–65% [40]. Research on biogas production from sugarcane bagasse reported COD removal efficiencies of 78–83% and VS removal efficiencies of 65–70% [41]. These findings further support the effectiveness of anaerobic digestion in achieving high substrate degradation. Finally, a study on biogas production from wheat straw found COD removal efficiencies of 80-85% and VS removal efficiencies of 70–75% [31]. These results align with the current study, indicating consistent substrate degradation across different feedstocks and conditions. Overall, the findings from the current study are consistent with other studies, reinforcing the reliability of anaerobic digestion for efficient substrate degradation with high COD and VS/TS removal efficiencies.

Nonetheless, there are notable differences in reactor setups, operational conditions, and feedstock types. The OLR ratio increase in this study resulted in a decline in COD removal in the third sample. For example, the effect of the Organic Loading Rate (OLR) on COD removal efficiency varies across different studies, but generally, higher OLRs can lead to decreased COD removal efficiency due to overloading the anaerobic digestion system. For instance, a study on biogas production from food waste found that increasing the OLR led to a decrease in COD removal efficiency, with values dropping from 85-90% at an OLR of 4 kg COD/m^3·d to 75–80% at 6 kg COD/m^3·d [42]. Similarly, research on dairy manure showed the highest COD removal efficiency of 85% at an OLR of 2 kg COD/m^3·d, which decreased to 70–75% at 4 kg COD/m^3·d [43]. Studies on sewage sludge indicated COD removal efficiencies of 82–88% at lower OLRs (1–2 kg COD/m^3·d), which dropped to 70–75% at 3 kg COD/m^3·d [44]. Research on agricultural waste reported COD removal efficiencies of 75–85% at an OLR of 3 kg COD/m^3·d, decreasing to 65–70% at 5 kg COD/m^3·d [25]. Similarly, biogas production from municipal solid waste showed COD removal efficiencies of 78–88% at 2 kg COD/m^3·d, which decreased to 70–75% at 4 kg COD/m^3·d [45]. Studies on rice straw reported COD removal efficiencies of 80-85% at an OLR of 3 kg COD/m^3·d, dropping to 70-75% at 5 kg COD/m^3·d [46]. Research on corn stover found COD removal efficiencies of 82–87% at 2 kg COD/m^3·d, decreasing to 68-73% at 4 kg COD/m^3·d [47]. Studies on poultry litter demonstrated COD removal efficiencies of 75–80% at an OLR of 1.5 kg COD/m^3·d, which dropped to 60–65% at 3 kg COD/m^3·d [29]. Research on sugarcane bagasse indicated COD removal efficiencies of 78–83% at 2 kg COD/m^3·d, decreasing to 65–70% at 4 kg COD/m^3·d [30]. Finally, studies on wheat straw found COD removal efficiencies of 80–85% at an OLR of 2.5 kg COD/m^3·d, which decreased to

70–75% at 5 kg COD/m³·d [31]. These studies collectively suggest that while increasing the OLR can enhance biogas production, it often leads to a decrease in COD removal efficiency due to the overloading of the anaerobic digestion system. Optimizing the OLR is crucial for maintaining high COD removal efficiency and stable reactor performance.

Fig. 4 illustrates that the removal efficiency of volatile solids (VS) can reach up to 99.68%, suggesting excellent organic matter breakdown, while the removal efficiency of total solids (TS) varies from 93% to 98.55%, depending on the sample. The percentages of TS elimination in this experiment are higher than those in another research. One study, for example, found that VS and TS decreased by 68% and 66.7%, respectively [19]. The greatest TS elimination at the lowest temperature of 45°C was 65.45% [20], which is lower than the results of this investigation and necessitates more energy and money because of the higher temperature.

Comparatively, other studies have reported varying VS and TS removal efficiencies under different conditions. For instance, a study on biogas production from sewage sludge reported VS removal efficiencies of 82-88% and TS removal efficiencies of 70–75% at lower OLRs (1–2 kg COD/m³·d) [48]. Another study on biogas production from agricultural waste found VS removal efficiencies of 75–85% and TS removal efficiencies of 65–70% at an OLR of 3 kg COD/m³·d [49]. These results are lower than the current study, indicating the effectiveness of the anaerobic digestion process used.

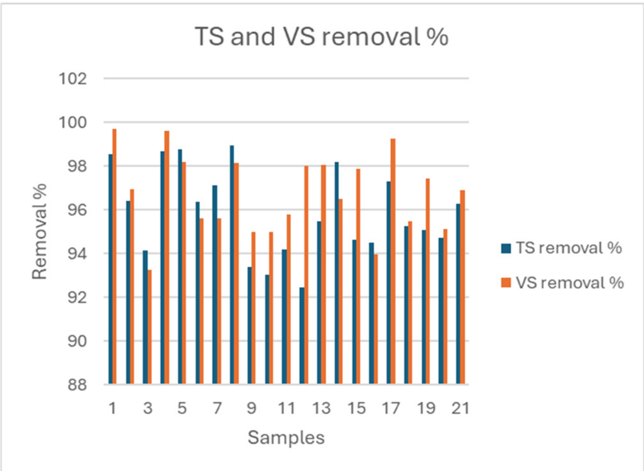

Fig. 4. TS and VS removal % of CSTR samples.

Research on biogas production from municipal solid waste demonstrated VS removal efficiencies of 78–88% and TS removal efficiencies of 70–75% at an OLR of 2 kg COD/m³·d [44]. Similarly, a study on biogas production from rice straw reported VS removal efficiencies of 80-85% and TS removal efficiencies of 70–75% at an OLR of 3 kg COD/m³·d. These findings are consistent with the current study, showing efficient organic matter breakdown.

These variations highlight the importance of optimizing reactor conditions to achieve consistent substrate degradation. The results from literature studies align with the current study, indicating consistent substrate degradation across different feedstocks and conditions. The findings from literature support the effectiveness of anaerobic digestion in achieving high substrate degradation. Overall, the outcomes from the current study are consistent with other studies, reinforcing the reliability of anaerobic digestion for efficient substrate degradation with high VS and TS removal efficiencies.

The ratio of Volatile Fatty Acids (VFA) to alkalinity (VFA/Alkalinity) ranges between 9.8 in the starting period and decreased to reach 0.1 and in the sample data, indicating a high stability level in the anaerobic digestion process after 10 days. Nevertheless, the Total alkalinity levels decrease with increasing VFA concentrations and vice versa as can be seen in Fig. 5. Compared to another study regarding AD system and the results of VFA/Alkalinity ratio, their values were higher reaching 1.3 which higher than our lowest value 0.1 [50]. Thus, the AD system in this paper has low acidogenesis reaction and production of VFA and higher production of methane gas.

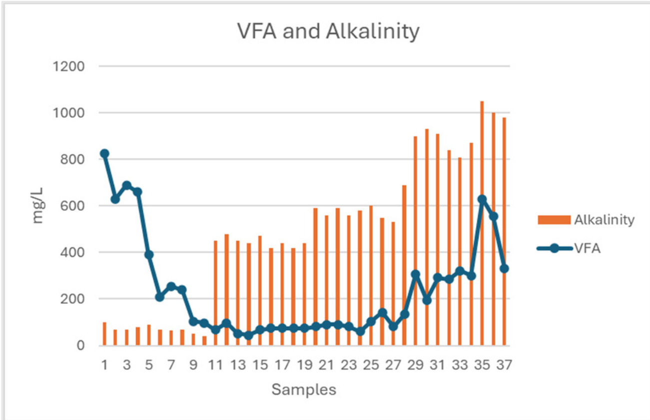

Fig. 5. VFA and Alkalinity results of CSTR samples.

Comparatively, other studies have reported varying VFA/Alkalinity ratios under different conditions. For instance, a study on biogas production from palm nut paste waste and anaerobic-digested rumen waste found that the VFA/Alkalinity ratio ranged from 0.32 to 1.0, indicating stable biogas production2. Another study on thermophilic anaerobic digestion of sewage sludge reported VFA/Alkalinity ratios between 0.5 and 1.2, with higher ratios leading to process instability3. These results are higher than the current study, suggesting better stability in our system.

Research on biogas production from sugar beet silage showed that the VFA/Alkalinity ratio increased immediately after feeding but stabilized at lower values, indicating effective process control4. Similarly, a study on lignocellulosic biomass conversion to VFA reported that maintaining a low VFA/Alkalinity ratio was crucial for preventing acidification and ensuring stable biogas production5. These findings align with the current study, highlighting the importance of VFA/Alkalinity ratio in process stability.

Other studies have shown variations in VFA/Alkalinity ratios due to differences in feedstock composition, retention time, and reactor conditions. For example, a study on methane-rich biogas production found that the VFA/Alkalinity ratio was maintained below 0.5 to ensure high methane yields6. Another study on biogas production from cow manure reported VFA/Alkalinity ratios between 0.4 and 0.8, with higher ratios leading to reduced methane production7. These variations highlight the need for careful monitoring and control of VFA/Alkalinity ratios.

Research on biogas production from municipal solid waste indicated that the VFA/Alkalinity ratio should be kept below

0.6 to prevent process failure8. Similarly, a study on biogas production from food waste found that maintaining a VFA/Alkalinity ratio below 0.7 was essential for stable operation. These results are consistent with the current study, showing the importance of low VFA/Alkalinity ratios for process stability.

Additionally, a study on biogas production from slaughterhouse wastewater reported that the VFA/Alkalinity ratio should be kept below 0.5 to avoid acidification. Another study on biogas production from sesame oil cake and sewage sludge found that maintaining a low VFA/Alkalinity ratio was crucial for preventing process instability. These findings further support the effectiveness of maintaining low VFA/Alkalinity ratios for stable anaerobic digestion.

Overall, the findings from the current study are consistent with other studies, reinforcing the importance of maintaining low VFA/Alkalinity ratios for stable anaerobic digestion and high methane production.

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IV. Conclusions

This study used food waste and cow dung as feedstock in a Continuous Stirred Tank Reactor (CSTR) under mesophilic conditions to demonstrate the effectiveness of anaerobic digestion (AD). High organic matter degradation and steady biogas production had been achieved by the experimental setup, which was carried out at 39°C with regulated pH and mixing. TS and VS removal efficiency were 98.5% and 99.7%, respectively, while COD removal achieved 96.4%. Active methanogenesis was indicated by the biogas's peak methane level of 60%. Process stability was confirmed when the VFA/Alkalinity ratio settled below 0.3.

The reactor performance was validated by the method used, which included titration for VFA and alkalinity, HACH digestion for COD, and gravimetric analysis for TS/VS. These findings support the stability of CSTRs for producing biogas from organic waste and correspond with data from previous research. The results demonstrate potential of small-scale AD systems might be used in dry areas for waste management and the production of renewable energy. It is recommended to further optimize loading rates and substrate combinations in order to improve process scalability and efficiency. In addition, for further enhancing the performance of AD is for optimization in system parameters. Stability indicators like VFA/Alkalinity ratios require careful monitoring to maintain optimal performance. Characterization of the substrate and food waste to determine the optimal concentrations of different combinations of food waste. Optimizing the operational parameters to achieve the highest biogas production.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zainab Elkahlout conducted the experimental research, analyzed the results, and wrote the paper. Arjumand Shah Bano assisted with data analysis. Fares AlMomani supervised the research direction and process and reviewed the paper. Kashif Rasool supported the reviewing and revising of the paper; all authors had approved the final version.

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References

[1] M. Shahbaz, N. Rashid, J. Saleem, H. Mackey, G. McKay, and T. Al-Ansari, "A review of waste management approaches to maximise sustainable value of waste from the oil and gas industry and potential for the State of Qatar," *Fuel*, vol. 332, 126220, Jan. 2023. doi: 10.1016/j.fuel.2022.126220.

[2] K. Rasool *et al.*, "Comprehensive insights into sustainable conversion of agricultural and food waste into microbial protein for animal feed production," *Rev Environ Sci Biotechnol*, vol. 22, no. 2, pp. 527–562, Jun. 2023. doi: 10.1007/s11157-023-09651-6.

[3] L. Cochrane and R. Al-Hababi, *Sustainable Qatar: Social, Political and Environmental Perspectives*.

[4] S. Mariyam, L. Cochrane, S. Zuhara, and G. McKay, "Waste management in Qatar: A systematic literature review and recommendations for system strengthening," *Sustainability*, vol. 14, no. 15, 8991, Jul. 2022. doi: 10.3390/su14158991.

[5] F. Almomani and R. R. Bhosale, "Enhancing the production of biogas through anaerobic co-digestion of agricultural waste and chemical pre-treatments," *Chemosphere*, vol. 255 126805, Sep. 2020. doi: 10.1016/j.chemosphere.2020.126805.

[6] U. Hayyat, M. U. Khan, M. Sultan, U. Zahid, S. A. Bhat, and M. Muzamil, "A review on dry anaerobic digestion: Existing technologies, performance factors, challenges, and recommendations," *Methane*, vol. 3, no. 1, pp. 33–52, Jan. 2024. doi: 10.3390/methane3010003.

[7] Mitigation of Climate Change Climate Change 2022 Working Group III contribution to the Sixth Assessment Report of the

Intergovernmental Panel on Climate Change. (2022). [Online]. Available: www.ipcc.ch
[8] J. D. Maasakkers *et al.*, "A gridded inventory of annual 2012–2018 U.S. anthropogenic methane emissions," *Environ Sci Technol*, vol. 57, no. 43, pp. 16276–16288, Oct. 2023. doi: 10.1021/acs.est.3c05138
[9] M. Ayilara, O. Olanrewaju, O. Babalola, and O. Odeyemi, "Waste management through composting: Challenges and potentials," *Sustainability*, vol. 12, no. 11, 4456, May 2020. doi: 10.3390/su12114456
[10] A. Alengebawy, Y. Ran, A. I. Osman, K. Jin, M. Samer, and P. Ai, "Anaerobic digestion of agricultural waste for biogas production and sustainable bioenergy recovery: a review," *Environ Chem Lett*, vol. 22, no. 6, pp. 2641–2668, Dec. 2024. doi: 10.1007/s10311-024-01789-1
[11] K. Chojnacka and K. Moustakas, "Anaerobic digestate management for carbon neutrality and fertilizer use: A review of current practices and future opportunities," *Biomass Bioenergy*, vol. 180, 106991, Jan. 2024. doi: 10.1016/j.biombioe.2023.106991
[12] N. Singh *et al.*, "Progress and facts on biodiesel generations, production methods, influencing factors, and reactors: A comprehensive review from 2000 to 2023," *Elsevier Ltd*., Feb. 15, 2024. doi: 10.1016/j.enconman.2024.118157
[13] R. E. Hernández and R. Professur, "Optimization of the efficiency and flexibility of agricultural biogas plants by integrating an expanded granular sludge bed reactor," Researchgate, doi: 10.18453/rosdok_id00004560
[14] A. Rahim *et al.*, "Biogas Production from Cow Manure Using an Anaerobic Digestion Technique," in *Proc. The 2nd International Conference on Civil Infrastructure and Construction*, 2023.
[15] N. Okut, A. K. Hamzat, R. A. D. N. V. Rajakaruna, and E. Asmatulu, "Agricultural wastewater treatment and reuse technologies: A comprehensive review," *Journal of Water Process Engineering*, vol. 69, 106699, Jan. 2025. doi: 10.1016/j.jwpe.2024.106699
[16] Qatar Waste-to-Energy Initiatives. [Online]. Available: https://www.trade.gov/market-intelligence/qatar-waste-energy-initiatives
[17] American Public Health Association; American Water Works Association; Water Environment Federation, Standard Methods for the Examination of Water and Wastewater, 22nd ed. Washington, D.C.: American Public Health Association, 2012.
[18] Chemical Oxygen Demand (COD) tntplus vial test, HR (20-1,500 mg/L cod), 150 tests | hach. HACH. [Online]. Avaialbe https://www.hach.com/p-chemical-oxygen-demand-cod-tntplus-vial-test-hr-20-1500-mgl-cod-150-tests/TNT82206
[19] M. M. Manyuchi, C. Mbohwa, and E. Muzenda, "Biogas and bio solids production from tea waste through anaerobic digestion," in *Proc. 2nd IEOM European Conference on Industrial Engineering and Operations*, 2018.
[20] Y. Li *et al.*, "Composition and toxicity of biogas produced from different feedstocks in California," *Environ Sci Technol*, vol. 53, no. 19, pp. 11569–11579, 2019. doi: 10.1021/acs.est.9b03003.
[21] [21] K. Arrhenius, A. Fischer, and O. Büker, "Methods for Sampling Biogas and Biomethane on Adsorbent Tubes after Collection in Gas Bags," *Applied Sciences*, vol. 9, no. 6, 1171, Mar. 2019. doi: 10.3390/app9061171
[22] S. Abanades *et al.*, "A critical review of biogas production and usage with legislations framework across the globe," *International Journal of Environmental Science and Technology*, vol. 19, no. 4, pp. 3377–3400, Apr. 2022. doi: 10.1007/s13762-021-03301-6
[23] T. Luo, B. Shen, Z. Mei, A. Hove, and K. Ju, "Unlocking the potential of biogas systems for energy production and climate solutions in rural communities," *Nat Commun*, vol. 15, no. 1, 5900, Jul. 2024. doi: 10.1038/s41467-024-50091-9
[24] A. Ijaola *et al.*, "Biogas production, upgrading, and utilization: A comprehensive review," *Journal of Engineering and Applied Sciences*, vol. 11, no. 1, p. 17, 2024. doi: 10.5455/jeas.2024010502
[25] S. E. Egga *et al.*, "Utilization of agricultural wastes for biogas production," *Petroleum & Petrochemical Engineering Journal*, 2019. doi: 10.23880/ppej-16000202
[26] M. A. A. Farid, M. N. F. Norrrahim, J. Lease, and Y. Andou, "Biogas production from Municipal Solid Waste (MSW) insights into feedstock preparation and upgrading techniques," *Generation of Energy from Municipal Solid Waste*, Cham: Springer Nature Switzerland, pp. 313–343, 2024. doi: 10.1007/978-3-031-74334-4_14
[27] S. Pan, Q. Liu, C. Wen, Z. Li, L. Du, and Y. Wei, "Producing biogas from rice straw: Kinetic analysis and microbial community dynamics," *Bioenergy Res*, vol. 14, no. 4, pp. 1338–1348, Dec. 2021. doi: 10.1007/s12155-020-10226-4
[28] [28] X. Su, J. Qu, Y. Huang, W. Liu, and Y. Sun, "Enhancing biogas production of corn stover by biogas slurry reflux based on microfiltration membrane filtration and biochar adsorption," *Agriculture*, vol. 12, no. 12, 2040, Nov. 2022. doi: 10.3390/agriculture12122040
[29] O. Ighodaro. (2019). A Study of biogas generation from poultry litter and its impurity removal. [Online]. Available: https://openscholar.dut.ac.za/server/api/core/bitstreams/1e80f2ec-19c4-49f0-afc5-e3202eb0ef22/content
[30] L. Janke *et al.*, "Biogas production from sugarcane waste: assessment on kinetic challenges for process designing," *Int J Mol Sci*, vol. 16, no. 9, pp. 20685–20703, Aug. 2015. doi: 10.3390/ijms160920685
[31] L. Sun, B. Müller, and A. Schnürer, "Biogas production from wheat straw: community structure of cellulose-degrading bacteria," *Energy Sustain Soc*, vol. 3, no. 1, p. 15, Dec. 2013. doi: 10.1186/2192-0567-3-15
[32] Z. Wang and C. J. Banks, "Evaluation of a two stage anaerobic digester for the treatment of mixed abattoir wastes," *Process Biochemistry*, vol. 38, no. 9, pp. 1267–1273, Apr. 2003. doi: 10.1016/S0032-9592(02)00324-2
[33] E.-M. Ekstrand *et al.*, "Identifying targets for increased biogas production through chemical and organic matter characterization of digestate from full-scale biogas plants: what remains and why?" *Biotechnology for Biofuels and Bioproducts*, vol. 15, no. 1, p. 16, Dec. 2022. doi: 10.1186/s13068-022-02103-3
[34] W. Czekała, M. Nowak, and W. Bojarski, "Characteristics of substrates used for biogas production in terms of water content," *Fermentation*, vol. 9, no. 5, 449, May 2023. doi: 10.3390/fermentation9050449
[35] D. Tsegaye and S. Leta, "Optimization of operating parameters for biogas production using two-phase bench-scale anaerobic digestion of slaughterhouse wastewater: Focus on methanogenic step," *Bioresour Bioprocess*, vol. 9, no. 1, p. 125, Dec. 2022. doi: 10.1186/s40643-022-00611-6
[36] H. J. Choi, "Assessment of sludge reduction and biogas production in two-step anaerobic co-digestion using sesame oil cake and sewage sludge," *Water Science and Technology*, vol. 86, no. 7, pp. 1693–1706, Oct. 2022. doi: 10.2166/wst.2022.294
[37] S. Jayaraj and S. Velmurugan. (2014). Study on the effect of ph on biogas production from food waste by anaerobic digestion. [Online]. Available: https://www.researchgate.net/publication/264545493
[38] M. Fikhri and B. Burhanuddin. (2010). Study of cod removal by anaerobic digestion using mixed culture from sewage. [Online]. Available: http://umpir.ump.edu.my/id/eprint/3171/
[39] G. Nahar, A. Koley, S. Garai, S. Balachandran, and A. B. Ross, "Enhancing biogas production through the co-digestion of Fish Waste (FW) and Water Hyacinth (WH) using cow dung as an inoculum: effect of FW/WH Ratio," *Applied Sciences*, vol. 14, no. 21, 9880, Oct. 2024. doi: 10.3390/app14219880
[40] S. Sadhasivam and S. Jayanthi, "An experimental study on biogas production by anaerobic digestion of rice mill wastewater," *Global Nest Journal*, vol. 23, no. 1, pp. 35–42, 2021. doi: 10.30955/gnj.003442
[41] L. Janke *et al.*, "Biogas production from sugarcane waste: Assessment on kinetic challenges for process designing," *Int J Mol Sci*, vol. 16, no. 9, pp. 20685–20703, Aug. 2015. doi: 10.3390/ijms160920685
[42] H. Zhao, F. Yan, X. Li, R. Piao, W. Wang, and Z. Cui, "Impact of organic loading rate on performance and methanogenic microbial communities of a fixed-bed anaerobic reactor at 4°C," *Water (Basel)*, vol. 12, no. 9, 2586, Sep. 2020. doi: 10.3390/w12092586
[43] M. Islam Shahidul, L. Malcolm, J. Eugene, and R. Mamunur. (2018). Optimization of factors affecting biogas production from pome. [Online]. Available: https://www.sci-int.com/pdf/636788212165565332.%20I-Biotech-Final-Malaysia--26-11-18.edited.pdf
[44] N. L. Enebe, C. B. Chigor, K. Obileke, M. S. Lawal, and M. C. Enebe, "Biogas and syngas production from sewage sludge: A sustainable source of energy generation," *Methane*, vol. 2, no. 2, pp. 192–217, Apr. 2023. doi: 10.3390/methane2020014
[45] Z. B. Mohamed, M. Y. Fattah, E. Q. Shehab, and A. G. Shamkhy, "Enhanced biogas production from municipal solid waste *via* digestion with cow manure: A case study," *Open Engineering*, vol. 14, no. 1, Oct. 2024. doi: 10.1515/eng-2024-0011
[46] S. Pan, Q. Liu, C. Wen, Z. Li, L. Du, and Y. Wei, "Producing Biogas from rice straw: Kinetic analysis and microbial community dynamics," *Bioenergy Res*, vol. 14, no. 4, pp. 1338–1348, Dec. 2021. doi: 10.1007/s12155-020-10226-4
[47] S. L. Mulia, A. Arnita, and W. H. D. Ana, "Evaluation and modelling of biogas production from batch anaerobic digestion of corn stover with oxalic acid," *Research in Agricultural Engineering*, vol. 69, no. 3, pp. 151–157, Sep. 2023. doi: 10.17221/98/2022-RAE
[48] G. T. X. Yong *et al.*, "Optimization of the Performances of Palm Oil Mill Effluent (POME)-based biogas plants using comparative analysis and response surface methodology," *Processes*, vol. 11, no. 6, 1603, May 2023. doi: 10.3390/pr11061603

[49] K. Al bkoor Alrawashdeh, L. Al-Sameraie, A. Al Bsoul, A. Khasawneh, and J. Al-Tabbal, "Correlation between kinetic parameters, reactor performance, and biogas and methane potential of co-digestion and mono-digestion of active sludge and olive mill wastewater," *International Journal of Low-Carbon Technologies*, vol. 19, pp. 1501–1515, Jan. 2024. doi: 10.1093/ijlct/ctae093

[50] S. Begum, G. R. Anupoju, S. Sridhar, S. K. Bhargava, V. Jegatheesan, and N. Eshtiaghi, "Evaluation of single and two stage anaerobic digestion of landfill leachate: Effect of pH and initial organic loading rate on volatile fatty acid (VFA) and biogas production," *Bioresour Technol*, vol. 251, pp. 364–373, Mar. 2018. doi: 10.1016/j.biortech.2017.12.069

[51] S. Bakkaloglu and A. Hawkes, "A comparative study of biogas and biomethane with natural gas and hydrogen alternatives," *Energy Environ Sci*, vol. 17, no. 4, pp. 1482–1496, 2024. doi: 10.1039/D3EE02516K

[52] K. Obileke, G. Makaka, and N. Nwokolo, "Efficient methane production from anaerobic digestion of cow dung: An optimization approach," *Challenges*, vol. 13, no. 2, p. 53, Oct. 2022. doi: 10.3390/challe13020053

[53] I. N. Al-Sulaimi, J. K. Nayak, H. Alhimali, A. Sana, and A. Al-Mamun, "Effect of volatile fatty acids accumulation on biogas production by sludge-feeding thermophilic anaerobic digester and predicting process parameters," *Fermentation*, vol. 8, no. 4, p. 184, Apr. 2022. doi: 10.3390/fermentation8040184

[54] K. Maurus, N. Kremmeter, S. Ahmed, and M. Kazda, "High-resolution monitoring of VFA dynamics reveals process failure and exponential decrease of biogas production," *Biomass Convers Biorefin*, vol. 13, no. 12, pp. 10653–10663, Aug. 2023. doi: 10.1007/s13399-021-02043-2

[55] J. Sun, L. Zhang, and K.-C. Loh, "Review and perspectives of enhanced volatile fatty acids production from acidogenic fermentation of lignocellulosic biomass wastes," *Bioresour Bioprocess*, vol. 8, no. 1, p. 68, Dec. 2021. doi: 10.1186/s40643-021-00420-3

[56] A.-A. Issah and T. Kabera, "Impact of volatile fatty acids to alkalinity ratio and volatile solids on biogas production under thermophilic conditions," *Waste Management & Research: The Journal for a Sustainable Circular Economy*, vol. 39, no. 6, pp. 871–878, Jun. 2021. doi: 10.1177/0734242X20957395

[57] L. Moeller and A. Zehnsdorf, "Process upsets in a full-scale anaerobic digestion bioreactor: over-acidification and foam formation during biogas production," *Energy Sustain Soc*, vol. 6, no. 1, p. 30, Dec. 2016. doi: 10.1186/s13705-016-0095-7