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Feasibility evaluation of using cattle manure for biogas production: A case study under household conditions in the Vietnamese Mekong Delta

Tran Sy Nam[1], Ai Leon[2], Tran Hoang Kha[1], Nguyen Van Cong[1], Huynh Van Thao[1], Dinh Thai Danh[1], Huynh Thi Diem[1], Huynh Cong Khanh[1*]

[1] College of Environment and Natural Resources, Campus II, Can Tho University, 3/2 Street, Cantho City, Vietnam
[2] Japan International Research Center for Agricultural Sciences, 1-1 Ohwashi, Tsukuba, Ibaraki, 305-8686, Japan
* Corresponding author's e-mail: hckhanh@ctu.edu.vn

ABSTRACT

Biogas production from cattle manure offers a promising and sustainable solution for managing livestock waste in the rural areas of the Vietnamese Mekong Delta (VMD), where smallholder cattle farming is common. The study aims to evaluate the impact of organic loading rates (OLR) of cattle manure (CM) on biogas production through anaerobic digestion under the tropical conditions typical of smallholder farming. Additionally, the research seeks to assess the stability, suitability, and continuous operational performance of biogas digesters in relation to the size of the cattle herd in each household. Nine biogas digesters achieved steady-state operation, with various numbers of cattle in households being monitored continuously over 13 weeks to assess daily biogas production. The results of the study can be categorized into three groups based on cattle herd size: Group 1 (two cattle), Group 2 (three cattle), and Group 3 (four cattle). The volume of the biogas digester is approximately 6.3 m³, which is typically suitable for households with three cattle, operating at an OLR of 5.78–6.00 kg-VS day^{-1}. Under these conditions, the digesters demonstrated stable performance and achieved high biogas yields of 270–310 L kg-VS$_{added}^{-1}$. In contrast, households with four cattle experienced a higher OLR of 7.52–8.67 kg-VS$_{added}$ day^{-1}, which resulted in lower biogas yields of 156–219 L kg-VS$_{added}^{-1}$. These findings suggest that the digester volume used in this study is not appropriate for households raising more than three cattle, as overloading can impair performance and reduce methane productivity. The study established the optimal digester volume corresponding to herd size to maximize biogas production efficiency. For future strategies, it is recommended to use post-digestion effluent (biogas effluent - BE) for cultivating Napier grass (*Pennisetum purpureum*). This approach is a crucial step towards creating a closed-loop circular economy in cattle farming systems.

Keywords: Cattle manure, organic loading rates, biogas production, Vietnamese Mekong Delta.

INTRODUCTION

The livestock sector has experienced rapid growth in many developing countries, contributing significantly to agricultural productivity, rural livelihoods, and national food security (FAO, 2018; Thornton, 2010). However, this expansion has also resulted in large volumes of organic waste, particularly cattle manure (CM), which poses major environmental risks if not properly managed. Inadequate handling of CM can lead to water pollution, greenhouse gas emissions, and odor nuisances (Rivera and Chara, 2021). In Vietnam, livestock farming is predominantly smallholder-based, especially in rural regions such as the VMD. In provinces like An Giang, where cattle farms are often located near residential areas, sustainable livestock waste management is vital for protecting both environmental and public health (Ho et al., 2015). This context calls for practical and cost-effective technologies that can convert waste into valuable resources.

Anaerobic digestion (AD) is a well-established and environmentally friendly method for treating livestock waste. It not only reduces organic load but also produces biogas for household energy use and digestate for agricultural reuse (Appels et al., 2008; Mata-Alvarez et al., 2011; Wang et al., 2012). CM is considered a suitable feedstock for AD due to its favorable carbon-to-nitrogen ratio and abundant biodegradable matter (Amon et al., 2007; Yadvika et al., 2004). Nonetheless, its high lignin content (11–13%) may limit methane production despite having substantial cellulose and hemicellulose contents (Fasake and Dashora, 2020; Fan et al., 2024). Several factors influence the efficiency of the AD process, including substrate characteristics, hydraulic retention time (HRT), mixing, and OLR (Weiland, 2010). Among these, OLR is critical, as excessive loading can lead to volatile fatty acid (VFA) accumulation, pH reduction, and process failure (Fantozzi and Buratti, 2009; Zhang et al., 2014). While numerous laboratory-scale studies have reported promising biogas yields from cattle manure in the VMD (Phuong et al., 2015), field data on household-scale systems – especially with varying herd sizes – remain scarce. In recent years, high-density polyethylene (HDPE) biogas digesters have become increasingly popular in the VMD due to their low cost, ease of installation, and adaptability to rural settings (Ni, 2024). However, limited empirical evidence exists on how herd size, manure input, and digester design affect gas production in practical conditions.

Therefore, this study aims to assess the biogas and methane production potential of cattle manure using HDPE biogas bag digesters at the household level in the VMD. It focuses on evaluating the relationship between cattle herd size and biogas system performance, and identifying appropriate digester volumes for achieving optimal gas yields. The findings are expected to support the development of sustainable waste-to-energy strategies and circular economy models in rural livestock-based communities.

MATERIALS AND METHODS

Study sites

This study was conducted in An Giang Province, situated in the VMD, where smallholder cattle farming is a common livelihood strategy. In January 2023, twenty HDPE biogas digesters were installed in 20 households as part of a rural biogas program. By the end of 2023, only nine of these digesters were found to be operating reliably, producing gas consistently and with no significant technical issues. These nine biogas systems were selected for further monitoring and evaluation. The selected digesters were distributed across two districts – Phu Tan and An Phu– covering three communes: Binh Thanh Dong, Phu Binh, and Vinh Truong (Figure 1). Specifically, one digester (H1) was located in Binh Thanh Dong Commune, two digesters (H7 and H8) in Phu Binh Commune, and six digesters (H2–H6 and H9) in Vinh Truong Commune. The study site selection aimed to reflect real-world conditions of household-scale livestock farming and biogas usage in tropical lowland regions.

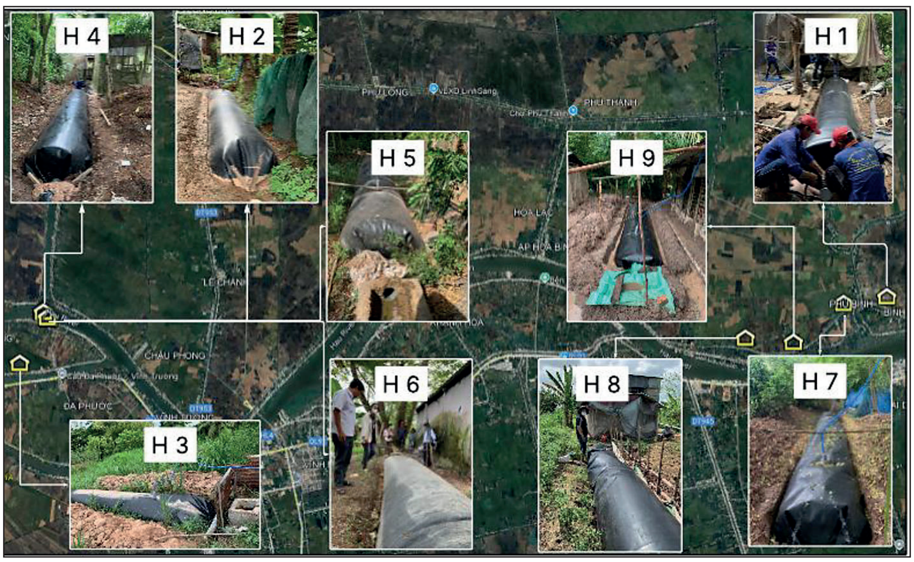

Figure 1. Installed sites of nine HDPE biogas digesters

Biogas digester installation

The household-scale biogas system consisted of two main components: (i) a high-density polyethylene digester buried in the ground, and (ii) an external polyethylene (PE) gas storage bag (Figure 2). Each system employed a bag-type HDPE digester constructed from 0.75 mm-thick material. To ensure thermal insulation and maintain structural integrity, the digesters were partially embedded in the soil. The overall digester design was adapted from previously established and field-validated models for household-scale use in the Mekong Delta (Le et al., 2021).

The HDPE digester measured 7.6 m in length and 1.8 m in diameter, with an operational liquid height of 0.75 m, resulting in a total working volume of approximately 6.3 m³. The digester was connected to a separate PE gas storage bag with a volume of 2.57 m³ (length: 6m and diameter: 1.2m). This storage unit consisted of an inner PE layer and an outer HDPE layer, designed for durability and gas retention. Biogas was conveyed from the digester to the storage unit through a 21 mm-diameter polyvinyl chloride (PVC) pipeline. A water trap was installed along the pipeline to remove moisture from the gas stream and prevent condensation-related blockages. Biogas production was continuously monitored using a G1.6 gas flow meter (Daemyoung I&T, South Korea).

Experimental design

An on-farm field trial was conducted in which each participating household served as an individual experimental unit. A total of nine households were selected based on consistent biogas system functionality and absence of technical issues. These households were categorized into three groups according to cattle herd size: Group 1 (two cattle: H1–H3), Group 2 (three cattle: H4–H6), and Group 3 (four cattle: H7–H9). This grouping aimed to assess the impact of varying OLRs on the performance of household-scale biogas digesters. Cattle herd size directly influenced the amount of fresh manure generated daily. Households in Group I produced approximately 24.1–24.8 kg day^{-1} of fresh manure, Group II generated 38.7–39.8 kg/day, and Group III yielded the highest amounts, ranging from 47.9 to 48.6 kg day^{-1}. Based on the VS content of the manure, estimated OLRs ranged from 4.2 kg VS day^{-1} to 8.7 kg VS day^{-1}, representing a realistic range for evaluating digester performance under practical field conditions. Detailed characteristics of the selected households and digester installation sites are provided in Table 1.

Sample collection and monitoring

Samples were collected weekly from each of the nine selected households over 13 weeks (n = 13), from February to May 2024. All samples were promptly transported to the laboratory at Can Tho University for analysis. Fresh CM samples were weighed at the time of collection. Parameters, including total solids (TS), volatile solids (VS), total organic carbon (TOC), total nitrogen (TN), and moisture content, were analyzed immediately upon arrival at the laboratory. Physicochemical analysis of cattle manure from the nine households showed TS contents ranging from 19.3% to 23.2%, and VS accounting for 74.1% to 80.4% of TS. TOC levels ranged from 43.3% to 46.8%.

In comparison, TN ranged from 1.8% to 2.2%, resulting in C/N ratios between 21.3 and

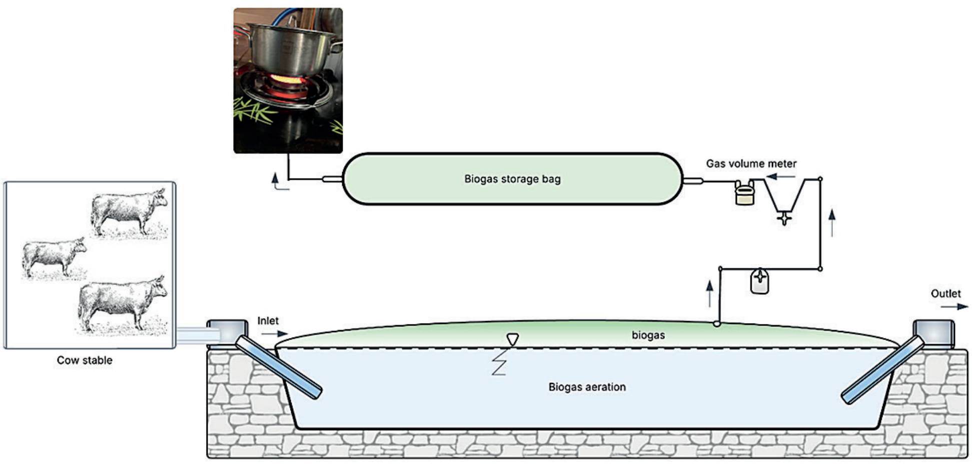

Figure 2. The biogas system for treating cattle waste was installed at livestock households

Table 1. Characteristics of cattle manure and OLR supplied to household-scale biogas digesters

Households	No. of cattle	Age of cattle (months)	FW (kg day^{-1})	Moisture (%)	DW (kg day^{-1})	OLR (kg-VS_{added} day^{-1})
H1	2	14–16	24.8±0.5	76.8±2.1	5.8±0.6	4.7±0.5
H2	2	18–20	24.1±0.5	77.7±1.7	5.4±0.4	4.2±0.4
H3	2	18–20	24.6±0.7	78.1±2.2	5.5±0.6	4.2±0.5
H4	3	18–20	38.7±1.3	80.6±1.3	7.4±0.5	6.0±0.5
H5	3	24–26	38.8±1.7	79.3±1.6	8.1±0.7	5.9±0.7
H6	3	20–26	39.8±1.3	80.7±1.1	7.6±0.4	5.8±0.5
H7	4	16–18	47.9±1.2	79.9±2.0	9.6±1.0	7.5±0.9
H8	4	16–18	48.2±0.9	78.1±1.9	10.6±1.0	8.2±0.6
H9	4	18–20	48.6±1.3	77.3±1.6	10.9±0.7	8.7±0.8

Note: FW, fresh weight; DW, dry weight; OLR, organic loading rates; Data are presented as mean ± standard deviation (n=13).

29.0, values considered optimal for anaerobic digestion. Manure moisture content ranged from 76.8% to 80.7%, consistent with fresh CM. The physicochemical properties are summarized in Table 2. In addition, BE samples were collected from each digester to assess operational parameters such as pH, volatile fatty acids (VFAs) concentrations, TOC, and TN.

Analytical techniques

Cattle manure samples: TS and VS were determined following standard methods. TS was measured by drying samples to a constant weight at 105 °C, while VS was analyzed by igniting the dried samples in a muffle furnace at 550 °C for 2 hours. TOC was quantified using the High-Temperature Combustion Method. TN was analyzed using the semi-Micro-Kjeldahl Method.

Biogas effluent samples: pH and VFAs were measured either on-site using portable equipment or immediately upon sample arrival at the laboratory to ensure data integrity. pH was measured using a portable meter (TOA-DKK Corporation, IM32P, Tokyo, Japan) equipped with compatible electrodes. For VFA analysis, the digestate samples were first centrifuged at 5000 rpm for 30 minutes, and the supernatant was filtered through a 0.20 µm Sartorius PTFE membrane filter (Goettingen, Germany). VFAs were then analyzed by high-performance liquid chromatography (HPLC) using both a refractive index (RI) detector and a UV detector.

Biogas composition: Methane concentration (v/v) in the collected biogas was measured using a Shimadzu GC-2014AT gas chromatograph (Shimadzu, Japan) equipped with a thermal conductivity detector (TCD) and a 60/80 Carboxen-1000 column.

Data processing

Statistical analyses were performed to evaluate differences among treatments in terms of daily biogas production, OLR, and biogas yield. One-way analysis of variance (ANOVA) was applied at a significance level of $p = 0.05$ ($n = 13$), following confirmation of data normality using the Shapiro–Wilk test ($p > 0.05$). Where significant differences were detected, Tukey's honest significant difference (HSD) test was employed for all pairwise multiple comparisons. All statistical analyses were conducted using IBM SPSS Statistics version 26 (IBM Corp., Armonk, NY, USA), with results considered statistically significant at $p < 0.05$.

RESULTS AND DISCUSSION

Organic loading rate

Based on the average VS loading rates, households were categorized into three groups, reflecting differences in herd size and manure management practices (Figure 3). Group 1 had the lowest OLRs, ranging from 0.67 to 0.75 kg-VS_{added} day^{-1} m^{-3} (equivalent to 4.21 to 4.71 kg-VS_{added} day^{-1}), indicating smaller herd sizes and possibly more conservative feeding or waste input strategies. Group 2 exhibited intermediate loading rates, between 0.92 and 0.97 kg-VS_{added} day^{-1} m^{-3} (equivalent to 5.78 to 5.99 kg-VS_{added} day^{-1}). Meanwhile, Group 3 showed the highest OLRs, ranging from 1.19 to 1.38 kg-VS_{added} day^{-1} m^{-3} (equivalent to 7.52 to 8.66 kg-VS_{added} day^{-1}), corresponding to

Table 2. Physicochemical characteristics of cattle manure substrates

Groups	Households	TS (%)	VS (%TS)	TOC (%)	TN (%)	C/N
Group I	H1	23.2±2.1	80.4±1.3	46.8±0.7	2.0±0.1	24.9±2.8
	H2	22.3±1.7	77.2±2.1	45.0±1.2	2.2±0.1	21.3±2.1
	H3	21.9±2.2	76.5±3.3	44.7±2.0	2.0±0.1	24.2±2.6
Group II	H4	19.4±1.3	79.8±2.8	46.7±1.7	2.0±0.1	25.3±2.4
	H5	20.7±1.6	74.1±5.2	43.3±3.1	2.1±0.1	22.5±2.3
	H6	19.3±1.1	75.4±3.8	44.0±2.3	2.0±0.1	22.9±1.4
Group III	H7	20.1±2.0	78.0±3.2	45.7±1.9	1.8±0.1	29.0±2.4
	H8	21.9±1.9	78.3±2.7	45.1±1.8	2.0±0.2	25.3±2.7
	H9	22.7±1.6	78.2±2.8	45.5±1.6	2.2±0.1	22.2±1.9

Note: TS, total solids; VS, volatile solids; TOC, total organic carbon; TN, total nitrogen.
Data are presented as mean ± standard deviation (n=13).

larger herd sizes and greater manure input volumes. This trend is consistent with previous findings that the amount of organic loading in anaerobic digesters is directly influenced by livestock scale and feeding systems (Møller et al., 2004; Cuéllar and Webber, 2008).

These findings reinforce the principle that biogas yield does not increase linearly with organic input (Figure 5). Instead, there exists an optimal OLR window that maximizes microbial efficiency without causing process stress. In the current study, this optimal range was around 0.9–1.1 kg-VS_{added} day^{-1} m^{-3}. This range aligns with earlier research, which identified 0.8–1.2 kg-VS_{added} day^{-1} m^{-3} as a stable operational window for small-scale digesters in tropical climates (Mata-Alvarez et al., 2000; Holm-Nielsen et al., 2009). At the lower end of the scale, Samadamaeng et al. (2024) reported that OLRs of 0.16–0.43 kg-VS_{added} day^{-1} m^{-3} in household-scale biogas systems are sustainable for biogas production at the Nern Ngam Cattle Community Enterprises in Yala Province, Thailand. Their study also demonstrated that applying solar thermal pretreatment at 40–60 °C for 20 hours markedly increased methane yield, suggesting that pretreatment strategies may help enhance biogas production when operating under sub-optimal loading conditions. Research by Ward et al. (2008) indicated that higher VS loading rates typically indicate more available organic substrate, which, if properly managed, can enhance biogas production. However, excessively high loading may exceed microbial degradation capacity, leading to process instability or acid accumulation (Angelidaki et al., 2003). The study of Marañón et al. (2012) found that increasing the OLR to 1.5 gVS per day resulted in a decrease in methane production of 20–28%. Therefore, understanding this relationship is essential for optimizing digester performance and avoiding operational issues. These results underscore the importance of tailoring loading rates to herd size and manure characteristics in smallholder farm settings. They also provide a basis for planning biogas systems that are technically appropriate and environmentally sustainable in rural agricultural contexts.

Total volume of daily biogas production per biogas digester

Figure 4 illustrates the average daily biogas production across the three household groups. Group 1, which included households raising two cattle each, exhibited the lowest VS loading rates and correspondingly produced the smallest volumes of biogas, ranging from 943 to 1,139 L/day. In contrast, Group 2, composed of households with three cattle, had intermediate VS loading rates but achieved the highest biogas production, ranging from 1.563 to 1.884 L/day. Interestingly, although Group 3 maintained the highest VS loading rates due to larger herd sizes (four cattle), their biogas production was lower than that of Group 2, ranging between 1.357 and 1.651 L/day. This trend suggests that the digesters in Group 3 may have experienced organic overloading, which can exceed the microbial community's capacity to degrade the input material efficiently. Such overloading could lead to the accumulation of intermediate compounds, potential acidification, or inhibition of methanogenic activity, ultimately reducing overall biogas yield despite the higher input load.

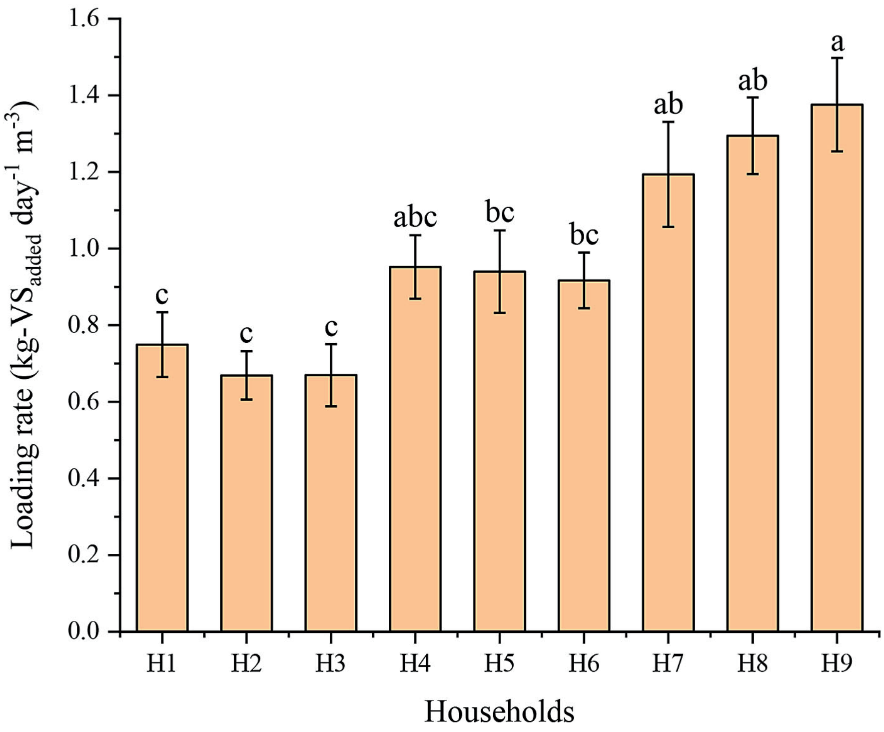

Figure 3. Organic loading rate at different sampling times. Vertical bars represent the standard deviation (SD) of the mean. Different letters above the column indicate statistically significant differences ($p < 0.05$) within the same measurement time

This inverse trend in Group 3 suggests that overloading the digester may lead to suboptimal gas production, likely due to microbial inhibition caused by the accumulation of volatile fatty acids (VFAs), ammonium (NH_4^+), or pH imbalance (Angelidaki et al., 2003; Rajagopal et al., 2013). Several studies have shown that there is an optimal loading threshold for each digester design, beyond which process efficiency drops (Ward et al., 2008; Appels et al., 2008). In this study, the optimal performance appears to occur at a moderate VS loading rate of around 0.9–1.0 kg VS m^{-3} day^{-1}, corresponding to households with three cattle. These findings are consistent with previous research that identified 0.8–1.2 kg VS m^{-3} day^{-1} as a stable operating range for small-scale plug-flow digesters under tropical conditions (Mata-Alvarez et al., 2000; Holm-Nielsen et al., 2009).

Moreover, excess OLRs can lead to HRT reduction, sludge washout, and methanogenic inhibition, particularly in small-capacity digesters such as the 8.36 m^3 polyethylene bag-type units used in this study (Roubík and Mazancová., 2019; Lansing et al., 2008). Therefore, the results underscore the importance of matching herd size, manure management, and digester design to maintain process stability and optimize gas yields. Simply increasing organic input from larger herds does not guarantee higher biogas production. It may instead result in digester overload and performance deterioration, especially in decentralized, rural-scale systems.

Biogas yield

The biogas yield in nice biogas digesters was presented in Figure 5. The results recorded the highest biogas yields in households H4 and H5, both exceeding 310.3–318.3 L $kgVS^{-1}$ (equivalent to 177.8–187.4 L CH_4 $kgVS^{-1}$). They were significantly greater ($p < 0.05$) than those observed in most other households. These two households, categorized in Group 2, demonstrated the most efficient biogas production, likely due to optimal feeding rates and effective digester management. In contrast, households H7 to H9 (Group 3), despite having a larger number of cattle and higher daily input of fresh manure, exhibited lower yields ranging from approximately 156.6 to 219.6 L $kgVS^{-1}$ (equivalent to 89.7–122.2 L CH_4 $kgVS^{-1}$). Interestingly, Group 1, characterized by fewer cattle and lower organic loading rates, achieved moderate yields between 220 and 270 L $kgVS^{-1}$ (equivalent to 114.6–159.5 L CH_4 $kgVS^{-1}$). In general,

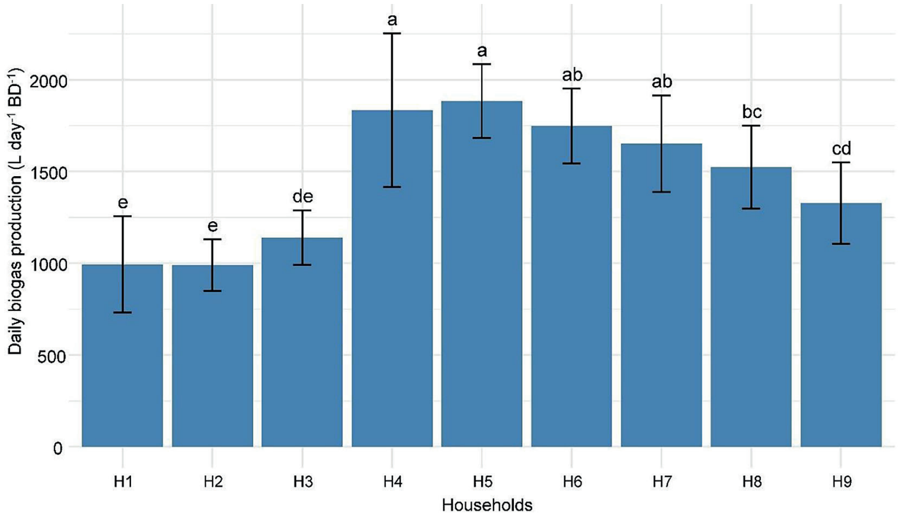

Figure 4. Daily biogas production volume per household. Data are expressed as mean ± SD (n=13)

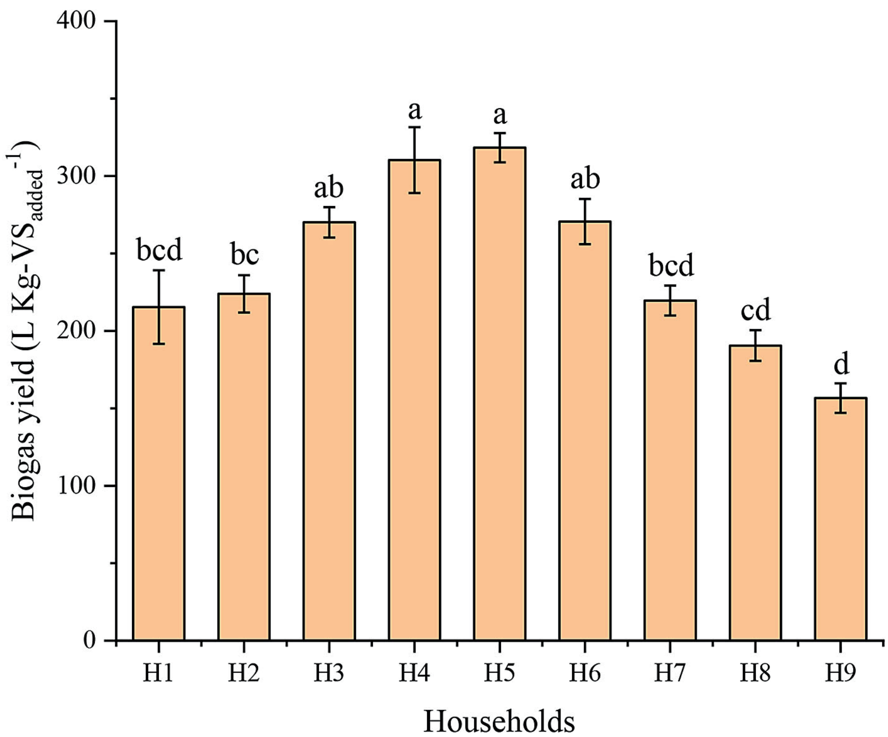

Figure 5. Biogas yield of household-scale anaerobic digesters using cattle manure across nine surveyed households (H1–H9). Bars represent mean values ± standard deviation (SD). Different lowercase letters above the bars indicate statistically significant differences among households ($p < 0.05$)

the methane yield results from this study are consistent with previous studies that used cattle manure in biogas production, ranging from 125.9–182.9 L CH_4 $kgVS^{-1}$ (Alkhrissat, 2024; Fan et al., 2024). These results imply better digestion stability and process balance under lower input conditions. Therefore, maintaining an optimal loading range and appropriate HRT is consequently essential for maximizing biogas production per unit of organic matter (Appels et al., 2008; Mata-Alvarez et al., 2000). The study reinforces the importance of designing and operating digesters according to actual manure availability and system capacity to avoid both underperformance and overload-induced inhibition.

Biogas composition

The methane (CH_4) concentration in biogas varied considerably across households and sampling periods, reflecting the influence of organic loading rates and digester operational conditions on gas quality. In Group 1, CH_4 concentrations were generally lower and more variable. Notably, Household H1 frequently recorded CH_4 levels below 50% (v/v), indicating potential process instability and suboptimal digestion. In contrast, Group 2 exhibited more stable and relatively high CH_4 concentrations, typically ranging from 55% to 65% (v/v). The H5 site consistently maintained methane levels within this range, suggesting a well-balanced organic loading rate and favorable microbial activity. Group 3, despite the highest feedstock input, showed pronounced fluctuations in CH_4 content. For instance, the H8 site experienced a sharp drop to nearly 40% (v/v) in early monitoring stages – likely due to digester overloading or acid accumulation – before gradually recovering in subsequent samples. These results align with previous findings, which report that methane concentrations between 55% and 70% (v/v) typically reflect stable anaerobic digestion (Appels et al., 2011; Angelidaki et al., 2003; Marañón et al., 2012). Overall, Group 2 demonstrated both the highest and most consistent CH_4 concentrations, supporting earlier observations that a moderate VS loading rate (~0.9–1.1 kg-VS_{added} m^{-3} day^{-1}) is optimal for maximizing both the quantity and quality of biogas. These findings underscore the importance of balanced feedstock management and digester stability in achieving high methane yields and consistent biogas composition (Figure 6).

pH and VFAs

The digestate pH values exhibited a slight increase with higher cattle herd sizes and OLRs, ranging from approximately 6.86 to 7.09 across all surveyed households. Group 1 recorded pH values (6.86–7.09), while Group 2 ranged between 6.91 and 6.98. Group 3, with the highest OLRs (up to 1.4), exhibited slightly elevated pH values of 6.98–7.09. However, these differences were not statistically

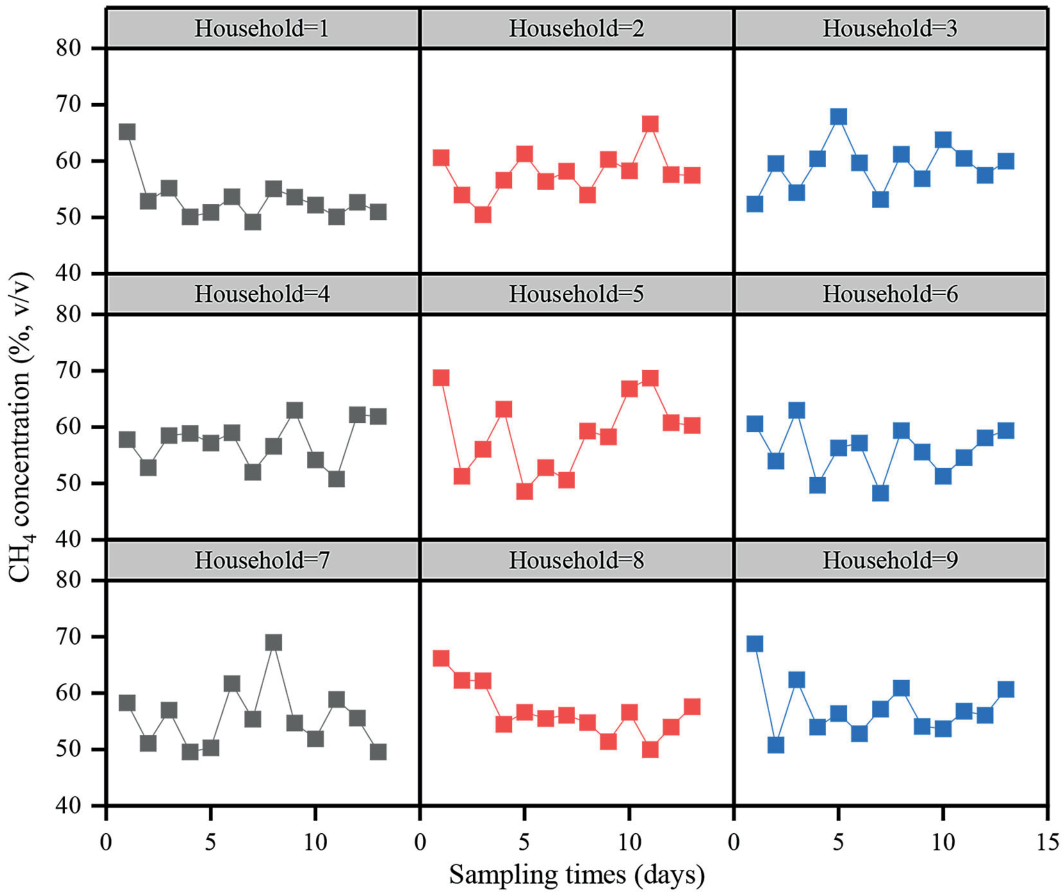

Figure 6. Methane concentration (%, v/v) in biogas produced from each household-scale digester

significant ($p > 0.05$) (Table3). The optimal pH range for methanogenic bacterial activity in BDs is 6.8–7.4 (Angelidaki et al., 2003; Appels et al., 2008). In this study, the pH values observed in the digester fell within this range, consistent with their findings. The counterintuitive performance differences among digesters in this study reflect classic signs of overloading, such as methanogenic inhibition caused by VFA accumulation, ammonia toxicity, or pH imbalance (Rajagopal et al., 2013).

Table 3 shows that VFA concentrations remained consistently low across all households, ranging from approximately 130 to 140 mg/L, with no significant differences among groups ($p > 0.05$). These uniformly low VFA levels indicate a well-balanced transition between acidogenesis and methanogenesis, with no signs of organic overloading or acid accumulation during the study period. In general, the stable pH and low VFA levels confirm that the anaerobic digestion systems were operating under favorable biochemical conditions. Notably, Group 2 – representing moderate OLRs – demonstrated optimal outcomes in terms of VFA control, methane concentration, and biogas yield, highlighting the importance of matching loading rates with the microbial and buffering capacities of small-scale digesters. These findings underscore the operational resilience and appropriateness of household-scale biogas systems for manure management in rural contexts, even under limited technical monitoring.

Nutrients in digestate and strategies for a circular economy

In this study, the best-performing digesters (Group 2) not only achieved higher biogas yields but also maintained stable pH and VFA concentrations, indicating efficient digestion. Nutrient analysis revealed that TOC in the effluent varied significantly among households, ranging from 63.2 mg L^{-1} in H9 to 427.7 mg L^{-1} in H7 (Table 3). Higher TOC values were generally associated with digesters operating at balanced OLRs, suggesting effective organic matter conversion while retaining dissolved carbon compounds beneficial for soil amendment. The average of TN concentrations ranged from 78.4 mgN L^{-1} in H9 to 134 mgN L^{-1} in H3, with no statistically significant differences among most households (Table 3). The combination of adequate TOC and TN highlights the potential of the effluent as a nutrient-rich fertilizer for direct field application without additional treatment. The effluent from these systems was successfully used to irrigate and fertilize cow grass, offering a dual advantage – effective waste treatment and on-farm nutrient cycling. When OLRs were aligned with system capacity, methane content remained high, and effluent quality met agronomic requirements for crop fertilization. These results highlight the potential of small-scale anaerobic digesters as multi-functional tools for sustainable livestock waste management, renewable energy production, and nutrient recycling in tropical smallholder systems.

The digestate itself is a nutrient-rich fertilizer containing nitrogen (N), phosphorus (P),

Table 3. pH, VFAs, TOC, and TN in all biogas digesters at each household

Households	pH	Volatile fatty acids	Total organic carbon	Total nitrogen
	-	mM L^{-1}	mg L^{-1}	mgN L^{-1}
H1	6.89±0.10^{bc}	134.6±5.90^{a}	149.3±37.0^{cd}	96.6±48.6^{a}
H2	6.86±0.23^{c}	135.2±7.07^{a}	366.6±102.9^{ab}	133.5±43.2^{a}
H3	6.91±0.14^{bc}	134.0±5.58^{a}	391.3±68.4^{a}	134.0±47.3^{a}
H4	6.96±0.15^{abc}	134.0±5.22^{a}	377.1±50.0^{a}	130.1±66.4^{a}
H5	6.98±0.14^{abc}	136.0±6.36^{a}	117.8±26.5^{d}	131.7±47.0^{a}
H6	6.98±0.14^{abc}	135.2±6.44^{a}	365.6±135.9^{ab}	116.3±48.3^{a}
H7	7.07±0.12^{ab}	135.8±6.93^{a}	427.7±153.2^{a}	127.8±51.1^{a}
H8	7.09±0.14^{a}	132.3±3.79^{a}	257.6±117.7^{bc}	111.9±51.1^{a}
H9	7.06±0.09^{ab}	134.2±6.69^{a}	63.2±20.3^{d}	78.4±34.7^{a}

Note: Data presented as mean ± SD (n=13). Values followed by different letters within the same column are significantly different at the 5% level ($p < 0.05$).

potassium (K), and trace elements in plant-available forms. Applied to fodder crops such as Napier grass (*Pennisetum purpureum*) or other cow grasses, biogas effluent can boost growth, biomass yield, and nutritional quality. The organic matter content also enhances soil structure and water retention. Previous studies have documented increased crude protein content and dry matter yields in grasses fertilized with biogas slurry compared to untreated controls or even synthetic fertilizers (Kebede et al., 2023; Möller and Müller, 2012). In rice cultivation, cattle biogas effluent is also demonstrated as a promising organic fertilizer in rice farming in the VMD (Minamikawa et al., 2020; 2021; Huynh et al., 2022). This promotes sustainable nutrient recycling and supports livestock productivity, aligning with the principles of circular agriculture. Finally, biogas offers a renewable household energy source for cooking and heating, reducing reliance on firewood, mitigating deforestation, and lowering indoor air pollution – ultimately improving rural living standards (Bond and Templeton, 2011).

CONCLUSIONS

This study evaluated the potential for biogas and methane production from CM using household-scale HDPE biogas digesters in the VMD. It focused on the relationship between cattle herd size, digester volume, and system performance. The results show that matching herd size with the appropriate digester capacity and maintaining an OLR within the optimal range (approximately one kgVS m^{-3}, which corresponds to 5.78–6.0 kgVS day^{-1} for a 6.3 m^3 volume) are crucial for ensuring process stability, maximizing methane yields, and preventing overload in rural digesters with fixed volumes. In addition to generating renewable energy, the nutrient-rich effluent produced has significant potential for direct application to fodder crops. This supports on-farm nutrient cycling and helps reduce reliance on synthetic fertilizers. These findings offer practical guidance for the design and operation of small-scale anaerobic digesters as part of integrated waste-to-energy strategies. Such approaches contribute to circular economy models, environmental protection, and climate-resilient livelihoods in tropical communities that depend on livestock.

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