

Evaluation of Site-Specific Methane Emission Factors from Biogas Production in Tapioca Industrial Wastewater Treatment Systems

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Article History:

Received : 21 November 2025

Revised : 25 February 2026

Accepted : 03 March 2026

Keywords:

Cassava wastewater,
Covered anaerobic lagoon (CAL),
COD-based biogas yield,
Greenhouse gas mitigation,
Methane emission factor (B_0).

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ABSTRACT

Tapioca processing in Indonesia generates high-strength wastewater that can emit substantial methane (CH_4) without sufficient treatment. The objective of this study is to determine a site-specific methane emission factor (B_0) for biogas power generation based on an anaerobic covered lagoon (ACL) and compares it with the IPCC default. Research was conducted on biogas power plant based on cassava wastewater with a capacity of 2×1.5 MW in Central Lampung. Twenty-two months of full-scale monitoring database included wastewater flow, COD, biogas yield volume, and methane concentration across wet and dry seasons. The results show that covered anaerobic lagoon systems with biogas recovery can effectively reduce fugitive methane. Using AMS-III.H and IPCC methods, a strong linear relationship between methane production and COD removal produced a site-specific B_0 of $0.2302 \text{ kg } CH_4/\text{kg COD}$ ($0.321 \text{ m}^3 \text{ } CH_4/\text{kg COD}$), slightly below the IPCC value. Lower yield was likely influenced by seasonal dilution, operational variability, and partial degradation of cassava-based organics. Results of this research emphasize the need for site-specific emission factors to improve Indonesia's GHG inventories and mitigation strategies.

1. INTRODUCTION

Tapioca production is a major agro-industrial activity in Indonesia that generates large volumes of high-strength organic wastewater, typically characterized by Chemical Oxygen Demand (COD) concentrations ranging from 18,000 to 30,000 mg/L, depending on processing technology and water usage efficiency (Elisabeth *et al.*, 2022). Given production capacities that can exceed 100–300 m³ of wastewater per ton of cassava processed, untreated tapioca wastewater effluent represents a substantial source of methane (CH_4) emissions if discharged or stored under anaerobic conditions. Methane has a global warming potential 28 times higher than CO_2 over a 100-year horizon, making effective wastewater management critical for climate mitigation (Skytt *et al.*, 2020). Anaerobic treatment systems are therefore widely applied for COD load reduction, frequently achieving COD removal efficiencies of 60–85% while simultaneously enabling energy recovery in the form of biogas (Achi *et al.*, 2020).

At the national scale, biogas-based wastewater treatment contributes to Indonesia's climate and energy targets by supplying renewable electricity and reducing greenhouse gas emissions, aligning with SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). In Lampung Province, one industrial-scale tapioca wastewater treatment

facility utilizes an anaerobic covered lagoon digester system equipped with biogas recovery, producing electricity with an installed capacity of 2×1.5 MW, equivalent to an annual energy generation potential of approximately 20–24 GWh, depending on operational conditions (Haryanto *et al.*, 2017; Marbun *et al.*, 2024). Such systems demonstrate the dual environmental and economic benefits of waste-to-energy pathways in agro-industrial sectors.

In national greenhouse gas (GHG) inventories, the IPCC recommends a default maximum methane-producing capacity (B_0) of 0.25 kg CH₄/kg COD for food-industry wastewater, which is equivalent to 0.35 m³ CH₄/kg COD removed under standard conditions (Paredes *et al.*, 2019). This value is derived from theoretical stoichiometric assumptions that presume near-complete conversion of biodegradable organic matter under ideal anaerobic conditions (Doorn *et al.*, 1997). However, empirical studies at full-scale facilities report substantially lower methane yields, with observed B_0 values ranging from 0.15 to 0.24 kg CH₄/kg COD removed, particularly in tropical regions where hydraulic dilution, fluctuating organic loading rates, and temperature-driven process instability are common (Nuraeni & Ashuri, 2018).

Evidence from Southeast Asia further indicates that IPCC default factors tend to overestimate methane generation in anaerobic covered lagoon systems by 10–40%, especially for cassava-based wastewater, which contains complex carbohydrates and fibrous residues that are not fully degradable under lagoon conditions (Kamahara *et al.*, 2010). Seasonal rainfall patterns can additionally reduce effective organic loading rates through dilution, leading to lower methane recovery despite high influent COD concentrations.

Although Kamahara *et al.* (2010) estimated emission factors for Indonesian tapioca wastewater, their analysis relied primarily on short-term observations and secondary datasets, without continuous biogas flow and methane concentration measurements under a CAL configuration. As a result, the reported methane-producing capacities were limited to estimated values in the range of approximately 0.18–0.27 kg CH₄/kg COD, which may not fully capture the influence of seasonal hydraulic variability under tropical conditions. Consequently, empirically derived B_0 values based on long-term, site-specific monitoring that captures both wet and dry seasonal dynamics remain scarce, particularly for full-scale CAL systems. Addressing this gap, the present study employs 22 months of continuous operational data from an industrial-scale CAL system to derive a site-specific B_0 for tapioca wastewater treatment. The resulting emission factor provides a more representative basis for national GHG inventories and supports mitigation strategies through renewable-energy-based wastewater management in Indonesia's tapioca industry (Eklund & Lacosse, 1998).

2. SITE DESCRIPTION AND METHODS

2.1. Observed Tapioca Industrial Wastewater Treatment System

The study was conducted at a biogas production facility based on tapioca wastewater in Central Lampung, Indonesia, a tropical monsoon region characterized by strong seasonal rainfall variability, with monthly precipitation ranging from approximately 2 to 300 mm and temperatures of 21–32 °C, providing stable mesophilic conditions for anaerobic digestion (BMKG, nd; Cecconet *et al.*, 2022). The facility treats combined tapioca effluents from multiple starch plants using a single anaerobic covered lagoon (ACL) with an approximate surface area of 84,000 m², lined with a 1.0–1.5 mm HDPE floating cover consistent with industrial standards. This configuration supports effective biogas capture and ensures structural and operational reliability. The hydraulic pathway from raw influent to final discharge was shown in Figure 1.

2.2. Wastewater Treatment and Biogas Production Process

Influent wastewater (COD > 20,000 mg/L) passed through a sequence of equalization, mixing, and acidification ponds before entering the CAL, where hydrolysis and methanogenesis occur under naturally maintained mesophilic temperatures (30–33 °C) and an estimated HRT of 30–40 days. Biogas accumulated beneath the HDPE cover is routed to the gas-utilization system, and methane production was quantified using daily recorded biogas flow rates and CH₄ concentrations obtained from routine operational monitoring logs of the biogas facility.

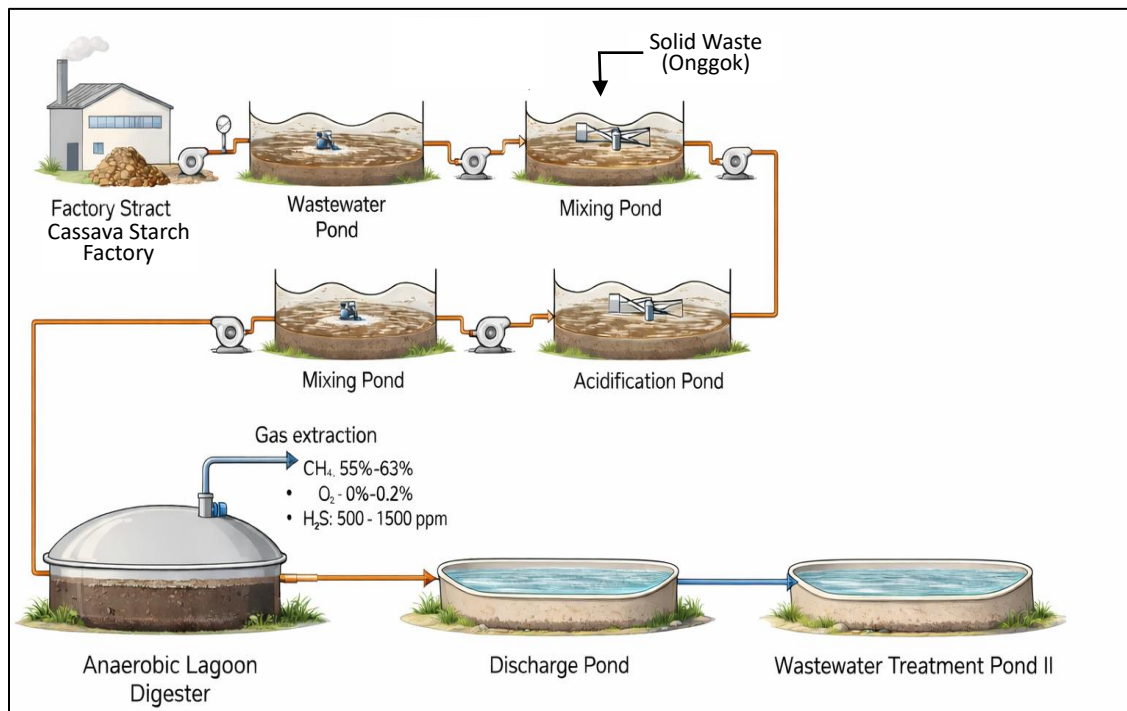


Figure 1. Process flow of the tapioca wastewater treatment system showing influent routing through mixing and acidification stages before anaerobic digestion in the covered lagoon and final effluent discharge

2.3. Measurement and Data Analysis

Field measurements included wastewater flow rates, influent and effluent COD concentrations, daily biogas volume, and methane percentage (% CH₄). Reported biogas volumes were normalized to standard conditions (0 °C, 1 atm). Methane density was assumed to be 0.714 kg CH₄/Nm³, consistent with standard gas density tables and IPCC normalization procedures (IPCC, 2008). Monthly methane emissions were calculated using the IPCC wastewater methodology:

$$\text{CH}_4 \text{ Emission} = \sum_i (Q_{ww,i,y} \times \text{COD}_{inflow,i,y} \times \eta_{COD,BL,i} \times \text{MCF}_{ww,treatment,BL,i}) \times B_o,ww \times \text{UF}_{BL} \quad (1)$$

where Q_{ww} is monthly wastewater flow rate, COD_{inflow} is influent COD, η_{COD} is COD removal efficiency, MCF_{ww} is methane conversion factor for CAL, UF_{BL} is uncertainty factor for biogas recovery systems, and B_o is methane-producing capacity (kg CH₄/kg COD).

Because methane was directly measured, the equation was rearranged to derive the site-specific B_o value empirically from the relationship between cumulative methane production and COD removed. A least-squares linear regression was performed to determine this relationship. Data points with clear anomalies (e.g., instrument malfunction, plant downtime) were excluded based on Cook's distance (> 1) and leverage metrics. The resulting site-specific B_o value was compared with the IPCC default (0.25 kg CH₄/kg COD) to evaluate its suitability for tapioca wastewater treatment under Indonesian industrial conditions.

3. RESULTS AND DISCUSSION

3.1. Characteristics of Tapioca Wastewater

The wastewater generated from tapioca production contains a high concentration of organic matter, primarily derived from residual starch and cassava peel (Fogaça *et al.*, 2014). During the 22-month monitoring period, the anaerobic system treated a total of 1,138,455 m³ of wastewater resulting from the processing of 43,123 tons of cassava into

approximately 18,543 tons of tapioca starch. Variations in daily and monthly production rates directly influenced wastewater quantity and characteristics, thereby affecting the organic loading entering the anaerobic digester (Yacob *et al.*, 2006).

As shown in Table 1, influent COD (COD in) ranged between 6,214–26,554 mg/L, while effluent COD (COD out) ranged between 162–1,577 mg/L, corresponding to a high COD removal efficiency of 90–99%. These COD levels are consistent with previously reported values for tapioca effluents in Southeast Asia, including 11,000–13,500 mg/L in Vietnam and 13,000–19,000 mg/L in Thailand (Sriroth *et al.*, 2000). Similar COD ranges have also been reported for anaerobic lagoons treating cassava wastewater in Malaysia (Zainuddin *et al.*, 2021) and southern China (Dou *et al.*, 2021), confirming the high-strength nature of tapioca effluents across the region. The resulting COD removal (COD rem) in this study was estimated at 11,461–40,279 kg/day, varying according to influent strength and hydraulic loading. Such fluctuations are influenced by differences in production throughput and water usage per unit tapioca produced, particularly across seasonal transitions between wet and dry periods (Kamahara *et al.*, 2010).

In 2023, daily wastewater flow rates ranged from 563.5 to 2,734.5 m³/day, with an average of approximately 1,646 m³/day, while in 2024 the flows were generally higher, ranging from 1,018.1 to 2,257.2 m³/day and averaging 1,762.9 m³/day, indicating an increase in tapioca production capacity. Influent COD concentrations (COD in) in 2023 varied widely between 6,214 and 26,554 mg/L, with the highest value recorded in July and the lowest in December, reflecting variations in raw material characteristics and plant operational conditions. In contrast, COD in values in 2024 were more stable, ranging from 8,781 to 18,950 mg/L.

Effluent COD concentrations (COD out) in 2023 exhibited substantial fluctuations, ranging from 180 to 1,577 mg/L, with elevated values observed in March, July, and August, indicating temporary reductions in treatment efficiency under higher organic loading conditions. In 2024, COD out concentrations were consistently lower and more stable (162–241 mg/L), demonstrating improved performance of the anaerobic treatment system. Correspondingly, COD removal (COD rem) in 2023 ranged from 9,207 to 34,375 kg/day, with the highest removal occurring in July, whereas in 2024 COD rem values were generally higher, ranging from 12,024 to 33,783 kg/day, indicating enhanced system capacity in reducing organic pollutant loads.

Table 1. Summary of tapioca wastewater flowrate, COD in, COD out, and COD removal

| Monthly Data | Tapioca Wastewater (m ³ /day) | Average COD in (mg/L) | Average COD out (mg/L) | COD removal (%) | COD removal (kg/day) |
|--------------|--|-----------------------|------------------------|-----------------|----------------------|
| 1 | 1,574.23 | 18.300 | 358 | 0.98 | 22.596 |
| 2 | 1,806.89 | 18.236 | 291 | 0.98 | 25.940 |
| 3 | 2,453.67 | 18.704 | 690 | 0.96 | 35.359 |
| 4 | 1,321.42 | 14.000 | 279 | 0.98 | 14.505 |
| 5 | 1,934.70 | 18.320 | 441 | 0.98 | 27.673 |
| 6 | 1,594.87 | 26.554 | 432 | 0.98 | 33.328 |
| 7 | 2,029.03 | 21.683 | 506 | 0.98 | 34.375 |
| 8 | 1,273.58 | 19.900 | 586 | 0.97 | 19.678 |
| 9 | 1,179.52 | 18.411 | 315 | 0.98 | 17.076 |
| 10 | 919.42 | 24.013 | 306 | 0.99 | 17.437 |
| 11 | 2,734.85 | 15.617 | 1,577 | 0.90 | 30.717 |
| 12 | 2,374.52 | 6.214 | 180 | 0.97 | 11.461 |
| 13 | 2,631.95 | 8.781 | 189 | 0.98 | 18.092 |
| 14 | 2,327.93 | 18.130 | 173 | 0.99 | 33.442 |
| 15 | 1,697.54 | 16.044 | 166 | 0.99 | 21.563 |
| 16 | 2,205.89 | 12.689 | 227 | 0.98 | 21.992 |
| 17 | 1,897.03 | 10.908 | 224 | 0.98 | 16.213 |
| 18 | 1,696.83 | 14.925 | 162 | 0.99 | 20.040 |
| 19 | 2,691.23 | 18.950 | 241 | 0.99 | 40.279 |
| 20 | 2,686.30 | 16.183 | 216 | 0.99 | 34.315 |
| 21 | 2,228.38 | 15.016 | 229 | 0.98 | 26.361 |
| 22 | 2,615.00 | 15.567 | 214 | 0.99 | 32.117 |

The covered lagoon system demonstrated stable anaerobic performance with an average COD removal efficiency of 97.9%, indicating effective degradation of organic pollutants and a well-acclimated microbial community suitable for assessing methane emission factors (Hasanudin *et al.*, 2023; Paredes *et al.*, 2019). Seasonal dynamics strongly influence wastewater characteristics in Indonesia's monsoon climate, where increased rainfall during the wet season (November–March) enhances runoff and plant washing activities, leading to influent dilution and lower COD concentrations, as similarly reported for tropical food-industry lagoons in Thailand and Vietnam (Kamahara *et al.*, 2010; Olal, 2021). Despite this dilution, organic loading rates may remain high because tapioca production typically peaks during the rainy period, increasing wastewater flow into the digester.

In contrast, the dry season (June–September) concentrates organic matter, resulting in higher influent strength and increased substrate availability for methanogenesis. Konaté *et al.* (2013) similarly observed higher biogas production during warm dry periods due to elevated organic loading, whereas rainy-season dilution reduced organic strength. These seasonal shifts therefore play a critical role in regulating organic loading patterns and biogas productivity throughout the monitoring period.

3.2. Total Biogas Production and Methane Composition

Biogas production from the anaerobic wastewater treatment system was continuously monitored over a 22-month period to evaluate methane formation stability under tropical operating conditions. Daily biogas output varied considerably, ranging from 5,633.80 to 26,783.74 m³/day, with an average of 17,188.6 m³/day. On a monthly basis, biogas production fluctuated between 169,014 and 830,296 Nm³, reflecting substantial temporal variability driven by changes in organic loading and hydraulic conditions. Methane concentrations ranged from 56.95% to 66.32%, with an overall mean value of 61.9%, while methane emissions varied between 5,070 and 15,092 kg CH₄/day, averaging approximately 10,700 kg CH₄/day.

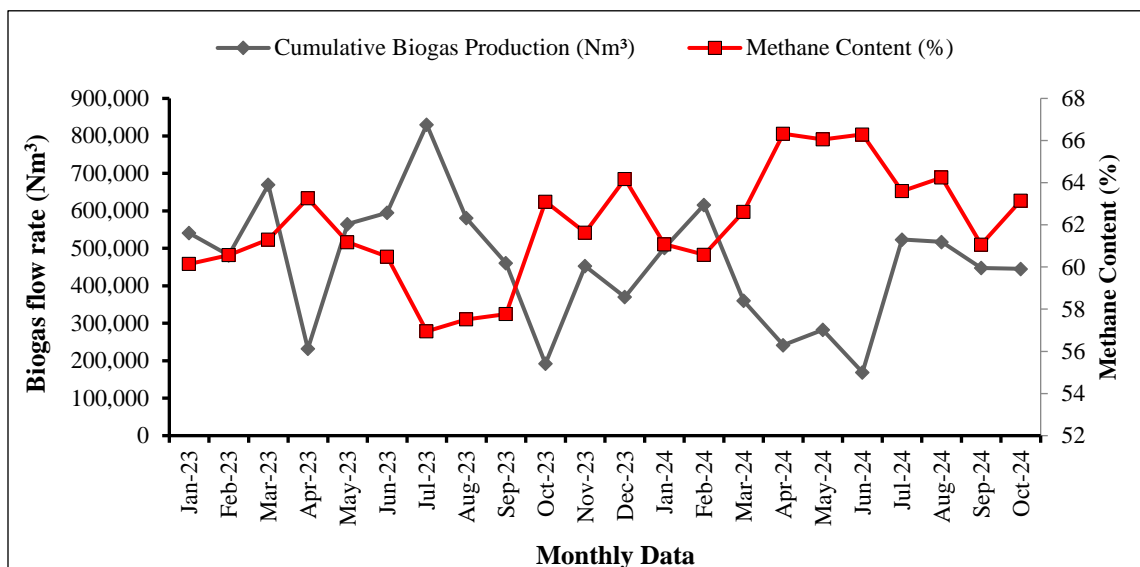


Figure 2. Monthly biogas production and methane content from the covered anaerobic lagoon

Seasonal trends in biogas production closely followed climatic patterns. Peak biogas volumes were generally observed during dry periods, such as July 2023 (830,296 Nm³) and August 2023 (580,813 Nm³), when minimal rainfall concentrated the wastewater and increased substrate availability for methanogenesis. In contrast, markedly lower volumes were recorded during wet-season months, including April 2023 (231,973 Nm³) and October 2023 (192,189 Nm³), when rainfall-induced dilution reduced influent COD and imposed greater hydraulic loading on the lagoon. The sharp decline observed in April 2023 corresponds to the onset of the rainy season, during which increased wastewater flow from runoff and intensified plant washing activities diluted organic strength and limited total biogas

generation despite stable anaerobic conditions. These observations are consistent with [Kamahara *et al.* \(2010\)](#), who reported reduced biogas yields in tropical anaerobic lagoons during high-rainfall periods due to diminished organic loading and lower methane recovery efficiency.

Methane concentration showed a clear inverse relationship with biogas volume, with higher CH₄ fractions during months of lower biogas output, such as October 2023 (63%), December 2023 (64%), and April–June 2024 (66%), and lower methane contents during peak production months such as July 2023 (57%). Based on cumulative biogas production, the corresponding potential methane generation ranged from approximately 1.1×10⁵ to 4.7×10⁵ Nm³ CH₄ per month, with the highest methane generation recorded in July 2023 (4.73×10⁵ Nm³ CH₄/month) and the lowest in June 2024 (1.12×10⁵ Nm³ CH₄/month). The elevated methane content observed during April–June 2024, despite reduced cumulative biogas production, reflects conditions of lower hydraulic loading and improved substrate conversion efficiency during the dry season, resulting in biogas with higher methane purity but lower total volume. Conversely, periods of high organic throughput may promote acidogenesis and increased CO₂ formation, temporarily reducing methane proportion due to substrate-overloading effects ([Yacob *et al.*, 2006](#)). Similar trends have been reported in large-scale agro-industrial lagoon systems operating under high organic loading conditions, where rapid VFA accumulation was shown to depress methane purity when methanogenic activity became rate-limiting ([Maurus *et al.*, 2023](#)). Although VFA was not directly measured in this study, the observed reduction in methane fraction during peak loading periods suggests a comparable process may have occurred.

Overall, these results demonstrate that both biogas production and methane composition are strongly regulated by seasonal variability in rainfall and temperature, which influence wastewater dilution, organic loading rates, and microbial activity within covered anaerobic lagoon systems ([Kamahara *et al.*, 2010](#)). The apparent extreme values observed in April 2023, July 2023, and April–June 2024 therefore reflect realistic operational and climatic dynamics rather than data anomalies. Consequently, stabilizing influent characteristics and minimizing hydraulic dilution during the rainy season are critical strategies for maintaining methane yield and maximizing energy recovery from tapioca wastewater treatment systems ([Hasanudin *et al.*, 2023](#)).

3.3. Relationship of Organic Loading, COD Removal, and Biogas Production

Monthly monitoring results show a strong linear relationship between total organic loading and total COD removal, indicating that increased substrate input was consistently accompanied by higher degradation performance in the covered anaerobic lagoon. As illustrated in Figure 3, COD removal rose steadily from 344,499 kg at a monthly OLR of 4.18 kg/m³ to more than 1.32 million kg at 16.39 kg/m³ monthly OLR, reflecting stable microbial activity and the absence of overloading throughout the study period. This pattern is consistent with typical CAL performance, where COD removal remains closely aligned with organic loading as long as the system operates below its biological capacity ([Zainuddin *et al.*, 2021](#)).

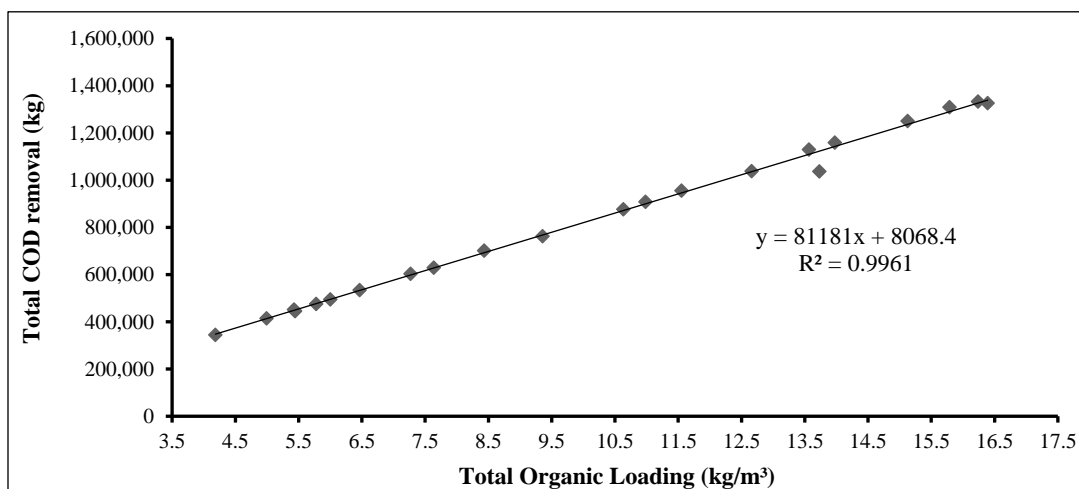


Figure 3. Relationship between total organic loading and COD removal

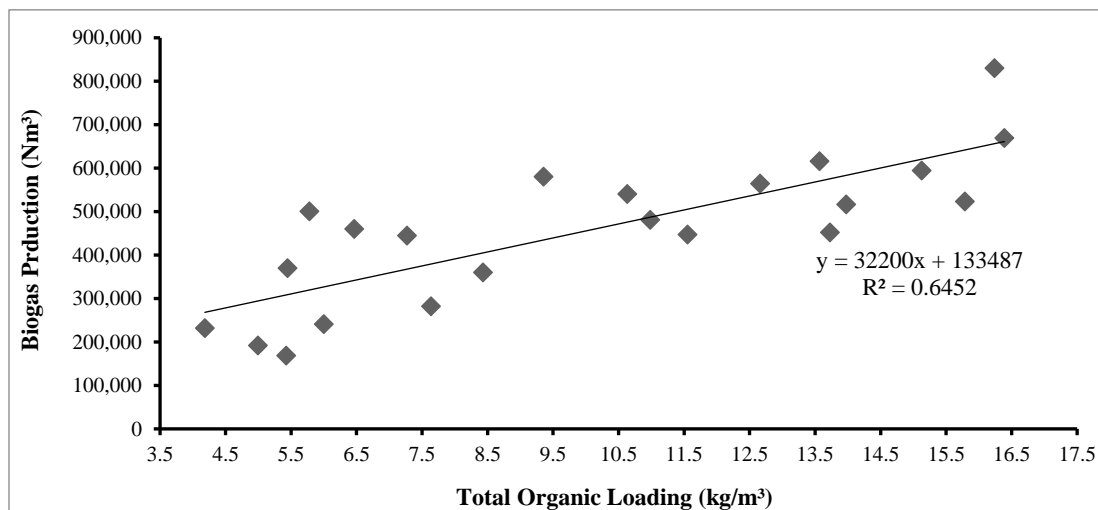


Figure 4. Relationship between total organic loading and biogas production

In contrast, the relationship between OLR and cumulative biogas production displayed a more dispersed distribution (Figure 4). Although higher OLR generally enhanced biogas output such as 830,296 Nm³ at monthly OLR 16.24 kg/m³ and 616,053 Nm³ at monthly OLR 13.57 kg/m³, several months with comparable loading produced substantially lower volumes, including 452,655–516,929 Nm³ at 13.73–13.97 kg/m³ monthly OLR. This variability indicates that biogas production is governed not only by organic loading but also by dynamic operational and environmental conditions that influence methanogenesis.

Three key factors contribute to this weaker correlation. First, seasonal dilution during high-rainfall months reduces influent COD concentration and alters substrate biodegradability, lowering methane conversion efficiency even when total loading remains high (Kamahara *et al.*, 2010). Second, fluctuations in hydraulic retention time (HRT) change the effective contact period between microbes and substrate; reduced HRT during wet months accelerates lagoon flow, limiting methanogenic conversion and increasing the fraction of partially degraded intermediates lost in the effluent (Chemicharo, 2007). Third, hydraulic short-circuiting can create uneven flow pathways, allowing portions of the wastewater to bypass active digestion zones, thereby diminishing methane yield (Ruto *et al.*, 2025).

Collectively, these factors explain the contrasting trends COD removal remained strongly correlated with OLR because it reflects total degradation whereas methane production depends specifically on methanogenic stability, substrate biodegradability, and adequate HRT. Biogas generation is therefore inherently more sensitive to environmental and hydraulic fluctuations than overall COD removal.

3.4. Methane Emission Factor and Greenhouse Gas Implications

The relationship between total COD removal and cumulative methane emissions exhibited a clear linear pattern, confirming that methane generation in the covered anaerobic lagoon was primarily driven by the extent of organic matter degradation. As shown in Figure 5, monthly COD removal ranged from 344,499 to 1,332,028 kg, while methane emissions varied from 57,012 to 334,048 kg. Linear regression indicated that CH₄ emissions were related to COD removal according to the equation.

$$\text{CH}_4 = 0.2302 \times \text{COD removed} \quad (2)$$

with $R^2 = 0.6034$, indicating that roughly 60% of methane variability was explained by COD removal. The slope represents the site-specific methane emission factor (B_0 site = 0.2302 kg CH₄/kg COD removed), equivalent to 0.321 m³ CH₄/kg COD removed under standard conditions. The standard error of ±0.021 kg CH₄/kg COD produced a 95% confidence interval of 0.19–0.27 kg CH₄/kg COD removed.

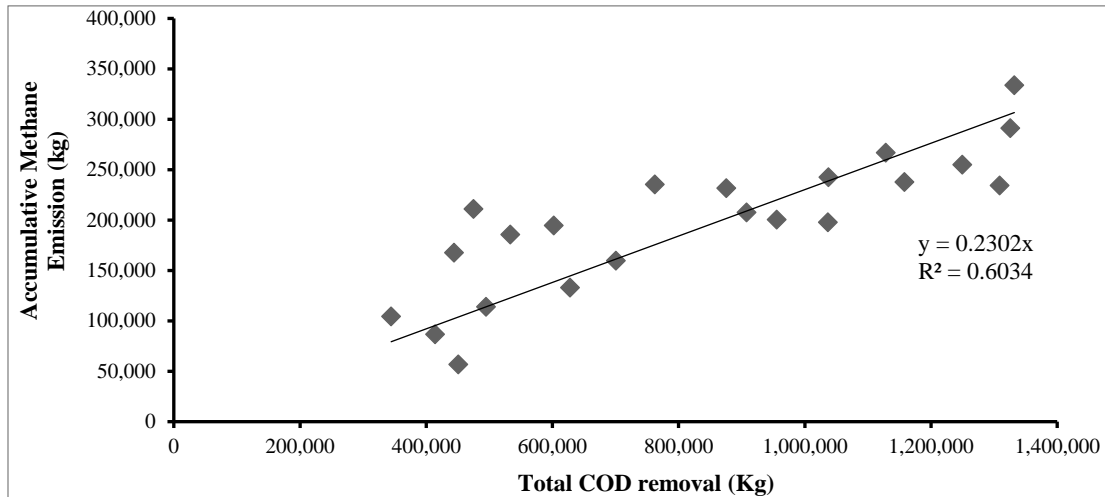


Figure 5. Relationship between total COD removal and cumulative methane emissions in the covered anaerobic lagoon system

This B_0 value aligns with emission factors reported for tropical covered anaerobic lagoons, including 0.20–0.30 kg CH_4/kg COD removed in Vietnam (Gustafson, 2015), 0.21–0.34 kg CH_4/kg COD removed in Thailand’s tapioca industry (Racho & Pongampornnara, 2020), and 0.18–0.29 kg CH_4/kg COD removed for cassava wastewater in Malaysia (Kamahara *et al.*, 2010), while remaining slightly below the IPCC default of 0.25 kg CH_4/kg COD for food-industry wastewater (IPCC, 2006).

The slightly lower B_0 observed in this study is likely influenced by operational and environmental constraints typical of tropical lagoon systems, including rainfall-driven hydraulic dilution that reduces influent COD (Kamahara *et al.*, 2010); partial biodegradation of fibrous cassava solids that are resistant to anaerobic breakdown (Fogaça *et al.*, 2014); transient methanogenic stress during fluctuating loads when acidogenesis exceeds methane formation (Yacob *et al.*, 2006); and hydraulic short-circuiting that limits effective retention time for complete methanogenesis (Chernicharo, 2007). Combined, these factors reduce methane conversion per unit COD removed, particularly during wet-season operation.

Monthly patterns further reinforce these relationships. Months with the highest COD removal, namely 1,332,028 kg and 1,302,083 kg, also exhibited elevated methane emissions of 291,374 kg and 234,586 kg. Conversely, methane output declined sharply to 57,012 kg when COD removal dropped to 450,906 kg during periods of heavy rainfall and hydraulic dilution. This seasonal sensitivity is consistent with findings from tropical ACLs, where monsoon conditions reduce CH_4 yield due to lower organic strength and stressed anaerobic performance (Kamahara *et al.*, 2010).

Converting methane emissions to CO_2 -equivalent using $\text{GWP}_{100} = 28$ (IPCC, 2014) results in a climate impact of 1,596–9,353 $\text{tCO}_2\text{-eq/month}$, underscoring the substantial warming potential of untreated or uncaptured methane from tapioca wastewater. Despite pronounced seasonal variability, the system maintained high organic removal efficiencies, supported by an acclimated methanogenic community capable of stable conversion even under diluted influent conditions (Hasanudin *et al.*, 2023).

The site-specific B_0 identified in this study was lower than the IPCC default, suggesting that applying default emission factors may overestimate methane emissions from Indonesia’s tapioca sector. This highlights the need for location-specific factors to enhance the accuracy of national GHG inventories and MRV systems. The empirically derived methane yield also demonstrates considerable renewable-energy potential: with an average CH_4 output of 10,700 kg/day, the system could theoretically generate more than 530 GJ/day, providing a significant opportunity for fossil-fuel displacement if biogas recovery and utilization were fully optimized. Improvements in HRT control during wet-season dilution could further increase methane capture and reduce fugitive losses (Paredes *et al.*, 2019).

Overall, the combined assessment of methane emission patterns, seasonal operating dynamics, and the derived emission factor demonstrates the critical importance of site-specific GHG accounting. These findings strengthen the

scientific basis for improving national inventory precision, guiding operational decision-making, and informing future mitigation strategies in Indonesia's tapioca processing industry.

4. CONCLUSIONS

This study empirically determined the methane-producing capacity (B_0) of a covered anaerobic lagoon treating tapioca wastewater based on 22 months of full-scale monitoring under tropical conditions. A strong linear relationship between cumulative methane production and COD removal produced a site-specific emission factor of 0.2302 kg CH₄/kg COD removed, which is slightly lower than the IPCC default value, indicating that default factors may overestimate methane emissions from real industrial systems. The lower B_0 is attributed to seasonal dilution and variability in organic loading, although the system consistently achieved high COD removal efficiencies (90–99%). Overall, these findings highlight the importance of adopting site-specific emission factors to improve the accuracy of national greenhouse gas inventories and reinforce the mitigation and energy-recovery potential of covered anaerobic lagoons in Indonesia's tapioca industry.

AUTHOR CONTRIBUTION STATEMENT

| Author | C | M | So | Va | Fo | I | R | D | O | E | Vi | Su | P | Fu |
|--------|---|---|----|----|----|---|---|---|---|---|----|----|---|----|
| EMP | ✓ | ✓ | ✓ | | ✓ | ✓ | ✓ | | ✓ | ✓ | | | ✓ | ✓ |
| DAI | ✓ | ✓ | | | | | | ✓ | | | ✓ | ✓ | | |
| RS | ✓ | ✓ | | | | | | | | | | ✓ | | |
| AH | | | | ✓ | | | | | | ✓ | | | | |
| SB | | | | ✓ | | | | | | ✓ | | | | |
| UH | ✓ | ✓ | | | | | ✓ | ✓ | | ✓ | | ✓ | ✓ | ✓ |

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|----------------------|---------------------|-------------------------------|---------------------------|
| C: Conceptualization | Fo: Formal Analysis | O: Writing - Original Draft | Fu: Funding Acquisition |
| M: Methodology | I: Investigation | E: Writing - Review & Editing | P: Project Administration |
| So: Software | D: Data Curation | Vi: Visualization | |
| Va: Validation | R: Resources | Su: Supervision | |

REFERENCES

- Achi, C.G., Hassanein, A., & Lansing, S. (2020). Enhanced biogas production of cassava wastewater using zeolite and biochar additives and manure co-digestion. *Energies*, *13*(2), 491. <https://doi.org/10.3390/en13020491>
- BMKG. (n.d.). *Data Online – Direktorat Data dan Komputasi BMKG*. <https://dataonline.bmkg.go.id/>
- Cecconet, D., Callegari, A., & Capodaglio, A.G. (2022). UASB performance and perspectives in urban wastewater treatment at sub-mesophilic operating temperature. *Water*, *14*(1), 115. <https://doi.org/10.3390/w14010115>
- Chernicharo, C.A.d.L. (2007). *Anaerobic Reactors* (Vol. 6). IWA Publishing. <https://doi.org/10.2166/9781780402116>
- Doorn, M.R.J., Strait, R.P., Barnard, W.R., & Eklund, B. (1997). *Estimates of global greenhouse gas emissions from industrial and domestic wastewater treatment* (EPA/600/R-97/091). United States Environmental Protection Agency.
- Dou, G., Wang, X., Zhao, B., Yuan, X., Pan, C., Tran, T., Zellweger, H., Zhu, K., Guo, Y., Wu, H., Yin, J., & Bai, Y. (2021). The transformation and outcome of traditional cassava starch processing in Guangxi, China. *Environmental Technology*, *42*(21), 3278–3287. <https://doi.org/10.1080/09593330.2020.1725647>
- Eklund, B., & LaCrosse, J. (1998). *Project summary: Field measurement of greenhouse gas emission rates and development of emission factors for wastewater treatment* (EPA/600/SR-97/094). United States Environmental Protection Agency.
- Elisabeth, D.A.A., Utomo, J.S., Byju, G., & Ginting, E. (2022). Cassava flour production by small scale processors, its quality and economic feasibility. *Food Science and Technology*, *42*, e41522. <https://doi.org/10.1590/fst.41522>
- Fogaça, F.H., Sant'Ana, L.S., Lara, J.A.F., Mai, A.C.G., & Carneiro, D.J. (2015). Restructured products from tilapia industry byproducts: The effects of tapioca starch and washing cycles. *Food and Bioproducts Processing*, *94*, 482–488. <https://doi.org/10.1016/j.fbp.2014.07.003>
- Gustafsson, A. (2015). *Wastewater to Renewable Energy at a Tapioca Factory in Vietnam*. [Master's Thesis], Lund University, Sweden.

- Haryanto, A., Marotin, F., Triyono, S., & Hasanudin, U. (2017). Developing a family-size biogas-fueled electricity generating system. *International Journal of Renewable Energy Development*, *6*(2), 111–118. <https://doi.org/10.14710/ijred.6.2.111-118>
- Hasanudin, U., Safira, N.D., Nurainy, F., Utomo, T.P., & Haryanto, A. (2023). Improving biogas production in tapioca industry by using onggok as co-substrate. *International Journal of Renewable Energy Research*, *13*(2), 741–749.
- IPCC (Intergovernmental Panel on Climate Change). (2006). *2006 IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies.
- Kamahara, H., Hasanudin, U., Atsuta, Y., Widiyanto, A., Tachibana, R., Goto, N., Daimon, H., & Fujie, K. (2010). Methane emission from anaerobic pond of tapioca starch extraction wastewater in Indonesia. *Journal of Ecotechnology Research*, *15*(2), 79–83. <https://doi.org/10.11190/jer.15.79>
- Konaté, Y., Maiga, A.H., Casellas, C., & Picot, B. (2013). Biogas production from an anaerobic pond treating domestic wastewater in Burkina Faso. *Desalination and Water Treatment*, *51*(10–12), 2445–2452. <https://doi.org/10.1080/19443994.2012.747642>
- Marbun, M., Despa, D., Septiana, T., & Martinus, M. (2024). Effectiveness analysis of biogas power plant at PT. Gree Energy Hamparan. *Proceedings of the 1st International Conference on Industry Science Technology and Sustainability (IConISTS 2023) (Advances in Engineering Research)*. https://doi.org/10.2991/978-94-6463-475-4_31
- Maurus, K., Kremmeter, N., Ahmed, S., & Kazda, M. (2023). High-resolution monitoring of VFA dynamics reveals process failure and exponential decrease of biogas production. *Biomass Conversion and Biorefinery*, *13*, 10653–10663. <https://doi.org/10.1007/s13399-021-02043-2>
- Nuraeni, R., & Ashuri, A. (2018). Nilai faktor emisi spesifik air limbah pada instalasi pengolahan air limbah (IPAL) komunal. *Widyariset*, *4*(1), 37–48.
- Olal, F.O. (2021). Effects of seasonal variation on performance of conventional wastewater treatment system. *Journal of Environment and Earth Science*, *11*(7). <https://doi.org/10.7176/JEES/11-7-06>
- Paredes, M.G., Güereca, L.P., Molina, L.T., & Noyola, A. (2019). Methane emissions from anaerobic sludge digesters in Mexico: On-site determination vs. IPCC Tier 1 method. *Science of the Total Environment*, *656*, 468–474. <https://doi.org/10.1016/j.scitotenv.2018.11.373>
- Racho, P., & Pongampornnara, A. (2020). Enhanced biogas production from modified tapioca starch wastewater. *Energy Reports*, *6*(Suppl. 1), 744–750. <https://doi.org/10.1016/j.egy.2019.09.058>
- Ruto, D.S., Jang, Z.S., Cornejo, P.K., Leverenz, H.L., & Orner, K.D. (2025). Toward sustainable lagoon wastewater treatment: A review of nutrient management technologies and their suitability for small communities. *ACS ES&T Water*, *5*(11), 6200–6216. <https://doi.org/10.1021/acsestwater.5c00757>
- Skytt, T., Nielsen, S.N., & Jonsson, B.-G. (2020). Global warming potential and absolute global temperature change potential from carbon dioxide and methane fluxes as indicators of regional sustainability – A case study of Jämtland, Sweden. *Ecological Indicators*, *110*, 105831. <https://doi.org/10.1016/j.ecolind.2019.105831>
- Sriroth, K., Piyachomkwan, K., Wanlapatit, S., & Oates, C.G. (2000). Cassava starch technology: The Thai experience. *Starch - Stärke*, *52*(12), 439–449. [https://doi.org/10.1002/1521-379X\(200012\)52:12<439::AID-STAR439>3.0.CO;2-E](https://doi.org/10.1002/1521-379X(200012)52:12<439::AID-STAR439>3.0.CO;2-E)
- Yacob, S., Hassan, M.A., Shirai, Y., Wakisaka, M., & Subash, S. (2006). Baseline study of methane emission from anaerobic ponds of palm oil mill effluent treatment. *Science of The Total Environment*, *366*(1), 187–196. <https://doi.org/10.1016/j.scitotenv.2005.07.003>
- Zainuddin, N.I., Bilad, M.R., Marbelia, L., Budhijanto, W., Arahman, N., Fahrina, A., Shamsuddin, N., Zaki, Z.I., El-Bahy, Z.M., Nandiyanto, A.B.D., & Gunawan, P. (2021). Sequencing batch integrated fixed-film activated sludge membrane process for treatment of tapioca processing wastewater. *Membranes*, *11*(11), 875. <https://doi.org/10.3390/membranes11110875>