

Effect of increase in organic loading of fermented rice noodles wastewater on biogas production in anaerobic biogas bag

S. Laowansiri¹ and P. Phothilangka^{2*} 

¹Energy and Environment for Sustainable Development Research and Training Center, Faculty of Environment and Resource Studies, Maharakham University, Kantarawichai, Maharakham-44150, Thailand

²Department of Environmental Science and Technology, Faculty of Science, Lampang Rajabhat University, Mueang, Lampang-52100, Thailand

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*Corresponding Author Email: phimpaka@g.lpru.ac.th

*ORCID: <https://orcid.org/0000-0002-9053-1141>

Abstract

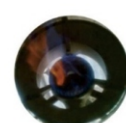
Aim: To investigate the effect of increase of organic loading of fermented rice noodles wastewater effect on the production of biogas and organic treatment efficiency using a low-cost anaerobic biogas bag system.

Methodology: The anaerobic biogas bag was setup for treating fermented rice noodles wastewater. The anaerobic biogas bag was filled with 20 l d⁻¹ wastewater feeding as batch mode system and the pH was adjusted to 7.00 with NaOH and H₂SO₄. The loadings of reactor was 7.5 g COD m⁻³ d⁻¹ for 15 days, later (the first phase) increased to 2.5, and 17.5 g COD m⁻³ d⁻¹ at every 15 days interval was considered as 2nd and 3rd phase, respectively. The effects of loading rates on biogas yield and its compositions were investigated.

Results: With 17.5 g COD m⁻³ d⁻¹, COD loading rate, with the fermented noodles were digested 77.7% removal of COD within 45 days, later stable anaerobic digestion was maintained after 30 days. At that point, a high biogas production (0.65±0.01 m³ biogas d⁻¹) with methane production rate of 0.400±0.01 m³ CH₄ d⁻¹ was achieved.

Interpretation: Wastewater with high COD loading rate (17.5 g COD m⁻³ d⁻¹) such as a rice noodles wastewater, can be treated with anaerobic biogas bag. This system provides high treatment efficiency and produces biogas as an alternative source of energy.

Key words: Anaerobic treatment, Biogas bag, Fermented rice noodles wastewater



Fermented rice noodles wastewater. pH was adjusted to 7.00±0.02.



Anaerobic biogas bag
The COD loadings to the reactor were 7.5, 12.5 and 17.5 gCOD m⁻³ day⁻¹. Each of the phase lasted 15 days and overall it took 45 days



Analysis, Soluble COD, TKN, SS, pH, Temperature, EC, Gas composition, Biogas production, Ignition time

Introduction

Fermented rice noodles are widely consumed in South-east Asia, particularly in Thailand, where small- to medium-scale production generates substantial volumes of carbohydrate-rich wastewater. This effluent contains high concentrations of starch residues, volatile fatty acids and fermentation by-products, if left untreated may lead to eutrophication, odor, and microbial contamination of surface and groundwater resources (Ledesma *et al.*, 2024; Drosig *et al.*, 2021; More, *et al.*, 2023). Anaerobic digestion has been recognized as a sustainable and cost-effective solution for treating such wastewater, while simultaneously producing biogas—a renewable energy source. It converts the organic matter into fermented rice noodles wastewater to biogas, a mixture of methane (CH₄) and carbon dioxide (CO₂) with residual fractions of gases like H₂ and H₂S (Loganath and Mazumder, 2018). The performance of anaerobic systems is largely governed by the organic loading rate, which influences the microbial activity, substrate conversion and methane yield (Ahmad *et al.*, 2023; Zhang *et al.*, 2023). While optimal organic loading rate enhances the system stability and biogas output, excessive loading may result in acid accumulation and inhibit the process (Karne *et al.*, 2025).

Optimizing the organic loading rate is widely recognized as a critical operational strategy for enhancing anaerobic digestion performance, as it directly affects microbial activity, process stability, and methane yield. Recent studies have shown that fine-tuning organic loading rate can markedly improve both treatment efficiency and biogas production in various food-processing effluents, including starch-based and protein-rich wastewaters (Zhang *et al.*, 2024; Ibrahim *et al.*, 2025). These findings indicate that maintaining an optimal organic loading rate not only maximizes substrate utilization but also reduces the risk of process inhibition caused by excessive accumulation of volatile fatty acids. Nevertheless, research focusing specifically on fermented rice noodle wastewater remains limited. This wastewater type poses unique challenges due to its inherently low pH, high carbohydrate content and rapid biodegradability, which can lead to acidification and process instability if the organic loading rate is not carefully controlled. Addressing these knowledge gaps is essential for developing tailored anaerobic digestion strategies that achieve both effective pollutant removal and sustainable bioenergy recovery from this under-studied effluent. In view of the above, the present study was carried out to investigate the effect of increasing organic loading rate on biogas production and organic treatment efficiency using a low-cost anaerobic biogas bag system. The findings are expected to contribute to the development of decentralized wastewater management strategies and promote energy recovery in rural food industries.

Materials and Methods

Collection of wastewater: The fermented rice noodles (rice vermicelli) wastewater used in this study (Table 1) was obtained

from a rice vermicelli production factory located in the Mueang District, Karasin Province, North-eastern Thailand. The sampling site is geographically located at 16°24'05.4"N, 103°31'24.3"E, corresponding to a rural freshwater body surrounded by agricultural land. Coordinates were recorded using a handheld GPS receiver (Garmin eTrex 32x, Garmin Ltd., USA), with an estimated positional accuracy of ±5 m. The physico-chemical properties of wastewater was estimated by the standard methods of APHA (2023).

Reactor start-up and operation: An 8 m³ anaerobic biogas bag with 4 m³ effective volume and 4 m³ biogas volume were used in the experiments. The schematic diagram of the anaerobic biogas bag is shown in Fig 1. The anaerobic treatment system was initiated by filling it with 300 l of swine manure and 100 l water, and left for 14 days to allow the anaerobic bacteria to acclimatize and create anaerobic condition in order to release biogas as the end product. The operation was filled batch-wise into the bag with 20 l d⁻¹ fermented rice noodles wastewater and the pH was adjusted to 7.00 ± 0.02 with NaOH and H₂SO₄. The experiment was designed for 3 phase investigation.

The COD loadings of fermented rice noodles as feeding was adjusted to 7.5, 12.5 and 17.5 g COD m³ d⁻¹ for the first phase, second phase and third phase, which corresponded to COD concentration of 1500, 2500, and 3500 mg l⁻¹, respectively. Each phase lasted for 15 days and overall, the process was completed within 45 days. At the top, anaerobic biogas bag was connected to a gas meter for measuring the biogas flow and biogas quality analysis before utilized as alternative energy. Full scale installation of anaerobic biogas bag is shown in Fig. 2. The methodology followed standard protocols for water quality analysis as outlined by APHA (2023). Experimental configurations were adapted from recent biogas optimization studies employing machine learning techniques (Karne *et al.*, 2025).

Analytical procedure: Influent and effluent samples were analyzed for soluble chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and suspended solids (SS) in accordance with the standard Methods of APHA (2023). The pH, temperature and electrical conductivity (EC) were measured with a multiparameter meter (HACH HQ30d, USA). Gas composition (CH₄, CO₂, and N₂) was analyzed using a portable gas analyzer (Geotech BIOGASS 5000, England) and the biogas production was measured by the rise of floating gas holders placed above the water level. Ignition time was measured using an ignition timer (CITIZEN8RDA55-002, Japan).

The effect of an increase in organic loading of fermented rice noodles wastewater on the biogas production, methane content, methane yield and ignition time was plotted as linear relationships between COD removal rate versus biogas production (m³ d⁻¹), methane content (%), methane production (m³ d⁻¹) and ignition time (min d⁻¹). The analysis was conducted using a linear regression based on the experimental data, following the biogas modeling framework described by Karne *et al.* (2025),

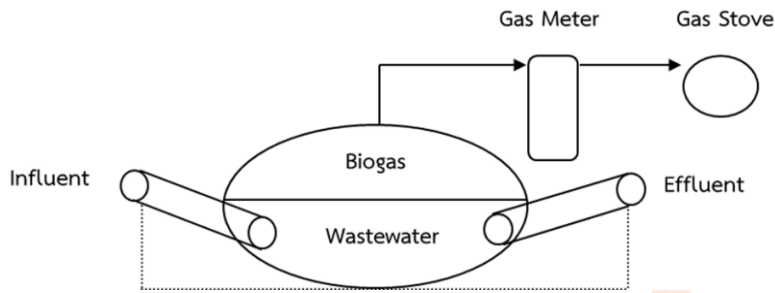


Fig. 1: Schematic diagram of the Anaerobic biogas bag.



Fig. 2: Semi-continuous feed pilot scale of anaerobic biogas bag used in this study.

which emphasizes the use of empirical data and machine learning to evaluate the correlations among the bioenergy variables.

$$Y = aX + b \quad (1)$$

Where, Y is the biogas production ($\text{m}^3 \text{d}^{-1}$), methane content (%), methane production ($\text{m}^3 \text{d}^{-1}$) and ignition time (min d^{-1}), X is the COD removal rate ($\text{g COD m}^{-3} \text{d}^{-1}$); a is the slope; b is the Y-intercept.

Statistical analyses: The experimental data reported in this work are expressed as mean values. One-way ANOVA was applied, followed by the Least Significant Difference (LSD) test to compare the mean values at a significance level of $P < 0.05$. Data processing and statistical computations were conducted using IBM SPSS Statistics, version 29.0 (IBM Corp., Armonk, NY, USA).

Results and Discussion

The perusal of data (Table 1) shows that the fermented rice noodles wastewater was characterized by high organic load and acidity, along with moderate levels of solids and low nitrogen content. These factors indicate that while the wastewater has

Table 1: Characteristics of fermented rice noodles wastewater

Parameters	Fermented rice noodles wastewater
COD (mg l^{-1})	16,360 \pm 3,712
EC (μScm^{-1})	13.8 \pm 0.01
TKN (mg l^{-1})	37 \pm 2
SS (mg l^{-1})	1,111 \pm 384
pH	3.3 \pm 0.3
Temperature ($^{\circ}\text{C}$)	26.7 \pm 0.8

Values are mean of three replicates \pm S.D

good potential for anaerobic digestion, careful control of organic loading rate and pH stabilization is essential to avoid process instability. The experimental procedure was structured into three consecutive phases to investigate the treatment performance of a system utilizing fermented rice noodles wastewater as a influent substrate. Each phase was defined by a specific organic loading rate, incrementally adjusted to evaluate the system's acclimatization and operational stability under progressively elevated chemical oxygen demand (COD) conditions. In the first

Table 2 : Average values of 15 days of first, second, and third phase treated fermented rice noodles wastewater

Feeding	First phase	Second phase	Third phase
COD loading (gCOD m ⁻³ d ⁻¹)	7.5	12.5	17.5
Concentration (mg COD l ⁻¹)	1,500	2,500	3,500
Parameters			
pH	7.60±0.16 ^a	7.81±0.05 ^b	7.85±0.04 ^b
Temperature (°C)	27.21±0.70 ^a	28.17±0.72 ^b	28.38±0.42 ^b
EC (µS cm ⁻¹)	13.84±0.01 ^b	13.85±0.01 ^b	13.83±0.00 ^a
CODresidue (mg l ⁻¹)	1159±54.33 ^b	1110±67.82 ^b	781±94.73 ^a
COD removal(mg l ⁻¹)	341±54.33 ^a	1390±67.82 ^b	2719±94.73 ^c
COD removal (%)	22.7±6.15 ^a	55.6±12.66 ^b	77.7±3.40 ^c
Biogas production (m ³ d ⁻¹)	0.57±0.00 ^a	0.63±0.02 ^b	0.65±0.01 ^c
Methane content (%)	48±0.1 ^a	55±0.2 ^b	61.5±0.7 ^c
Methane production (m ³ d ⁻¹)	0.275±0.00 ^a	0.348±0.01 ^b	0.400±0.01 ^c
Ignition time (min d ⁻¹)	229.4±1.42 ^a	253.3±8.76 ^b	261.8±3.47 ^b

Note: a, b, c with different letter shows significant statistical difference (P<0.05)

phase, the initial organic loading rate was maintained at 7.5 g COD m⁻³ d⁻¹, which was increased to 12.5 g COD m⁻³ d⁻¹ in the second phase and further to 17.5 g COD m⁻³ d⁻¹ in the third phase, with each phase operating over a period of 15 days for each phase. The mean values of key operational parameters and feeding characteristics observed throughout the experimental phases are presented in Table 2, offering insights into the system performance under varying organic loading regimes.

The pH values of treated fermented rice noodles wastewater with different COD loading in the range of 7.5 -17.5 g COD m⁻³ d⁻¹ remained nearly constant throughout the operation of about 7.60-7.85, which favored the growth of methanogenic bacteria as well as supported methane production. Similar buffering conditions were reported by Banu *et al.* (2006), who demonstrated that anaerobic biogas bag systems provide a stable environment for hydrolysis and methanogenesis. This stability is crucial, as significant pH fluctuations, particularly drops to acidic conditions, can severely inhibit methanogenic activity by increasing the decay rate of archaeal biomass and hindering their metabolic pathways (Sun *et al.*, 2020). Extremely low pH conditions, such as pH 5.5, have been shown to reduce the viability of methanogenic consortia, although some acclimated systems can exhibit long-term survival even under such acidic stress (Han *et al.*, 2019). Similarly, the temperature of anaerobic biogas bag system with different COD loadings of 12.5 and 17.5 g COD m⁻³ d⁻¹ was observed in the range 27.21-28.38°C, indicating the degradation process under mesophilic condition. Although the optimum temperature of mesophilic conditions for bacterial growth to produce biogas was reported at 31-37 °C (Alam *et al.*, 2022), the observed range is acceptable for tropical climates such as Thailand, where ambient temperatures often reach 37-40°C during summer. Mesophilic digestion under such conditions has been shown to maintain stable biogas production with 60–70% methane concentrations (Lovato *et al.*, 2017). This low EC range

suggests minimal accumulation of dissolved ions, which is favorable for microbial activity and prevents inhibitory effects associated with elevated salinity. Similar EC profiles have been reported in low-strength wastewater treatment systems, where ionic stability contributes to consistent microbial performance (de Mes *et al.*, 2003; Pratima, 2017). Overall, the anaerobic biogas bag system demonstrated robust physico-chemical conditions under moderate organic loading, supporting stable methanogenic activity and biogas generation. These results reinforce the importance of maintaining environmental parameters within optimal range to ensure the efficiency and resilience of anaerobic digestion systems.

The results showed that the COD removal efficiencies increased with increased COD concentration (referred as COD loading) of fermented rice noodles wastewater. The COD removal was 22.7% in the first phase. The efficiency of the reactor increased slightly during the first phase, which could be probably due to unstable of suspended solids concentration (Arafath *et al.*, 2019). However, the COD removal efficiencies gradually increased and reached 55.6% in the middle of second phase, indicating successful acclimatization of methanogens in the degraded organic matter of fermented rice noodle wastewater (Banu *et al.*, 2006). The COD removal at third phase showed statistically significant differences (P<0.05) from COD loadings in other phases. From second phase to third phase, the anaerobic biogas bag still showed increasing COD removal of 77.7%. These results revealed that degradation within anaerobic biogas bag was on steady state condition that may be able to handle more organic loading for decomposition. However, studying COD removal at a higher organic loading rate (>17.5 g COD m⁻³ d⁻¹) is suggested to investigate the stability of anaerobic biogas bag. Fig. 3 revealed lower concentration of COD in the effluent when the fermented noodle was treated through second and third phase, respectively, although the COD loading rates were increased.

Variations in biogas production and methane content were evaluated under different COD loadings (7.5, 12.5, and 17.5 g COD m⁻³ d⁻¹). The perusal of data (Table 2) showed that an increase in biogas production, methane content and methane yield occurred with increase in COD loading of fermented rice noodles wastewater. The increase in COD loading resulted in an increase of organic matter available for anaerobic degradation into biogas (Toutian *et al.*, 2019; Eslami *et al.*, 2018; Mel *et al.*, 2015; Laowansiri *et al.*, 2008). The maximum biogas production (0.65±0.01 m³ d⁻¹) was obtained at 17.5 g COD m⁻³ d⁻¹ loading (3rd phase) of fermented rice noodles wastewater and tend to increase if the organic loading was increased. The methane content was 61.5% at 17.5 g COD m⁻³ d⁻¹ loading rate. An increase in organic loading (initial COD loading increase) had a significant (P<0.05) effect on biogas production, methane content, and methane production of anaerobically fermented rice noodles wastewater. The average biogas flow was 0.57, 0.63 and 0.65 m³ d⁻¹ at loading rates of 7.5, 12.5 and 17.5 g COD m⁻³ d⁻¹ (first, second and third phase), as well as the concentration of methane at the aforementioned COD loading rates was 48±0.1, 55±0.2 and 61.5±0.7%. Likewise, the methane production levels recorded were 0.275, 0.348 and 0.400 m³ d⁻¹, respectively. The results of this study revealed that methane concentration was high enough for ignition. However, there was no specific standard for methane concentration for ignition due to variation depending on the specific application and the condition used, in particular, at least methane concentration of 30% was required for combustion (Borowski *et al.*, 2019; Zarei., 2020). Earlier, Yin *et al.* (2010) elucidated that catalytic combustion gas required a minimum methane concentration of 25%. The ignition time increased with increase in COD loading of fermented rice noodles wastewater. Similarly, ignition times at the aforementioned COD loading rates were 229.4, 253.3 and 261.8 min d⁻¹, respectively.

As anaerobic digestion takes place in the fermentation reactor, it is a cumbersome process to improve the reaction

conditions of the fermenter's structure and function to achieve a higher methane yield. Significant achievements of anaerobic digestion process has been summarized in Table 3. An anaerobic biogas bag was evaluated for treating fermented rice noodle wastewater at an exceptionally high organic loading rate of 17.5 g COD m⁻³ d⁻¹ within 45 days, the system achieved 77.7% COD removal. At steady state, it produced 0.65 m³ biogas d⁻¹, containing 61.5% methane content, corresponding to 0.400 m³ methane d⁻¹. Compared to Ahmad *et al.* (2023), who obtained 13.0-85.0% COD removal at 0.5-27.5 g COD l⁻¹ d⁻¹ of COD loading rate using an anaerobic fixed-bed digester of co-digestion of food waste and solid poultry slaughterhouse waste, the anaerobic biogas bag delivered robust performance under single-substrate operation and simpler configuration. Racho and Pongampornnara (2020) reported > 70% COD removal at 7.5-25.0 kg COD m⁻³ d⁻¹ with modified tapioca starch wastewater, the anaerobic biogas bag system used in this study, however, tolerated over three-times higher loading while maintaining higher removal and gas yield.

Co-digestion of rice noodle wastewater and chicken manure in an anaerobic digestion, Jijai and Siripatana (2017) achieved 30.38-50.66% methane content at 9,570-31,050 mg COD l⁻¹; the anaerobic biogas bag in this study, matched removal efficiency without supplementary co-substrates. Thermophilic condition treating co-digestion of food waste and sewage sludge studies (Zhang *et al.*, 2023) showed 81% COD removal and 300 ml methane g⁻¹ COD fed, but required strict temperature control. Anaerobic baffled reactors treating tofu industrial wastewater (Ningsih *et al.*, 2024) demonstrated 95% COD removal and molasses wastewater (Zhua *et al.*, 2016) reported 88-95% removal at higher COD loadings rate, indicating trade-offs between loading intensity and conversion efficiency. Chen *et al.* (2020) demonstrated ~94% COD removal in an up flow anaerobic sludge blanket at 2.08±0.12 g COD l⁻¹ d⁻¹ and producing 74.1%

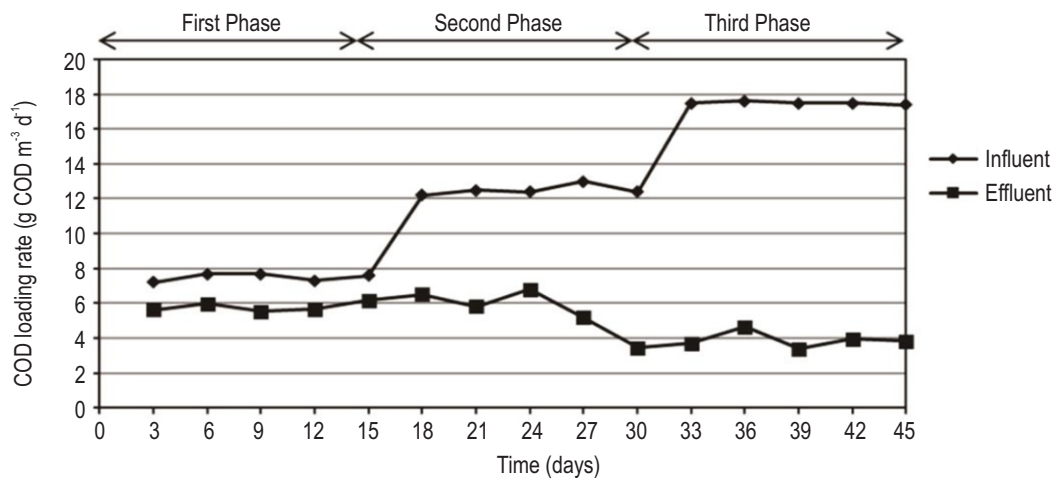


Fig. 3: COD loading and COD degradation of fermented rice noodles wastewater treatment in an anaerobic biogas bag.

Table 3: Comparison of different anaerobic technologies

Wastewater types and sources	Wastewater treatment system	COD loading rate	Initial COD (mg l ⁻¹)	COD removal (%)	Biogas production (m ³ d ⁻¹)	Methane content (%)	Methane Production (m ³ d ⁻¹)	Methane yield
Fermented rice noodles wastewater Thailand	anaerobic biogas bag	7.5–17.5g COD m ⁻³ d ⁻¹	1,500-3,500	22.7-77.7	0.57-0.65	48.0-61.5	0.275-0.400	N.R.
Co-digestion of Thai rice noodle wastewater (Khanomjeen) with chicken manure. Thailand	anaerobic digestion	N.R.	9,570-31,050	N.R.	N.R.	30.38-50.66	N.R.	28-299 ml CH ₄ g ⁻¹ COD added
Co-digestion of food waste and solidpoultry slaughter house waste Oman	anaerobic fixed bed digester	0.5-27.5 g COD l ⁻¹ d ⁻¹	2,950-4,3150	13.0-85.0	12-74 l g COD d ⁻¹	N.R.	N.R.	1.2-7.8 l l ⁻¹ d ⁻¹
Modified tapioca starch wastewater Thailand	upflow anaerobic sludge blanket	7.5-25.0 kg m ⁻³ d ⁻¹	16,700±3,503	> 70	0.23-0.34 m ³ kg ⁻¹ COD removed d ⁻¹	54.36-67.43	N.R.	N.R.
Tofu industrial wastewater Czech Republic	biofilter in anaerobic baffled reactor	0.4 g COD l ⁻¹ d ⁻¹	N.R.	95	69.48 l d ⁻¹	58.05	N.R.	0.147 l g ⁻¹ COD removal
monosodium glutamate wastewater China	upflow anaerobic sludge blanket (UASB)	2.08±0.12 g COD l ⁻¹ d ⁻¹	2,078.44 ±124.89	93.79±4.13	N.R.	74.1	N.R.	0.25±0.03l g ⁻¹ COD
Molasses wastewater China	anaerobic baffled reactor	1.5-3.6 kg COD m ⁻³ d ⁻¹	3,000	88-92	N.R.	N.R.	N.R.	N.R.
Fish meal factory wastewater Thailand	anaerobic digestion (single-stage operation)	0.28-1.71 kg COD m ⁻³ d ⁻¹	8,530	39.17-75.04	N.R.	N.R.	0.057-0.129	32-45 l kg ⁻¹ COD degraded

N.R. not reported

methane content, comparable to the anaerobic biogas bag used in this study, despite half the organic loading rate. Sinbuathong *et al.* (2019) investigated anaerobic digestion of high-salinity effluent from fish meal factory wastewater and reported 39.17-75.04% COD removal at 0.28- 1.71 kg COD m⁻³ d⁻¹ with methane yields of 32-45 l kg⁻¹ COD degraded. A principal innovation of this work is the development of a linear predictive model correlating influent COD with biogas production. A strong linear relationships among loading rate, removal efficiency, and gas output confirm the model's practical utility for process control and scale-up in decentralized, low-cost applications. Overall, these findings demonstrate that anaerobic biogas bag technology can reliably treat high-strength starch wastewaters under mesophilic conditions without complex infrastructure or co-substrate requirements. Its performance parallels that of more elaborate reactor systems, underscoring the bag's suitability for rural or small-scale agro-industrial settings.

The correlation between biogas production, methane content, methane yield, and ignition time with COD removal rate is illustrated in Fig. 4, where all regression lines exhibited positive slopes, indicating that increase in COD removal is associated with enhanced biogas performance parameters. The rate constants derived from the linear regression equations during the first, second and third phases of COD removal are summarized in Table 4. Specifically, the rate constants for biogas production, methane content, methane yield, and ignition time was 0.0061 m³ biogas-m³ wastewater g⁻¹ COD, 1.0621% m³ d g⁻¹ COD, 0.0101 m³ methane-m³ wastewater g⁻¹ COD, and 2.6705 min m³ g⁻¹ COD, respectively. These results are consistent with the findings of Choeisai *et al.* (2014), who investigated the treatment of sugarcane molasses-based bioethanol wastewater using a two-phase, multi-stage up-flow anaerobic sludge blanket (UASB) system combined with a down-flow hanging sponge reactor. Their study demonstrated that increased COD removal was strongly

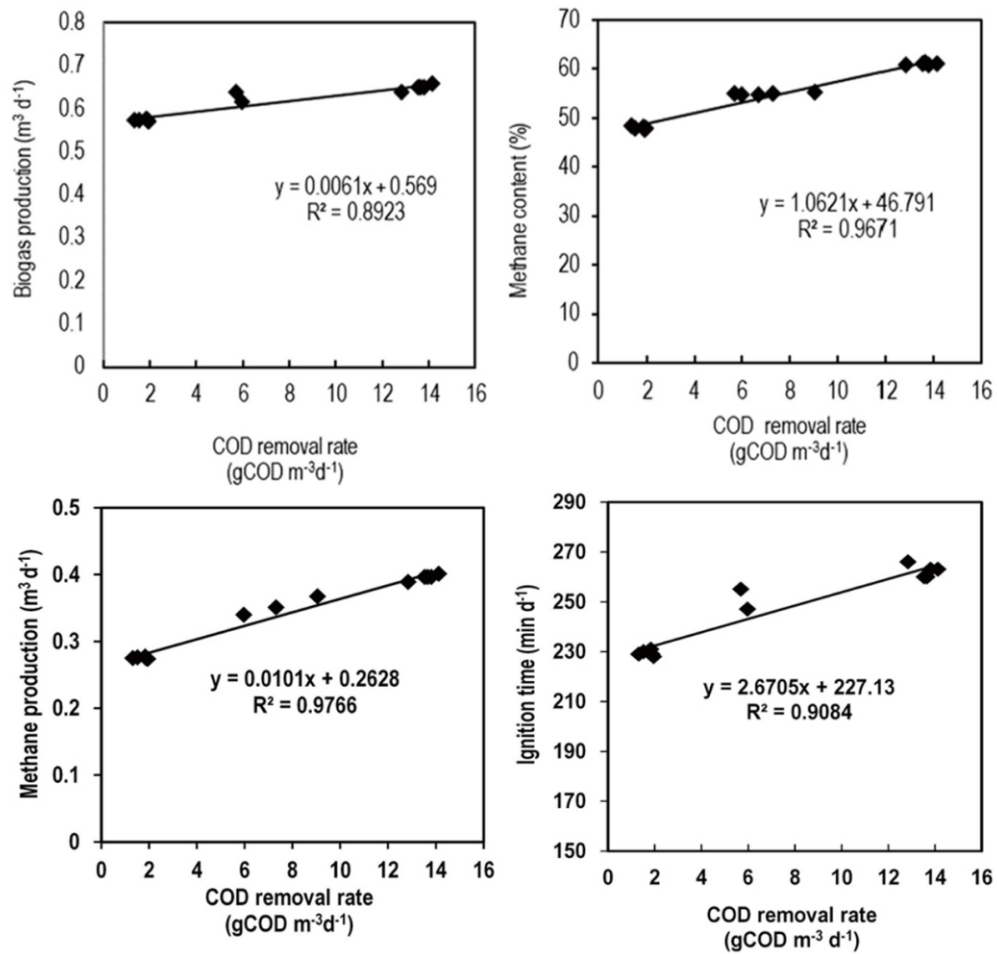


Fig. 4: Correlation of biogas production, methane content, methane yield and ignition time to COD removal to first, second, and third phase removal of COD.

Table 4: Linear equations and corresponding rate constant values (slope) were obtained from the variation of biogas production, methane content, methane production, and ignition time during the first, second, and third phase removal rate of COD

Y-axis	Linear equation	Slope (Rate constant)	R ²
Biogas production (m ³ d ⁻¹)	Y=0.0061X + 0.569	0.0061 (m ³ biogas m ³ wastewater g ⁻¹ COD)	0.8923
Methane content (%)	Y=1.0621X + 46.791	1.0621 (% m ³ d g ⁻¹ COD)	0.9671
Methane production (m ³ d ⁻¹)	Y=0.0101X + 0.2628	0.0101 (m ³ methane m ³ wastewater g ⁻¹ COD)	0.9766
Ignition time (min d ⁻¹)	Y=2.6705X + 227.13	2.6705 (min m ³ g ⁻¹ COD)	0.9084

X axis is COD removal rate (g COD m⁻³ d⁻¹)

correlated with higher methane yield and improved fuel quality. Mao *et al.* (2015) highlighted the importance of substrate composition and initial pH in optimizing methane yield during co-digestion of swine manure and corn straw. Their findings showed that adjusting feedstock ratios and maintaining a near-neutral pH improved both COD removal and methane generation. Gaby *et al.* (2017) examined the influence of temperature and hydraulic

retention time (HRT) on methane production, revealing that shorter HRTs (10 days) significantly enhanced methane output compared to extended retention periods.

Additionally, Tsegaye and Leta (2022) demonstrated that anaerobic treatment of slaughterhouse wastewater under optimized conditions (HRT of 6 days and organic loading rate of

298 mg COD l⁻¹) produced of 55–67% methane and COD removal efficiencies exceeding 80%. These outcomes are consistent with the present study and emphasize the significance of operational control in maximizing biogas recovery. The observed decrease in ignition time with increasing COD removal may be attributed to elevated methane concentration and enhanced calorific value of biogas, which promotes faster combustion. Although ignition time is less frequently reported in biogas studies, it provides practical insight into the fuel quality and usability of biogas as a renewable energy source.

In conclusion, this study demonstrated the novel application of fermented rice noodle wastewater as a viable substrate for anaerobic digestion in anaerobic biogas bag systems, highlighting its potential for sustainable waste management. The reactor maintained stable performance across varying organic loading rates, with significant gains in COD removal, biogas production, and methane yield. Integration of a predictive model represents a key innovation, accurately linking influent COD concentrations with biogas production dynamics. Strong linear correlations between system parameters and COD removal reinforce the model's practical utility. These findings offer new insights into the design and operation of low-cost, decentralized anaerobic systems for tropical agro-industrial contexts. Overall, this work contributes to the advancement of circular economy strategies through renewable energy generation and wastewater valorization.

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