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Wastewater treatment and biogas production from fish cracker (Krepoh) production process using anaerobic digestion system

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ABSTRACT

The point of this study was to find out how well anaerobic digestion (AD) can clean up wastewater from making fish crackers (Krepoh). Specifically, they wanted to find the best hydraulic retention time (HRT), rate system performance, and make sure it could be used on a large scale in communities. First, batch experiments were done with HRTs of 7, 14, 21, and 30 days to find the best time for biogas production. Next, a 19-liter continuous AD system was used to compare single-phase and single-phase with medium setups for treatment efficiency and biogas stability. Finally, a 500-liter system with a 400 L working volume was tested to make sure it could be used in real life. Results indicated that the 14-day HRT produced the highest biogas yield (3.248 mL), outperforming shorter and longer HRTs. The continuous system achieved COD reduction of 65.18%, TSS reduction of 70.42%, and stable biogas production of 5.32 ± 0.52 L/day. The larger system was still about as efficient as the smaller one. It cut COD by 57.87%, TSS by 70.42%, and EC by 28.11%, and it made high-quality biogas (400–500 L/day) with 59.49% methane that could be used for cooking in homes. System stability was demonstrated through pH normalization from acidic to neutral levels. These findings validate AD as an effective, scalable solution for wastewater treatment, offering renewable energy generation, waste reduction, and environmental benefits at the community level.

Keywords: biogas, fish cracker, anaerobic digestion (AD).

INTRODUCTION

Fresh fish crackers, locally known as "Krepoh," are a popular and culturally significant snack in Thailand's southern border provinces of Pattani, Yala, and Narathiwat. These crispy, savory treats are widely consumed as appetizers and hold a special place in local culinary tradition. The production process involves grinding fish meat, mixing it with tapioca flour, sago starch, and salt, and then shaping the dough into cylindrical logs for boiling and air-drying. While Krepoh production is an important economic activity, it poses significant environmental challenges due to untreated wastewater discharge. A study by Hamdani et al. (2024) revealed that households produce 30–40 liters of wastewater for every 100 kg of daily Krepoh production, with each village generating 3.000–4.000 liters of wastewater per day. This effluent contains high levels of organic pollutants, far exceeding Thailand's environmental standards. Critical parameters such as pH (4.27 ± 0.27), total suspended solids (7.250 ± 206.40 mg/L), chemical oxygen demand (14.480 ± 585.06 mg/L), total nitrogen (4.73 ± 0.40 % w/w), and total phosphorus (2.14 ± 0.22 % w/w) significantly surpass permissible limits (Suwanpakdee et al., 2024). The untreated discharge leads to severe water pollution, characterized by blackened water, foul odors, and reduced surface water quality, adversely affecting aquatic ecosystems and local livelihoods dependent on clean water for fishing and agriculture (Pal et al., 2023; Nahar et al., 2024). The environmental impact is exacerbated by budget constraints, insufficient human resources, and ineffective ecological management guidelines. Studies have shown that the wastewater contains high levels of proteins, carbohydrates, and fats, which contribute to long-term ecological and economic consequences when left untreated. as shown in Figure 1. To address these challenges, AD technology has emerged as a promising solution. A small-scale AD system, designed for rural households, utilizes a 500-liter tank to treat the organic-rich wastewater. This system creates controlled anaerobic conditions that activate microorganisms to break down organic matter, converting it into biogas containing 50–70% methane (CH_4), a renewable energy source for cooking. The process significantly reduces pollutant levels while adjusting the pH to an acceptable range of 5.5–9.0 before discharge. Additionally, the nutrient-rich byproduct serves as an organic fertilizer, supporting sustainable agriculture and reducing dependence on chemical fertilizers. Constructed from locally available materials, the system is cost-effective, easy to install, and maintainable, making it ideal for rural households in Thailand's southern border provinces (Arifan et al., 2021; Pal et al., 2023). This study aims to optimize methane production through improved reactor design, addressing the dual challenges of wastewater management and renewable energy generation. Laboratory-scale experiments have demonstrated the feasibility of the system, with a 500-liter digester effectively treating the daily wastewater volume generated by Krepoh production. The research investigates factors affecting biogas quality and explores real-world applications, aiming to provide a practical and scalable solution for small-scale producers. By integrating AD technology, the system aligns with circular economy principles, promoting sustainability in rural areas. It offers multiple benefits, including reducing environmental pollution, providing clean energy, and promoting sustainable agricultural practices. The adoption of AD technology presents a sustainable pathway to manage wastewater, produce renewable energy, and support local agriculture, contributing to the broader goal of promoting sustainable practices in rural communities. This approach not only mitigates environmental pollution but also aligns with the principles of the circular economy, providing a model for sustainable development in similar contexts across Thailand's southern border provinces and beyond.

MATERIALS AND METHODS

Batch experiment

This experiment evaluated the wastewater treatment process from fish cracker (*Krepoh*) production and the associated biogas generation using a batch fermentation system. The system utilized 630 mL saline bottles with four experimental setups, each performed in triplicate. The four setups explored hydraulic retention times (HRTs) of 7, 14, 21, and 30 days selected based on evidence from previous studies and practical considerations. The selection of HRTs ranging from 7 to 30 days was based on prior research and preliminary experiments. This range aimed to balance the trade-off between biogas yield and operational expenses, with shorter HRTs potentially reducing yields due to incomplete degradation and longer

Figure 1. The area surrounding the factories discharging wastewater from the production process of fish crackers (Krepoh)

HRTs increasing costs despite higher yields. The study sought to identify the optimal HRT for efficient biogas production in small-scale systems, maximizing yield while minimizing expenses.

The rationale for selecting HRT

HRT values of 7, 14, 21, and 30 days were chosen to explore a range of conditions based on their documented impact on biogas production efficiency. Haryanto et al. (2018) and Suresh et al. (2018) reviewed the influence of retention times. They reported that shorter HRTs generally resulted in reduced biogas yields due to incomplete substrate degradation. By contrast, longer HRTs enhanced biogas yield but increased operational costs. The chosen range balanced the trade-offs between yield and efficiency, optimizing biogas production for small-scale systems. Preliminary experiments conducted on wastewater from similar food production processes suggested that this range would likely encompass the optimal HRT for efficient substrate conversion and biogas generation. The wastewater used in the experiments was sourced from a fish cracker production facility. Key characteristics of the wastewater were as follows:

- pH: 6.8–7.2, indicating a neutral to slightly acidic environment conducive to anaerobic digestion (APHA, 2017).
- chemical composition: high concentrations of organic compounds including fats, oils, and proteins typical of fish processing effluents.
- organic load: the chemical oxygen demand (COD) was measured at 15.000–20.000 mg/L, reflecting a high potential for biogas production (Chowdhury et al., 2010).

These properties were determined using standard wastewater analysis methods, ensuring the input was suitable for anaerobic digestion (AD). The wastewater was introduced into the fermentation system at calculated flow rates based on the desired HRT. The system also incorporated cow manure as an inoculum, added at a ratio of one-fourth of the 150 mL container's volume (Putri et al., 2012). The feed rate was calculated using the hydraulic retention time formula: the formula for calculating HRT can be represented as:

$$HRT = V/Q \tag{1}$$

where: V – 7 days = 450 mL / Q (mL per day), Q – 64.3 mL/day. HRT – hydraulic retention time (in days, hours, or other time units); V – volume of the reactor or treatment tank (in liters, mL, m^3, or other volume units); Q – flow rate of the influent entering the system (in liters/day, mL/day, m^3/day, or other volume/time units).

The flow rates for each HRT were calculated as follows: HRT 14 days: 32.1 mL/day, HRT 21 days: 21.4 mL/day and HRT 30 days: 15.0 mL/day.

Figure 2 The primary objective was to assess the wastewater treatment efficiency and biogas generation rate in an anaerobic fermentation system under varying conditions. Each setup consisted of one fermentation tank and one gas storage tank, facilitating controlled observation of biogas output. The average wastewater generated from the fish cracker production process was 30 ± 5 liters /day, and suitable for biogas production.

The batch experiment for biogas production from fish cracker (Krepoh) wastewater was meticulously designed to evaluate biogas production efficiency under varying hydraulic retention times (HRT). The setup utilized twelve 630 mL saline bottles as reactors, with triplicate experiments for each HRT of 7, 14, 21, and 30 days, conducted over a total period of 30 days. This approach aligns with the study by Haryanto et al. (2018)

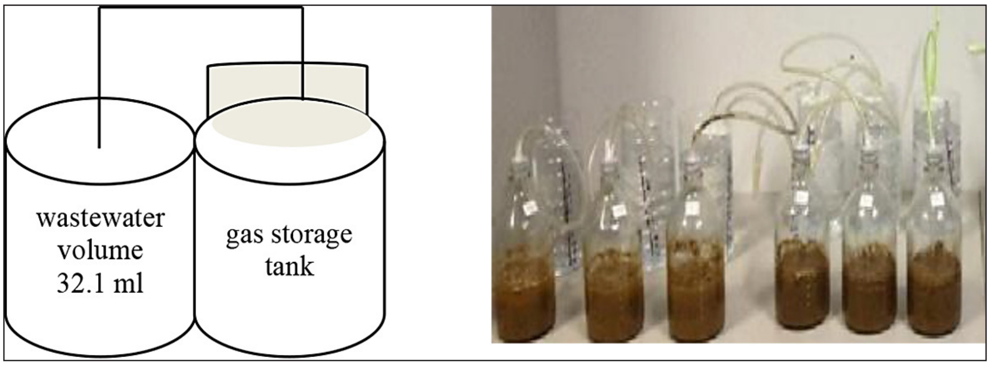

Figure 2. A batch anaerobic digestion (AD) system utilizing a 630 mL saline bottle

on the effects of HRT on biogas production from cow dung. The experimental procedure began with reactor preparation, involving cleaning and sterilizing the bottles. Each reactor was then filled with 450 mL of reaction liquid, comprising 337.5 mL of wastewater and 112.5 mL of cow manure inoculum in a 3:1 ratio. The initial pH was adjusted to 7.0 ± 0.2, and the reactors were sealed and flushed with nitrogen gas for 2 minutes to create anaerobic conditions, following the method described by Wagner et al. (2019) for strict anaerobic cultivation. Monitoring and analysis were conducted regularly, including daily biogas volume measurements, weekly biogas composition analysis, pH and alkalinity checks every 3 days, weekly COD, TSS, and VFA analyses, and microbial analysis at the beginning and end of the experiment, in accordance with standard methods (APHA, 2017). This comprehensive approach allowed for a thorough assessment of system efficiency and biogas quality, contributing to the development of sustainable wastewater management and renewable energy production strategies, as highlighted in the work of Arifan et al. (2021) on anaerobic digestion of organic waste.

Continuous experiment

The experiment utilized 19-liter fermentation tanks, selected for their scalability and practical laboratory use (Gholizadeh et al., 2024; Abdel daiem et al., 2022). Each tank was filled to 80% capacity (15.2 liters) to provide adequate headspace for biogas accumulation and facilitate efficient mixing dynamics (APHA, 2017). Two systems were tested:

1. Single-phase fermentation system (Set 1) as a single fermentation tank connected to a separate gas storage tank.
2. Single-phase system with sponge medium (Set 2) as a fermentation tank equipped with sponge material to immobilize microorganisms and improve microbial retention and biogas production efficiency (Phillip et al., 2024).

Both setups employed polypropylene hoses (38 mm diameter) for gas transfer, ensuring airtight conditions and directing the biogas through a T-way collection point into storage tanks, as shown in Figure 3.

Inoculum preparation and system startup

1. Initial inoculation: cow manure was mixed with water to create a slurry, which was added to each fermentation tank at 80% capacity.
2. Incubation period: the mixture was incubated for 14 days to establish a robust microbial community, creating an active inoculum essential for efficient anaerobic digestion.
3. Acclimation phase: following the incubation period, fish cracker wastewater was introduced at a rate of 1.1 liters per day for 14 days to acclimate the microbial community to the new substrate.

Feeding strategy

The fish cracker wastewater was introduced into the system at precisely calculated feeding rates corresponding to the predetermined hydraulic retention time (HRT). This consistent feeding regime ensured stable substrate availability for the microbial community while preventing system overloading. The feeding was conducted at the same time daily to minimize variations in system performance due to temporal fluctuations.

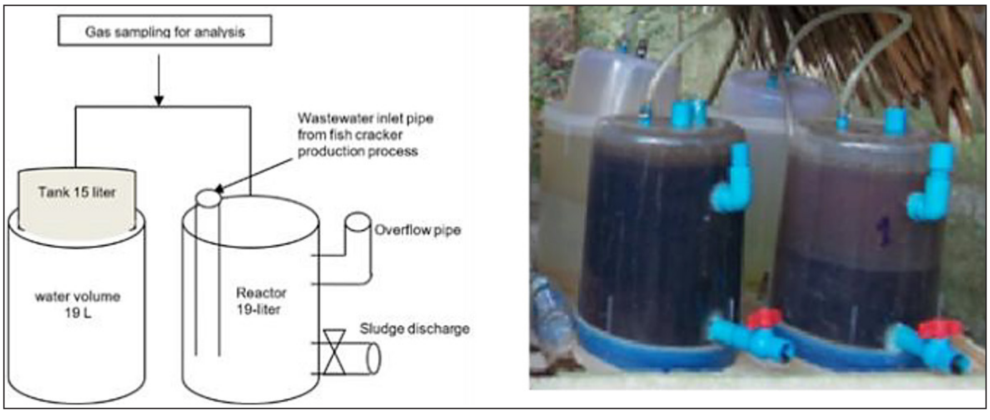

Figure 3. Continuous AD system

Biogas production monitoring

Biogas production was quantified daily using the water displacement method as described by Kougias and Angelidaki (2018). This approach allowed for accurate measurement of gas volume production over time, providing critical data on system performance and stability. The daily monitoring enabled prompt identification of any operational issues that might affect biogas yield.

Anaerobic environment maintenance

Maintaining strict anaerobic conditions was essential for optimal methanogenic activity. Multiple strategies were employed to ensure oxygen exclusion:

1. All fermentation tanks were hermetically sealed with airtight lids equipped with rubber gaskets to prevent atmospheric oxygen infiltration.
2. The entire system underwent regular leak inspections using soap solution to detect potential gas escape points, with immediate repairs conducted when necessary.
3. Following each feeding and sampling event, the headspace of the reactors was flushed with nitrogen gas for approximately 2 minutes to displace any introduced oxygen, following the protocol established by Wagner et al. (2019).

Analytical procedures

A comprehensive analytical regime was implemented to monitor system performance:

1. Liquid effluent samples were collected at 3-day intervals for analysis of pH, alkalinity, and volatile fatty acids (VFA) concentration. These parameters served as key indicators of process stability and potential inhibition.
2. Weekly gas composition analysis was performed using gas chromatography (Shimadzu GC-2014, Japan) equipped with a thermal conductivity detector to determine methane and carbon dioxide content.
3. Microbial community analysis was conducted at three critical points (initiation, mid-operation, and conclusion) to track population dynamics and functional shifts throughout the experimental period.

All analytical procedures strictly adhered to the Standard Methods for the Examination of Water and Wastewater (APHA, 2017), ensuring data reliability and comparability with existing literature.

500-liter biogas system for households

In Figure 4, a 500-liter household biogas system utilizes water displacement with three stacked concrete pipes (90–100 cm diameter, 150 cm total height). A plastic tank inverted in a water-filled concrete chamber collects biogas through AD, where rising gas displaces water to create natural storage pressure. The AD Process is shown in Figure 5.

Stage 1: Hydrolysis

During hydrolysis, hydrolytic bacteria break down complex organic molecules like carbohydrates, proteins, and lipids into simpler compounds, directly absorbing nutrients. This process, crucial for anaerobic digestion (AD), influences substrate availability and overall efficiency (Baldi et al., 2019).

Stage 2: Acidogenesis

In the acidogenesis stage, acid-forming bacteria metabolize the simpler molecules produced

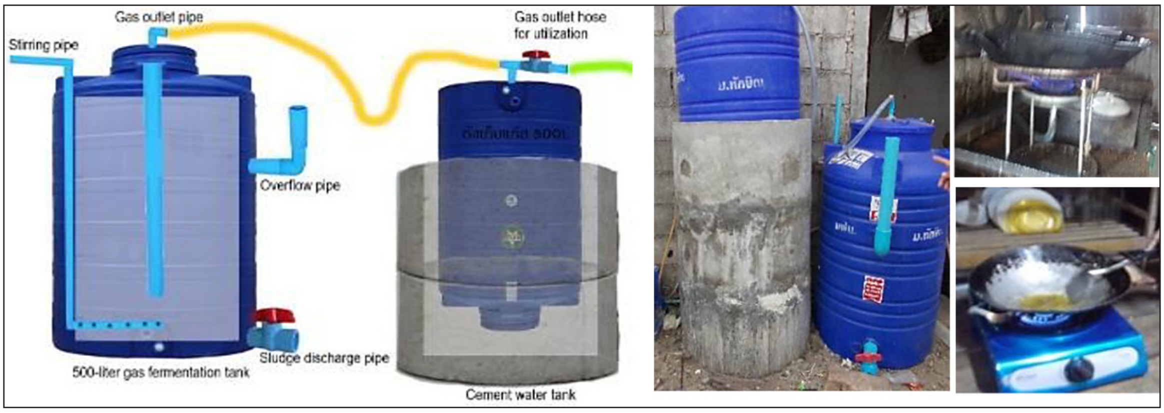

Figure 4. Continuous biogas fermentation system from fish cracker production process wastewater (500-liter)

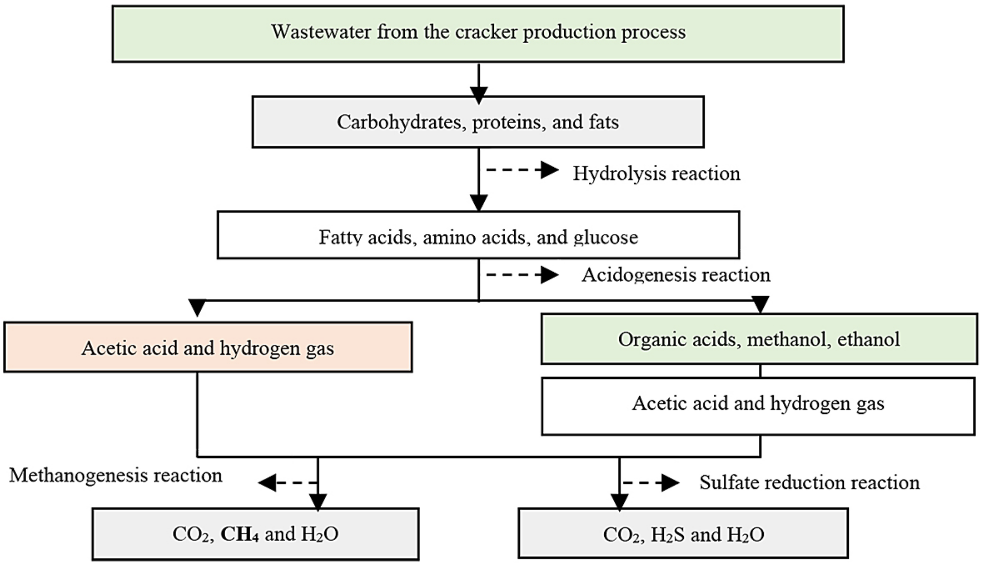

Figure 5. The decomposition reactions of organic matter occurring in an anaerobic digester

during hydrolysis. These bacteria convert the molecules into organic acids, primarily acetic acid and byproducts such as hydrogen (H_2) and carbon dioxide (CO_2). Acid-forming bacteria can thrive in both aerobic and anaerobic environments. Demirel and Scherer (2008) emphasized that acidogenesis is vital in creating the substrates necessary for methane production in the methanogenesis stage. This stage also generates volatile fatty acids (VFAs), critical intermediates in biogas production.

Stage 3: Methanogenesis

The final stage, methanogenesis, involves methanogenic bacteria converting acetic acid and hydrogen into methane (CH_4) and carbon dioxide. Methanogens require strictly anaerobic conditions to function effectively. Studies by Kougias & Angelidaki (2018) highlighted that methanogenesis is the most crucial stage in biogas production, as it determines the yield and composition of the biogas. However, specific components that are challenging to decompose include the remaining organic sludge, while inorganic substances exit the system unchanged. Biogas primarily consists of methane (CH_4) at 50–70%, which serves as the main energy source due to its excellent combustion properties, followed by carbon dioxide (CO_2) at 30–40%, which does not support combustion and is often removed to enhance gas quality. Hydrogen (H_2) is present at 5–10%, while nitrogen (N_2) at 1–2% is an inert gas that may reduce the

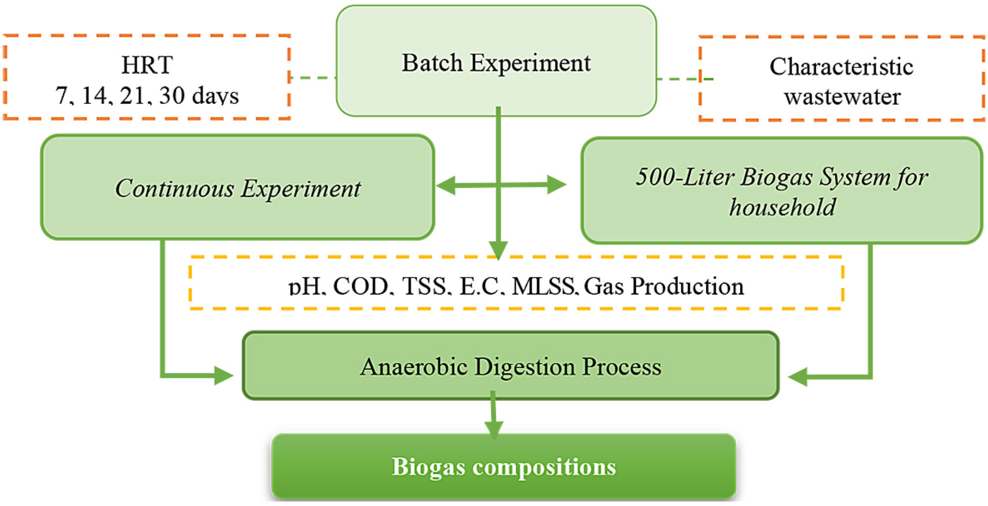

Figure 6. Diagram of the study framework

quality of biogas if found in excessive amounts. Lastly, water vapor (H_2O) at 0.3% is typically removed to improve the purity and efficiency of biogas for various applications.

Analytical procedures followed APHA (2017)

Data analysis

Water quality parameters were presented as mean ± standard deviation (SD). An independent sample t-test was done using SPSS version 22.0 to look at the differences in water quality parameters, WL weights, and levels of pollution reduction efficiency. Prior to performing the t-test, the data were checked for homogeneity of variance to ensure the reliability of the results. A one-way ANOVA and Duncan's post hoc test were used to find significant differences in the levels of pollution reduction across the ponds for comparisons between more than one group. A nonparametric test for K-independent samples was used as an alternative method if the assumption of homogeneity of variance was broken. All statistical tests were carried out at a significance level of 5% ($p < 0.05$) to ensure the accuracy and robustness of the findings.

RESULTS AND DISCUSSION

Batch experiment and continuous experiments

Wastewater generated from fish cracker production possesses distinct characteristics that may have significant environmental impacts if not adequately treated. The primary characteristics of this wastewater are outlined below (Table 1).

This study evaluated the efficiency of fish cracker (Krepoh) production wastewater treatment, and the biogas production rate using an anaerobic digestion system with cow manure as the inoculum. Table 1 shows the physical and chemical properties of the wastewater generated from the fish cracker (Krepoh) production process. The wastewater sample was acidic due to the high amount of starch-based carbohydrates and proteins used in the production process. Therefore, the pH of the wastewater was adjusted to neutral before further analysis using ash from boiling fish crackers. The chemical oxygen demand was 14.480 ± 585.06 mL/liter. Such a high COD was suitable as a feedstock for biogas production. The effect of HRT on the biogas production rate was evaluated for 14, 21, and 28 days. Figure. 7 presents the biogas production rate at different HRTs. The highest biogas production rate was observed at an HRT of 14 days with a total biogas volume of 3.248 mL, indicating an optimal balance between substrate degradation and microbial activity. This result concurred with previous research on the anaerobic digestion of food industry wastewater. A similar range of HRT was commonly used in anaerobic digestion studies to optimize biogas production. The lowest biogas production rate was found at an HRT of 7 days with a total biogas volume of 590 mL. This finding aligned with previous studies that have reported optimal biogas production at medium-range HRT. Therefore, the data from the second experimental setup was selected for further study in a continuous system, a common practice in scaling up biogas production processes.

For the continuous experiments, the two setups of biogas production systems were compared as a single-phase anaerobic digestion system and a one-phase anaerobic digestion system with a medium. These setups were inoculated with cow manure as the initial inoculum with an HRT of 14 days. Microbial sludge quantity was analyzed in single phase without the medium and in the other phase with the medium and compared with the control. Mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids

Table 1. Characteristics of wastewater from the fish cracker (Krepoh) production process

Parameter	Range	Average	Characterization method (APHA, 2017).
pH	4.00–4.54	4.27 ± 0.27	pH meter
Chemical oxygen demand, COD (mg/L)	13.900–15.070	14.480 ± 585.06	Spectrophotometer
Total suspended solids, TSS (mg/L)	7.120–7.488	7.250 ± 206.40	Filtration and drying
Electric conductivity: E.C. (ms/cm)	13.0–13.55	13.2 ± 0.30	Conductivity meter
Total nitrogen, TN (%w/w)	4.3–5.1	4.73 ± 0.40	Digestion and titration
Total phosphorus, TP (%w/w)	1.93–2.37	2.14± 0.22	UV-Vis Spectrophotometer

Note: mean ± S.D. (standard deviation).

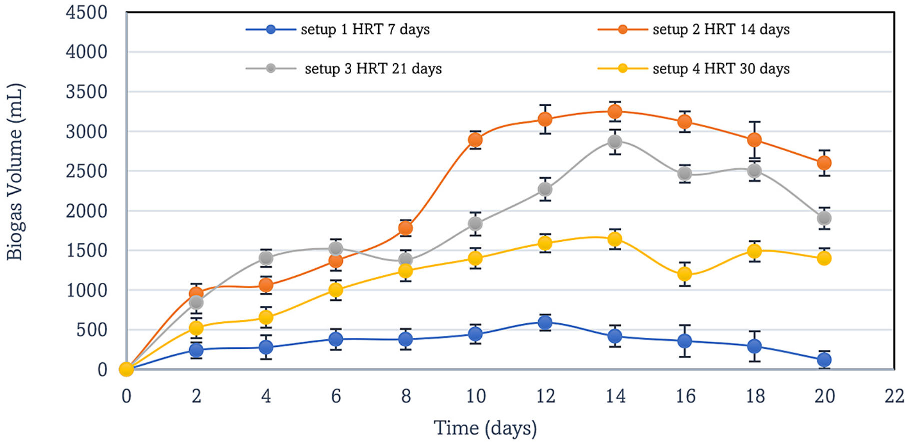

Figure 7. The operation of a batch system with four experimental setups at different HRTs (hydraulic retention times)

(MLVSS) measurements were taken to determine the microbial concentrations, as shown in Table 2.

Table 2 presents the MLSS and MLVSS values and MLVSS/MLSS ratios for the three different biogas fermentation setups as the vital indicators of biomass concentration and organic matter content in anaerobic digestion systems (Curry et al., 2012). The data showed that the single-phase setup had the highest MLSS value of 3.53 g/L, slightly higher than the control. The control setup had the highest MLVSS value of 2.9.4 g/L and the highest MLVSS/MLSS ratio of 0.84, while the single-phase with medium setup recorded the lowest values for all three parameters. A slight decreasing trend in the MLVSS/MLSS ratio was observed from the control to the single-phase with medium setup. The minimal variations in MLSS and MLVSS suggested that the experimental conditions had a limited impact on overall biomass concentration, while the slight differences in the MLVSS/MLSS ratios indicated minor shifts in the proportion of volatile organic matter, with negligible effects on treatment efficiency and biogas production. Therefore, the experimental results showed no significant variation in microbial sludge quantities across the different setups, suggesting comparable microbial growth and adaptation across all experimental conditions.

pH and COD reduction

The comparison of pH levels between the single-phase and single-phase intermediary treatment systems (Figure 8) revealed significant trends in wastewater treatment efficiency. Both systems effectively neutralized the initial acidic pH levels (4.0–4.5), aligning with the findings of Thomas et al. (2020). Proper pH control is important for optimal coagulation and treatment efficiency. The single-phase intermediary treatment consistently achieved slightly higher pH values, reaching 7.0–7.5 and demonstrating enhanced buffering capacity. Okeke et al. (2022) analyzed the performance using advanced monitoring techniques. They found that pH stabilization was critical for maintaining optimal microbial activity and treatment effectiveness. The intermediary system's superior performance in pH control correlated with improved overall treatment efficiency, particularly in organic matter removal and system stability. Suresh et al. (2018) supported this observation, finding that stable pH levels between 7.0 and 7.5 optimized biological treatment processes and enhanced COD removal efficiency. Both systems demonstrated consistent pH control over the treatment period, with the intermediary treatment showing marginally better results. These findings aligned with a recent study by Zuo

Table 2. MLVSS, MLSS and the MLVSS/MLSS ratio in various experimental biogas fermentation tanks

Experimental setup	MLSS(g/L)	MLVSS(g/L)	MLVSS/MLSS ratio
Control	3.52	2.94	0.84
Single-phase	3.53	2.88	0.82
Single-phase with medium	3.43	2.79	0.81

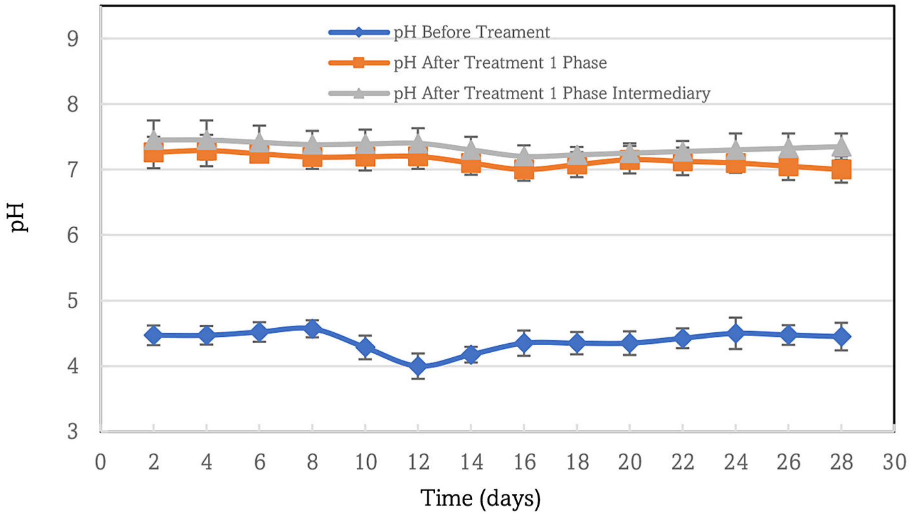

Figure 8. pH Values of wastewater from the fish cracker production process before and after treatment in each experimental set

et al. (2022) on wastewater treatment system optimization. They emphasized the importance of maintaining neutral pH levels to meet environmental discharge standards and ensure optimal biological activity.

Figure 9 presents COD levels in the single-phase and single-phase intermediary treatment systems. Significant reductions were observed over 28 days. Initial COD concentrations of 14.000–15.000 mg/L decreased to around 5.000 mg/L in both systems. The single-phase system demonstrated marginally better COD reduction efficiency: 65.18% (single-phase) and 63.30% (single-phase intermediary), particularly after day 14. The consistent COD decline in both systems indicated stable and effective treatment performance. The single-phase system showed slightly superior organic matter breakdown. The removal efficiency (RE) for COD in this study (65.18%) was lower than the 81% reported in previous studies by Baldi et al. (2019) and Tsegaye & Leta (2022). The COD reduction in both treatment systems (single-phase and single-phase intermediary) was consistent and practical but results demonstrated a slightly lower COD removal efficiency than previous studies.

TSS and EC reduction

Over the course of 28 days, with a hydraulic retention time (HRT) of 14 days, the single-phase and single-phase intermediary treatment systems effectively removed total suspended solids (TSS) (Figure 10). The average TSS concentration of the wastewater before treatment was 7.397 ± 103 mg/L. After treatment, during days 16–28, the

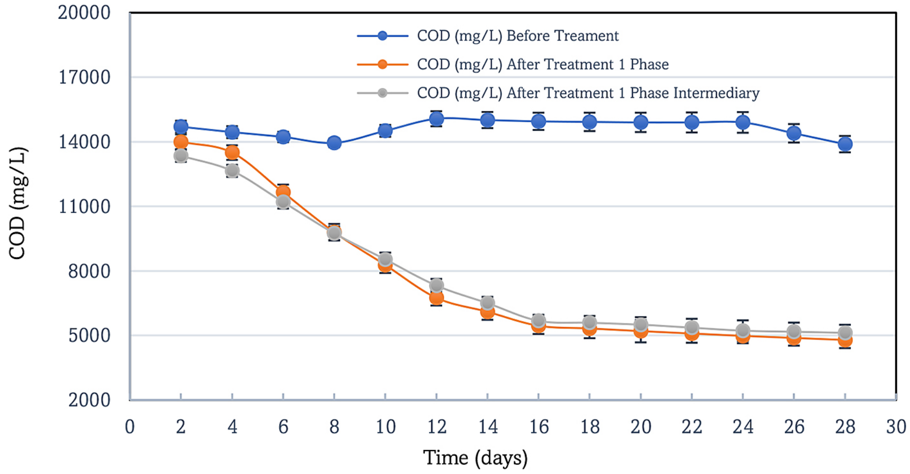

Figure 9. COD levels before and after treatment in the single-phase and single-phase intermediary systems

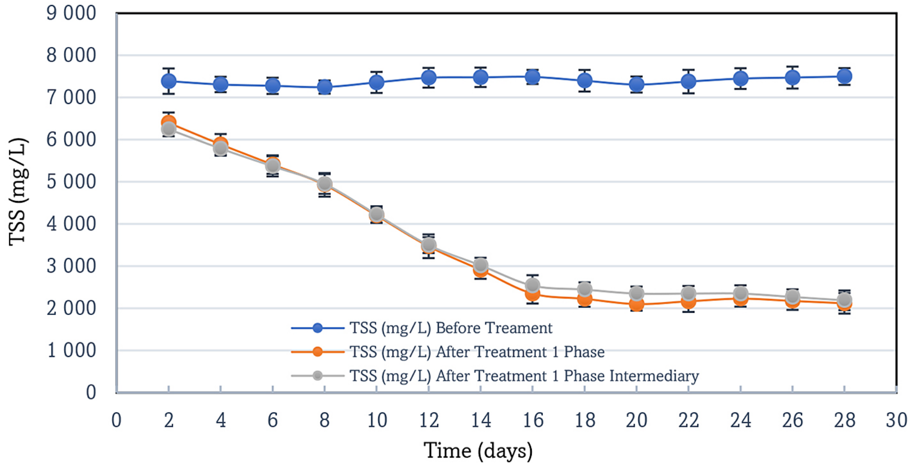

Figure 10. TSS Levels before and after treatment in the single-phase and single-phase intermediary systems

TSS levels decreased to 2.201 ± 114 mg/L in the single-phase system and to 2.358 ± 143 mg/L in the single-phase intermediary system, achieving removal efficiencies of 70.42% and 68.30%, respectively. These results concurred with research using Magnetic Granular Activated Carbon (GAC) for treating tofu wastewater, which achieved a maximum TSS removal efficiency of 56.76% under specific conditions (Hardyanti et al., 2023). The removal of TSS depends on system design, operational parameters, and advanced technologies such as electrocoagulation, which can remove up to 85% of TSS within 80 minutes (Munandar et al., 2023). Other studies also demonstrated the effectiveness of various treatment systems in TSS removal. For example, using ferric chloride as a coagulant achieved 60% TSS removal (Naghan et al., 2015), while floating treatment wetlands showed 87–95% TSS removal (Gabr et al., 2022). Natural treatment systems also exhibited high TSS removal rates (Halicki et al., 2022). Research on modified Vertical Flow Constructed Wetlands (VFCWs) reported a 69 ± 16% TSS removal efficiency under harsh operating conditions (Arévalo-Durazno et al., 2023). Overall, the results of this study demonstrated that both treatment systems effectively reduced TSS concentrations from approximately 7,500 mg/L at the start to around 2,300 mg/L by the end of the experiment. The single-phase intermediary system gave a better performance in the initial phase. These results showed how efficiently the systems removed TSS and their potential for use in future wastewater treatment processes.

Figure 11 displays the changes in electrical conductivity (EC) levels over 28 days in the

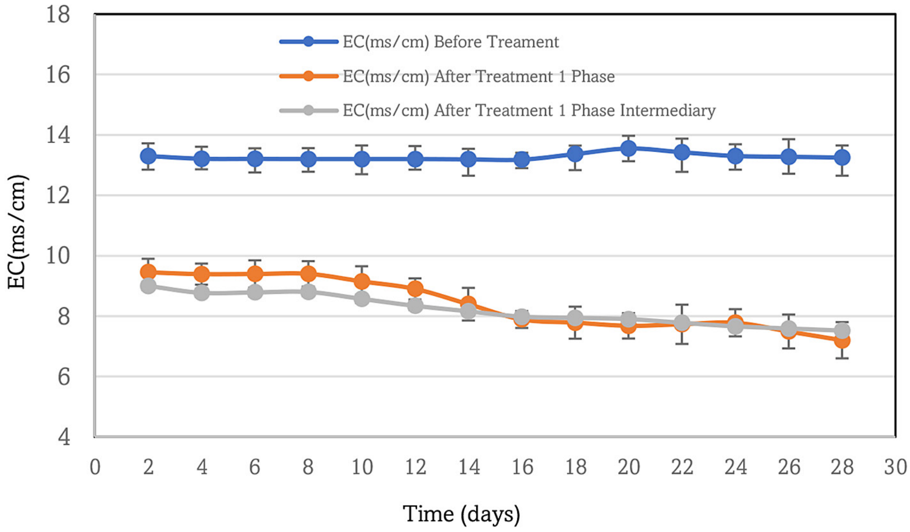

Figure 11. EC levels before and after treatment in the single-phase and single-phase intermediary systems

single-phase and single-phase intermediary treatment systems. Initial EC measurements showed consistent levels of 13.2 mS/cm before treatment. Both systems demonstrated a gradual reduction in EC after treatment, with the intermediary treatment system showing slightly better performance in the early stages. By the end of the 28-day period both systems achieved comparable results, reducing EC to around 7.5 mS/cm for the single-phase system and 7.7 mS/cm for the single-phase intermediary system. These results concurred with Gholizadeh et al. (2024) who demonstrated that both systems reduced electrical conductivity and improved the water quality. The initial EC value averaged 13.27 ± 0.13 mS/cm. After treatment, the EC levels dropped to 7.63 ± 0.30 mS/cm in the single-phase digester and 7.765 ± 0.21 mS/cm in the intermediate single-phase digester, giving 42.66% and 41.70% matter reduction, respectively. These results concurred with AlSayed et al. (2023), further validating the effectiveness of the treatment systems.

Biogas production

This study compared the performance of single-phase and single-phase intermediary wastewater treatment systems in biogas production and wastewater treatment from the fish cracker production process. Results showed that the single-phase system outperformed the single-phase intermediary system. The superior performance of the single-phase system was attributed to its higher stability in controlling internal reactor conditions, such as pH and temperature, which enabled the methanogen microorganisms to function efficiently. This stability also reduced the accumulation of intermediate compounds, such as volatile fatty acids (VFAs), which inhibited biogas production. The single-phase system demonstrated more complete degradation of organic matter, as all the microbial groups worked together in a single reactor, preventing residue accumulation. The single-phase system was more effective in reducing COD and TSS, with removal efficiencies of 65.18% and 70.42%, respectively, compared to the single-phase intermediary system's removal efficiencies of 63.30% and 68.30%. The single-phase system was also more straightforward in design as cost-effective and suitable for scaling up to community or industrial levels, and offered higher stability and performance than the single-phase intermediary system which required a more complex design to achieve similar performance.

Figure 12 compares biogas production rates between the single-phase and single-phase intermediary treatments over 28 days. Both systems showed similar production patterns, with biogas production increasing from day 4 to day 20, reaching peaks of 5.8 l/d for single phase and 5.7 l/d for single phase intermediary. After day 20, the biogas production gradually declined to around 4.7 l/d by day 28. The single-phase treatment maintained marginally higher gas production throughout the experiment. These patterns aligned with the stages of the anaerobic digestion process, including hydrolysis, acidogenesis, and methanogenesis. These three stages are critical in converting complex organic matter into biogas, with methanogenesis playing a pivotal role in methane production.

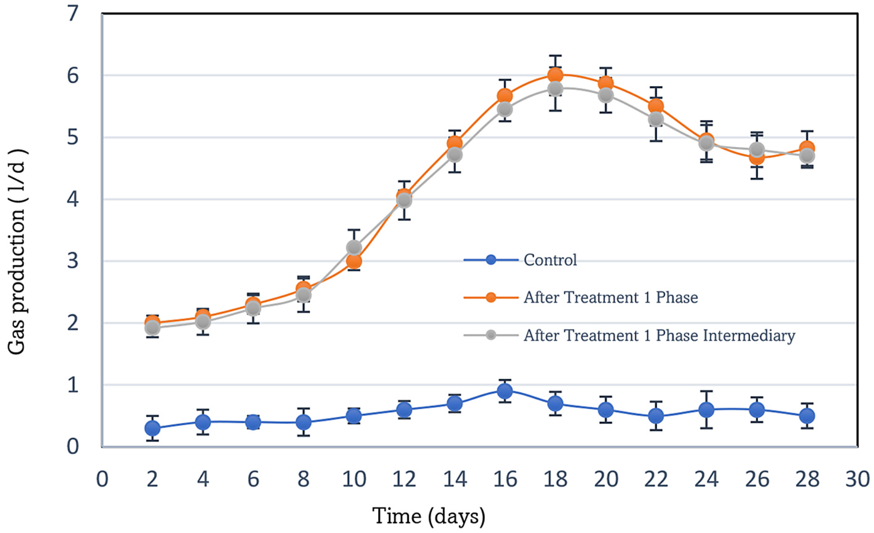

Figure 12. Gas production over time in the single-phase and single-phase intermediary systems

Biogas composition

The composition of biogas produced from fish cracker production wastewater was measured using gas chromatography. Figure 14 presents the concentration of each component of biogas as 59.49% methane (CH_4), 35.49% carbon dioxide (CO_2), 1.40% oxygen (O_2), 3.50% nitrogen (N_2), and 0.12% hydrogen sulfide (H_2S). Consistent with research by Bücker et al. (2020), the experimental results demonstrated that fish waste (FW) and fish crude oil waste (FCOW) had a high potential for biogas production, yielding methane at 540.5 and 426.3 mL/g of volatile solids, respectively. Kumar (2024) showed that when fish waste and cow manure were digested together in an 80:20 ratio, 61% methane content was produced. Chairattanawat et al. (2021) presented a comprehensive review highlighting the optimization potential of fish waste anaerobic digestion, and Rajendiran et al. (2022) achieved promising results through the co-digestion of fish waste with market waste, producing biogas with a 59% methane content. These studies reported methane yields ranging from 459 to 554 mL/g VS added, and optimal conditions were achieved at mesophilic temperatures around 36.5 °C, primarily through co-digestion strategies with carefully controlled mixing ratios. In the biogas fermentation tank system, the temperature ranged from 32 to 37 °C, consistent with many previous research studies. A temperature range of 31–34 °C was reported by Nahar et al. (2020) aligning with established research on mesophilic anaerobic digestion, which typically operates between 30 and 40 °C (Shi et al., 2018). Most studies indicated that the optimal temperature for maximum bacterial growth and biogas production was slightly higher, between 37 and 40 °C (Hossain et al., 2022). A 32–37 °C temperature maintained stable digestion conditions but was at the lower end of the mesophilic spectrum. As a result, microbial activity and methane production rates

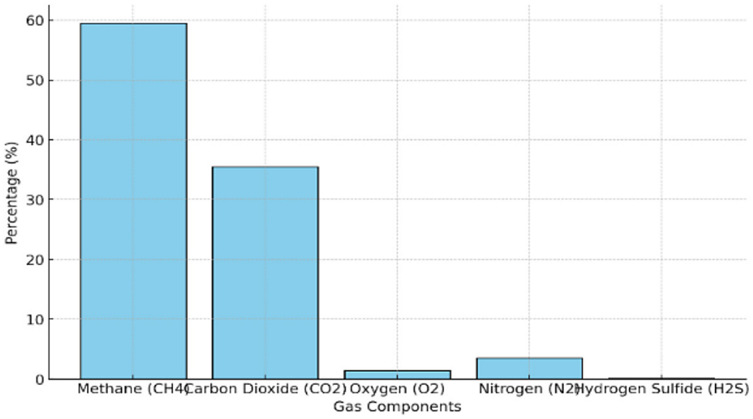

Figure 13. Biogas composition

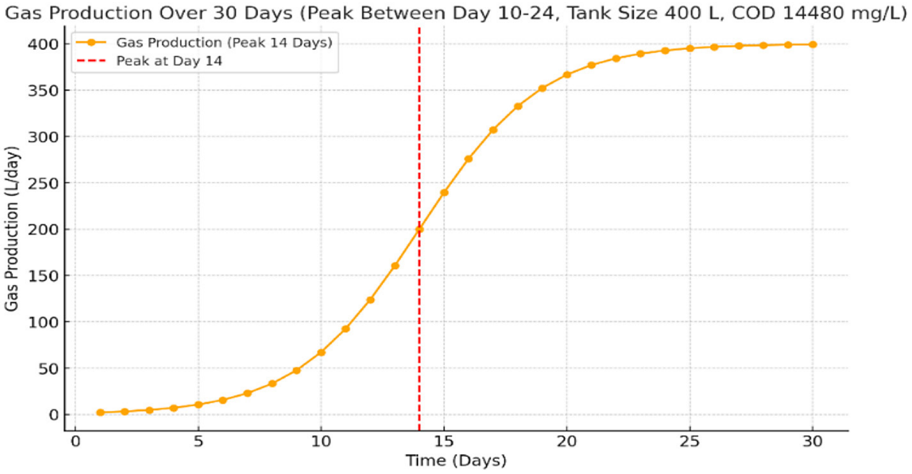

Figure 14. Gas production over time for a 500-liter tank

reduced compared to the conventional mesophilic operating temperature range of 35–40 °C, which is widely recognized as optimal for maximizing anaerobic digestion (Kougias & Angelidaki, 2018; Naghavi et al., 2020). Operating at the lower end of this range led to slower degradation rates and lower biogas yields, as microbial metabolism was less active than at the higher end of the mesophilic range. Therefore, maintaining temperatures closer to 35–40 °C further enhanced the performance of the anaerobic digestion process.

The composition analysis demonstrated typical biogas characteristics, with methane as the primary component. Recent studies have shown varying methane concentrations in biogas systems. Biogas produced on a farm usually contains 63.4% CH_4, 21.1% CO_2, and 15.2% N_2. Bio-desulfurization systems can eliminate up to 96.7% of H_2S (Oukili et al., 2022). Two-phase anaerobic digestion systems have achieved methane concentrations of 65 to 69% in the final biogas output, demonstrating stable production rates (Chorukova et al., 2022). Temperature control significantly impacts biogas production, with studies showing that temperature shifts between 42 and 48 °C impact methane yields by up to 83% (Sudiartha et al., 2023). Typical small-scale biogas plants, with a daily production capacity of 400–500 liters, require careful monitoring of ammonia concentrations to prevent toxicity effects, which can reduce methane production by up to 14% (Kalamaras et al., 2021).

A 400-liter tank with a COD level of 14.480 mg/L produced gas over 30 days, and the gas production curve had a sigmoid shape, typical of anaerobic digestion processes. The first 5-day lag phase showed how microbes adapted, in line with Zuo et al. (2022) who reported that Fe_0O_4 nanoparticles boosted microbe activity during this phase. The rapid exponential growth phase peaked at day 14, indicating maximum microbial activity and substrate conversion efficiency. This aligned with Rocamora et al. (2020) who emphasized the importance of optimizing the solid inoculum to substrate ratio and total solids content for efficient biogas production. After day 14, the curve plateaud, suggesting substrate depletion or inhibitory byproduct accumulation. Li. (2023) reported that high ammonia levels suppressed methane release, with cumulative methane production inhibited by up to 41% under elevated ammonia concentrations. The final gas production stabilized at around 400 L/day and was consistent with the tank size and organic load, reflecting the importance of reactor configuration and operational parameters in maximizing gas yields. These observations corresponded with established research on microbial degradation dynamics. Sudiartha et al. (2023) found that methane production rates strongly correlated with methanogenic microbial growth and substrate availability. Their research on changes in microbial communities over time in industrial anaerobic digestion systems has helped to improve biogas production by increasing microbe activity.

Community biogas system implementation

The implementation of biogas production from agricultural waste offers significant environmental and economic benefits, addressing broader concerns such as pollution reduction, waste management, and renewable energy generation (Kougias & Angelidaki, 2018; Mignogna et al., 2023). The project's output of 726.300 liters of biogas per year (135.0 liters/system/day) demonstrates the substantial potential for renewable energy production. This biogas production will contribute to

Table 3. Results of community biogas system implementation from shrimp cracker production wastewate

Data	Results*
Pilot households	20 households
System size per household	500 liters
Wastewater treatment from shrimp cracker production	128.044 liters/year (23.8 liters/system/day)
Biogas production in the community	726.300 liters/year (135 liters/system/day)
LPG replacement	334.98 kg (11,359.3 baht)
Electricity replacement	871.56 kWh)
Reduction in electricity costs	3,486.2 baht (4 baht/unit)
Firewood replacement	1,089.4 kg
Greenhouse gas emission reduction	3,604.26 ($kgCO_2eq$)

Note: *The calculation is based on the formula from the Department of Alternative Energy Development and Energy Conservation, Ministry of Energy, Thailand.

reducing greenhouse gas emissions by 3,604.26 $kgCO_2eq$, highlighting its role in mitigating climate change. The replacement of 334.98 kg of LPG and 871.56 kWh of electricity will also reduce reliance on fossil fuels and decrease energy costs for the community by 3,486.2 Baht/year (99.6 USD/year) at a rate of 1 USD = 35 THB. Treating 128.044 liters of wastewater per year from shrimp cracker production addresses waste disposal challenges, potentially reducing associated costs and environmental impacts. Using agricultural waste for biogas production aligns with the circular economy principles, transforming a waste product into a valuable energy resource. Haryanto et al. (2017) conducted a study on a biogas production system using four samples of cow dung. This system produced 1.582 liters of biogas per day with 53.6% methane gas, providing energy equivalent to 167 kg of LPG per year, saving 108.1 USD/year and reducing greenhouse gas emissions by 5,292.5 ($kgCO_2eq$)year from substituting household LPG and using sludge as fertilizer. Therefore, this system showed high potential to reduce environmental impacts, even though it did not provide a high economic return. This approach reduces the environmental burden of waste disposal and creates a sustainable energy source for rural communities. By replacing 5.475 kg of firewood, the project also contributes to forest conservation efforts. The multi-faceted benefits of this biogas project demonstrate its potential to address interconnected environmental and economic challenges, promoting sustainable development in rural areas (Mignogna et al., 2023; Alayi et al., 2022; Kougias & Angelidaki, 2018).

CONCLUSIONS

This study employed a three-step experimental approach to optimize biogas production from fish cracker wastewater. Batch tests identified a 14-day hydraulic retention time as optimal, yielding 3,248 mL of biogas. Scaling up to a 19-liter continuous system demonstrated significant water quality improvements, including pH normalization, 63–65% COD reduction, 68–70% TSS removal, and 42% EC reduction. Further scaling to a 500-liter reactor proved real-world applicability, producing biogas with 59.49% methane content suitable for cooking in 20 households. The system can annually treat 128.044 liters of wastewater, produce 726.300 liters of biogas, reduce greenhouse gas emissions by 3,604.26 $kgCO_2eq$, and replace 334.98 kg of LPG. This research bridges laboratory experiments with practical applications, contributing to sustainable wastewater management and renewable energy generation. Future research should focus on optimizing the system for various food industry wastewaters, exploring co-digestion possibilities, conducting long-term stability studies, and assessing economic feasibility across different operational scales to promote wider adoption of this technology.

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