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Socio-technical Drivers of Greenhouse Gas Emissions From on-site Sanitation Systems in Tropical Urban Communities

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Abstract

On-site sanitation systems (OSS), particularly septic tanks, are still widely used in tropical urban settlements where centralised sewage treatment infrastructure is limited. Although these systems improve access to sanitation, their contribution to greenhouse gas (GHG) emissions is still underrepresented in the emissions inventory, especially under real household conditions. This study investigated the socio-technical factors affecting CO_2 and CH_4 emissions from individual septic tanks in East Pontianak District, Indonesia, using the modified IAEA closed-chamber method. Gas samples were collected from 15 household septic tanks at 5, 10, 15, and 20 minutes, and analysed by gas chromatography. Emission variability was examined across household income levels and household size using descriptive statistics, Spearman correlations, and multiple linear regression. The results showed significant spatial variability, with average CO_2 concentrations ranging from 609 to 3176 ppm and CH_4 concentrations ranging from 19.18 to 3452.48 ppm. Income levels show a strong, significant relationship with CO_2 concentration, while population size is consistently associated with all emission indicators. Regression analysis showed that income levels and population size explained 88.9% of the variability in CO_2 concentration, with both predictors showing significant positive effects. For CH_4, the concentration model was significant, but only the number of inhabitants was a significant predictor, suggesting that methane formation was influenced more by organic loads, anaerobic conditions, and local system characteristics than by income. The flux model is weaker, showing greater sensitivity to transient microfactors in the environment and operations. These findings highlight that OSS emissions are not merely technical outcomes but also socio-technical processes influenced by household behaviour, infrastructure performance, and environmental conditions. This study provides preliminary empirical evidence to improve local emission factors and develop more targeted mitigation strategies in the management of urban sanitation sensitive to climate change.

1. Introduction

Urban sanitation systems play an important role in environmental quality, public health, and climate sustainability. In many developing cities, limited centralised waste treatment has led people to prefer on-site sanitation systems (OSS), such as septic tanks, as the primary option. Although OSS improves sanitation access, its contribution to greenhouse gas (GHG) emissions, especially CO_2 and CH_4, is still poorly understood, especially in tropical urban environments with diverse social, economic, and infrastructural conditions.

Environmental micro-conditions, such as ventilation, septic tank size, and sludge accumulation, as well as socio-economic factors, such as income levels and consumption patterns, affect the performance and emissions generated by self-sanitation systems. Previous research has generally relied on laboratory simulations or generalised emission factors, with little field data measuring emissions under real operational conditions. Therefore, understanding how these factors interact in influencing GHG emissions in self-sustaining sanitation systems in the tropics is critical.

This study aims to investigate the relationships between CO_2 and CH_4 emissions and socio-economic factors in household environments using a self-sanitation system in the city of Pontianak, Indonesia. Using the modified IAEA closed-chamber method, this study collected field data on GHG concentrations and fluxes from 15 sample locations. Correlation analysis and multiple linear regression were used to evaluate the influence of socio-technical factors on emissions. The findings of this study are expected to provide a scientific basis for developing a more targeted GHG mitigation strategy, which integrates socio-economic characteristics, infrastructure performance, and environmental conditions in urban sanitation systems.

2. Methods

The study was conducted in East Pontianak District, Pontianak City, Indonesia, an urban residential area characterised by the prevalence of individual septic tank systems. (Fig. 1). The district encompasses a wide range of socio-economic situations, including low-income (LI), middle-income (MI), and high-income (HI) families. The city has a humid tropical climate, characterised by consistent year-round temperatures and substantial annual rainfall. These climatic conditions facilitate anaerobic processes in sewage systems, potentially increasing greenhouse gas production. On-site sanitation systems, especially pit latrine septic tanks, are widely used in residential areas due to inadequate centralised sewage disposal infrastructure. The sanitation facilities inspected include a pit toilet and a septic tank, typically used in urban residential areas. Non-sewer sanitation systems (NSSS) are recognised as a substantial source of greenhouse gases (GHGs), mainly due to biological activity in containment systems (Poudel et al., 2024). The discharge of sewage into the environment and the application of decentralised sanitation technologies, including septic tanks and pit latrines, contribute to greenhouse gas (GHG) emissions (Shaw et al., 2021).

The closed chamber model used in accordance with IAEA guidelines, modified to accommodate the physical characteristics of the latrine septic tank at the study site and made of gas-tight material having dimensions of 50 cm long, 50 cm wide, and 30 cm high equipped with a gas sampling port (septum vial), mercury thermometer, 12 volt fan and battery, and modified at the base of the closed chamber frame with the addition of a rubber gasket as an anchor (modification-1), placing a load of 5 kg on the upper side of the closed chamber during collecting samples to apply pressure to the rubber gasket to prevent gas release (modification-2) (Fig. 2). The non-flow-through method is the most widely used for identifying greenhouse gases in the field, with a chronology of the main sampling steps of installing the retainer, placing the enclosed space, recording the temperature, drawing the gas sample, and injecting the sample into a bottle, where the anchor and the enclosed space can be sealed with a rubber gasket if needed (Mazengo et al., 2024). This adjustment is intended to improve the reliability of measurements under the field setting of urban OSS characteristics.

The study focused on CH_4 and CO_2 emissions, although the latter is categorised as biogenic CO_2. Concentration levels are monitored for comparative purposes, given that the findings of existing studies are limited, to evaluate the significance of these emissions, which should not be overlooked. Biogenic

CO_2 is produced during microbial respiration from the degradation of organic matter and is often considered carbon-neutral because it arises from short-term biological cycles (Anh & Le Luu, 2025), and measuring CH_4 emissions from septic tanks will advance monitoring of greenhouse gas emissions in the wastewater sector (Moonkawin et al., 2023).

The samples were collected from 15 different septic tanks (SP-1 to SP-15) taken at 5, 10, 15, and 20 minutes using a 10 mL syringe from the closed chamber positioned on the top septic tank investigation hole. The inside chamber temperature was measured with a mercury thermometer at each sampling, and the number of domestic users was documented at each sampling location. The samples were then transferred into 10 mL vacuum vial bottles, and the concentrations of CO_2 gas and CH_4 were analysed using gas chromatography. The quality control process includes leak assessment, over-measurement correction, and the elimination of nonlinear concentration patterns to ensure data reliability.

The emission flux (E) was calculated based on the temporal change in CO_2 and CH_4 concentration within the closed chamber using the modified standard flux calculation approach, adjusted for closed chamber volume, surface area, temperature, area per person standard, GHG concentration, and molecular weight (modification-3):

E_{person} = $\frac{d_c}{d_t}$ x $\frac{V_{ch}}{A_{ch}}$ x $\frac{MW}{MV}$ x $\frac{273,2}{273,2+T}$ x A_p... (1) (Arifin, 2023). Where E_{person} is flux per person (mg/person·hour), $\frac{d_C}{d_t}$ is the rate of change in GHGs concentration (ppm), V_{ch} is the closed chamber volume (m^3), A_{ch} is septic tank investigation hole area (m^2), MW is molecular weight of GHGs compounds (g), MV is constant molecular volume (22,41 L), A_p is area per person (3,0) (m^2/person)(SNI 03-173392004, Standar Nasional, 2004), and T is the average temperature inside the closed chamber (°C).

In addition, to increase the reliability of the analysis, descriptive statistics were applied to summarise the emission characteristics across the observation site, and Spearman correlation was used as a robustness check to show that relationships in this dataset behave consistently under non-parametric assumptions. The strength of the correlation is interpreted using standard criteria:> 0.7 indicates a strong correlation, 0.4–0.7 a moderate one, and < 0.4 a weak one. Multiple linear regression analyses were conducted to estimate the synergistic effects of socio-economic and environmental variables on greenhouse gas emissions. The dependent variables include CO_2 and CH_4 concentrations and fluxes; the independent variables include income level and the number of users. Income level is encoded as ordinal variables: low income (LI) = 1, middle income (MI) = 2, and high income (HI) = 3, while the number of users is included as a numerical variable. Model performance was assessed using the coefficient of determination (R^2) and statistical significance at $\alpha = 0.05$.
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3. Results and Discussions

3.1. Results

3.1.1 Spatial Variability and Driving Factors of CO_2 Emissions Across Household Septic Tanks

The CO_2 concentration showed significant variability between the sample locations. The average value varies from 609 ppm (SP-1) to 3176 ppm (SP-4), indicating a persistent source of emissions. Low-concentration sites (SP-1 and SP-13) exhibit relatively more open environmental conditions and negligible anthropogenic activity.

Septic tanks in HI households often show high CO_2 levels, allegedly due to higher consumption, which increases the organic load in wastewater. An increase in CO_2 concentration over time indicates a continuous buildup of gases within the closed chamber. CO_2 concentrations in most locations changed slightly, suggesting that the source of emissions was persistent rather than temporary. Locations with high emission levels showed consistently high values during the observation period.

Households with more occupants (6–7 individuals) have higher emission potential than households with fewer (5 individuals), resulting in higher average CO_2 concentrations, especially in SP-2, SP-3, SP-4, SP-9, and SP-11. Nonetheless, this relationship is not entirely linear, as some locations with a smaller number of users (5 users) show high emissions, as shown in SP-14. It shows that the number of users is a significant factor, but not the only determinant of CO_2 emissions.

High-income (HI) homes have a higher average concentration than low-income (LI) households, demonstrating socio-economic impacts on wastewater production and septic tank performance. Households that showed the most significant average CO_2 values, especially in SP-4, SP-9, and SP-11. Middle-income families (MI) occupy a middle position characterised by considerable variability. Low-income (LI) families often have reduced CO_2 concentrations, while there are outliers, such as SP-14. Certain locations, such as SP-12 and SP-13, have low CO_2 concentrations and are consistently stable over time, with little natural emissions or strong ventilation.

3.1.2. Spatial Patterns and Driving Factors of CH_4 Emissions

The CH_4 emission concentration showed significant geographic variability among the sample points (SP), albeit with a higher amplitude of variation than CO_2. The average concentration of CH_4 varies from 19.18 ppm (SP-12) to 3452.48 ppm (SP-4). The locations with the highest levels of emissions were identified as SP-4, SP-3, SP-9, SP-11, and SP-14, each with average concentrations exceeding 900 ppm, with SP-4 reaching nearly 3500 ppm, indicating the persistent prevalence of anaerobic processes. SP-12 and SP-13 consistently produce minimum CH_4 readings (< 30 ppm), indicating the absence of a CH_4-emitting source or the presence of environmental factors that inhibit gas buildup. The high concentration of emissions is estimated to result from a progressive buildup, indicating a persistent source rather than a transient

event. It indicates ongoing CH_4 emissions, potentially related to household activities or anaerobic biological processes.

Locations with a larger number of users (7 users) have high average CH_4 concentrations, as shown in SP-2, SP-3, SP-4, and SP-9. However, these links are not entirely proportional, as some locations with five users also show high emissions (e.g., SP-14). The data show that user numbers affect CH_4 emissions, with this effect mediated by activity patterns and local environmental factors.

High-income (HI) households account for the greatest CH_4 emissions, especially in SP-4, SP-9, and SP-11. Middle-income (MI) families showed moderate CH_4 values with considerable variability. Low-income (LI) families typically exhibit lower emissions; however, local factors, such as SP-14, can lead to high emissions even when they are included in the LI category.

3.1.3. Spatial Variability of CO_2 and CH_4 Emissions and Their Socio-Environmental Determinants

CO_2 and CH_4 emissions exhibit highly variable geographic distributions across sample sites (SP). The highest levels of emissions were consistently found at some observation sites, indicating greenhouse gas hotspots in this area. Generally, CH_4 shows a more pronounced relative change than CO_2, especially in areas of significant household activity. It suggests that CH_4 emissions are more responsive to local factors, including sanitation systems, organic waste buildup, and microventilation.

The high-income (HI) group is the largest emitter of CO_2 and CH_4. This indicates that higher consumption patterns and better sanitation systems facilitate the formation of CO_2 and CH_4. In contrast, low-income (LI) populations often exhibit lower emissions, although exceptions to SP-14 indicate that environmental factors and infrastructure conditions have a greater impact than wealth. CO_2 more accurately reflects the magnitude of human activity and consumption, while CH_4 is more directly related to waste management and the state of the microenvironment.

Areas with higher user densities (6–7 users) show higher levels of CO_2 and CH_4. These connections are not linear, as some locations with low user numbers still produce substantial emissions. It suggests that user density plays a role as a triggering factor, but the effect is mediated by environmental behaviour, activity type, and infrastructure.

Table 1
CO_2 and CH_4 emissions concentration and fluxes at sampling Points (SP) 1–8

Variables	**Sampling Points**							
	SP-1	**SP-2**	**SP-3**	**SP-4**	**SP-5**	**SP-6**	**SP-7**	**SP-8**
Number of Users	5	7	7	7	5	5	6	5
Income Levels	LI	HI	MI	HI	LI	LI	MI	HI
CO_2 Concentrations Average (ppm)	609,82	2676,72	2463,52	3176,18	712,43	719,20	905,61	2243,52
CO_2 Fluxes (mg. person^{-1}. hour^{-1})	0,157	0,158	0,561	0,281	0,641	0,38	0,52	0,05
CH_4 Concentrations Average (ppm)	548,26	609,87	2463,52	3452,48	752,55	707,41	158,05	172,01
CH_4 Fluxes (mg. person^{-1}. hour^{-1})	0,100	0,051	0,182	0,230	0,035	0,03	0,01	0,04

(Arifin, 2023).

Table 2
CO_2 and CH_4 emissions concentration and fluxes at sampling Points (SP) 9–15

Variables	Sampling Points						
	SP-9	SP-10	SP-11	SP-12	SP-13	SP-14	SP-15
Number of Users	7	5	5	6	5	5	5
Income Levels	HI	MI	HI	LI	LI	MI	LI
CO_2 Concentrations Average (ppm)	2573,57	1803,17	2817,05	701,74	894,44	945,26	669,27
CO_2 Fluxes (mg. person^{-1}. hour^{-1})	0,07	0,28	0,641	0,377	0,519	0,052	0,065
CH_4 Concentrations Average (ppm)	1338,02	120,23	1308,64	19,18	25,04	945,26	670,01
CH_4 Fluxes (mg. person^{-1}. hour^{-1})	0,14	0,01	0,308	0,001	0,001	0,008	0,01

(Arifin, 2023).

3.1.4. Correlation Analysis Between Greenhouse Gas Emissions and Socio-economic Factors

The analysis was conducted to evaluate the relationship between socio-technical factors, i.e., household income levels and the number of users of sanitation facilities, with variations in CO_2 and CH_4 concentrations and flux from on-site sanitation systems. The results of the Spearman correlation showed that income level had a strong positive correlation with CO_2 concentration ($r = 0.923$; $p < 0.05$), as well as a significant moderate positive correlation with CO_2 flux ($r = 0.554$; $p < 0.05$) and CH_4 flux ($r = 0.589$; $p < 0.05$). However, the correlation between income level and CH_4 concentration was moderate and positive, but not significant at the 5% level ($r = 0.433$; $p > 0.05$). Meanwhile, the number of users showed a positive, significant correlation with all emission indicators: CO_2 concentration, CO_2 flux, CH_4 concentration, and CH_4 flux.

Table 3
Spearman correlation between independent variables and emission indicators

Prediktor	Emission variables	r	α result = 5%
Income levels	CO_2 Concentrations	0,923	✓Signif.
Income levels	Flux CO_2	0,554	✓Signif.
Income levels	CH_4 Concentrations	0,433	X
Income levels	CH_4 Fluxes	0,589	✓Signif.
Number of users	CO_2 Concentrations	0,663	✓Signif.
Number of users	CO_2 Fluxes	0,576	✓Signif.
Number of users	CH_4 Concentrations	0,593	✓Signif.
Number of users	CH_4 Fluxes	0,593	✓Signif.

The results of multiple linear regression showed that the CO_2 concentration model was statistically significant at the 5% level, with $F(2, 12) = 48.290$ and $p < 0.05$. The R^2 value of 0.889 indicates that income levels and the number of users can explain 88.9% of the variation in CO_2 concentration. The CO_2 flux model was also significant, with $F(2, 12) = 4.321$ and $p < 0.05$, although the R^2 was lower at 0.419. In the CO_2 flux model, the income level and the number of users have positive coefficients, but neither is significant at the 5% level.

Partially, income level had a positive and significant effect on CO_2 concentration ($B = 787.852$; $p < 0.05$), indicating that a one-unit increase in income was associated with a 787.852 ppm increase in CO_2 concentration after controlling for the number of users. The number of users also had a positive and significant effect on CO_2 concentration ($B = 330.672$; $p < 0.05$), indicating that each additional user was associated with an increase of 330.672 ppm in CO_2 concentration.

The CH_4 concentration model was significant with $F(2.12) = 5.881$ and $p < 0.05$, while the CH_4 flux model was not significant at the level of 5% ($p > 0.05$). The number of users was a positive and significant predictor of CH_4 concentration ($B = 718.463$; $p < 0.05$), whereas income level was not significant ($B = 32.071$; $p > 0.05$). In the CH_4 flux model, both income level and the number of users show a positive relationship, but neither is significant at the 5% level.

Income levels and the number of users positively and significantly influence CO_2 concentration. Income level is the most dominant predictor of CO_2 concentration. Regarding CO_2 flux, neither revenue level nor number of users showed a significant effect. Meanwhile, at the CH_4 concentration, only the number of users had a positive and significant effect, while the income level was insignificant.

Table 4
Multiple linear regression coefficient

Prediktor	Emission variables	B	ß	R^2	F	α result = 5%
Income levels	CO_2 Concentrations	787,852	0,725	0,889	48,290	✓Signif.
Number of users		330,672	0,315			
Income levels	CO_2 Fluxes	2,210	0,437	0,419	4,321	✓Signif.
Number of users		1,404	0,288			
Income levels	CH_4 Concentrations	32,071	0,030	0,411	5,881	✓Signif.
Number of users		718,463	0,686			
Income levels	CH_4 Fluxes	2,771	0.424	0,244	3,261	X
Number of users		1,499	0,237			

3.2. Discussions

3.2.1. CO_2 Emission Patterns and Socio-Economic Drivers in On-Site Sanitation Systems

Highly variable average CO_2 values increased steadily over the observation period, indicating a persistent source of emissions. Locations with low concentrations show more open environmental conditions and less bowel activity. Similar variability in CO_2 accumulation in confined sanitation systems has been reported in recent studies, where gas buildup is strongly influenced by organic loading and hydraulic use patterns (Wang, 2022). Sustained high values over time indicate that emissions result from ongoing decomposition. Greenhouse gases are produced by the breakdown of organic waste in blackwater, which contains high levels of organic compounds, nitrogen, and phosphorus, during the anaerobic treatment process typical of septic tanks. Greenhouse gas emissions can increase due to effects on soil, flora, and microorganisms (Li et al., 2024).

Increased CO_2 emissions at certain intervals indicate significant user activity, which in turn increases microbial activity in septic tanks by allowing organic compounds to enter the wastewater. Microbial transformation of carbon and nitrogen in blackwater can result in emissions of CO_2, CH_4, and N_2O (Truhlar et al., 2019). Blackwater comprises more than 30% of total wastewater and is characterised by high concentrations of ammonia, nitrogen compounds, and phosphorus. Blackwater from the water cabinet accounts for 30.4% of the total wastewater volume, contributing 93.0%, 81.7%, and 67.3% of the NH4+-N, TN, and TP loads, respectively (F. Cheng et al., 2021).

The results show that socio-economic factors, particularly income levels, have a greater influence on CO_2 emissions and use intensity. It is related to increased water consumption and organic burden on high-income households. The number of users contributes to increased CO_2 emissions from defecation;

however, user density alone cannot explain differences in emissions across regions. Affluent demographics exhibit higher CO_2 emissions, which can qualitatively correlate with increased consumption levels. This finding aligns with existing research showing that higher family income is associated with higher consumption, particularly in metropolitan areas.

Although low-income populations often exhibit lower emissions, the presence of high-emission locations suggests that additional contextual factors, such as spatial density and inadequate gas ventilation, also play a role, independent of income level. It underscores that an income-centric approach is insufficient without accounting for users' geographic attributes and behaviours. Blackwater consists of varying amounts of urine, faeces, wastewater, and cleaning agents (Shaw et al., 2021).

Assessing greenhouse gas emissions from OSS using the correct approach is crucial for gaining an accurate understanding of emissions patterns in a particular region or country. Accurate and timely GHG emissions inventories are necessary to track progress in climate change mitigation efforts (Hu et al., 2025).

3.2.2. CH_4 Emissions in Sanitation Systems: Socio-Economic and Operational Influences

Elevated CH_4 emissions at a specific location indicate conditions conducive to methane formation and storage, including household activities that generate organic waste, inadequate waste-disposal systems, and possible anaerobic processes in the microenvironment. Increased CH_4 emissions at specific sites indicate favourable environmental conditions for CH_4 production and accumulation, including high organic loads, inefficient waste management practices, and anaerobic decomposition in closed sanitation systems. Previous studies have shown that sanitation systems such as septic tanks and household wastewater infrastructure are significant sources of CH_4 emissions due to microbial degradation of organic matter under anaerobic conditions (Manga & Muoghalu, 2024).

The increased prevalence of emissions among high-income groups suggests that wealthier households produce more organic waste and exhibit higher consumption intensities, thereby contributing to methane formation through anaerobic decomposition (Mor et al., 2024). Additionally, sanitation systems such as septic tanks provide an anaerobic environment conducive to CH_4 formation (Manga & Muoghalu, 2024). Gaps in low-income groups are increasingly highlighting the importance of local factors, including population density and waste infrastructure, that significantly affect emission levels (Wei et al., 2026). The increase in the number of users also increases the potential for methane generation by increasing organic loading in wastewater; however, infrastructure characteristics and operational conditions—such as sludge accumulation and ventilation—remain important determinants of CH_4 emissions (Moonkawin et al., 2023).

These findings confirm that CH_4 emission control should focus on sanitation systems with high emission potential, particularly in septic tank installations affected by operational conditions, sludge accumulation, and wastewater treatment efficiency. On-site sanitation systems have been identified as a significant

source of greenhouse gas emissions, with emissions varying strongly in response to environmental and operational factors (Manga & Muoghalu, 2024). Suboptimal septic tank performance, such as long drain intervals and low organic matter processing efficiency, has been shown to significantly increase methane production and emissions (Moonkawin et al., 2023). Uncontrolled anaerobic biological processes in such systems can accelerate CH_4 formation due to limited electron acceptors and low waste degradation efficiency. Optimising operational conditions, such as controlling redox parameters and improving biodegradation, can suppress CH_4 formation and enhance overall wastewater treatment performance (Gao et al., 2024). Therefore, a mitigation approach that improves technical design, operational management, and biological process optimisation is key to sustainably reducing methane emissions from household sanitation systems.

3.2.3. Influence of Social and Technical Factors on Greenhouse Gas Emissions on Local Sanitation Systems

In general, the results of the study show that socio-technical factors are more strongly explained by the variation in gas concentration than the variation in gas flux. The CO_2 concentration model had the highest clear power, followed by CH_4 concentration and CO_2 flux, and CH_4 flux was simultaneously insignificant at 5%. This pattern indicates that the accumulation of gases in the on-site sanitation system is easier to understand in terms of variations in income levels and user numbers. At the same time, the actual emission flux into the atmosphere is estimated to be more influenced by technical and microenvironmental factors that have not been measured in this study, such as anaerobic conditions, faecal sludge lifespan, temperature, humidity, organic load, tank design, ventilation, and the frequency of septic tank suction.

The finding that income levels were positively and significantly related to CO_2 concentration suggests that socio-economic categories can serve as proxies for water use characteristics during sanitation activities, household consumption patterns, domestic wastewater volume, and the quality of sanitation facilities. This interpretation needs careful attention because income levels are not a direct biological cause of CO_2 formation, but rather a social variable that can be related to the intensity of domestic activities and the characteristics of the sanitation system. In a broader context, Manga & Muoghalu (2024) reported that local environmental conditions strongly influence emissions from on-site sanitation systems, underscoring the need for local data to improve emission estimates. (Johnson et al., 2022) also highlight that a general assumption-based inventory approach has not sufficiently captured the complexity of urban sanitation service chains that blend on-site and off-site sanitation systems. Therefore, the strong relationship between income and CO_2 concentration in this study can be positioned as early evidence that the socio-economic dimension needs to be considered in the development of a tropical urban sanitation emission model.

The number of users showed a more consistent relationship with income levels than did CO_2 and CH_4 concentrations. The number of users was positively and significantly correlated with all emission indicators, namely CO_2 concentration, CO_2 flux, CH_4 concentration, and CH_4 flux. Mechanically, more users will increase domestic wastewater discharge and the organic loads entering sanitation facilities,

thereby increasing the likelihood of gas formation through aerobic and anaerobic decomposition. These results are in line with S. Cheng et al. (2022), who reported that on-site sanitation systems are a global source of methane that cannot be ignored and that existing estimation methods still tend to underestimate their contribution. Poudel et al. (2024) also showed that environmental conditions and containment characteristics can amplify CH_4 formation, because biochemical processes in sanitary facilities are affected by humidity and anaerobic conditions. Thus, the number of users in this study can be understood as an indicator of organic load pressure in OSS.

In contrast to the gas concentration model, the flux model shows more complex results. The CO_2 flux model was simultaneously significant, but the revenue level and number of users were not significantly different. It suggests that both variables still contribute to CO_2 flux variation, but the strength of each predictor is not sufficiently stable when tested partially on a small sample. The CH_4 flux model was also not significant simultaneously, although the correlation showed a significant positive relationship between the number of users and CH_4 flux, as well as between income level and CH_4 flux.

This difference between regression and correlation results suggests that the relationships between variables are likely monotonous but not yet strong enough to form a stable linear predictive model. Jan Knappe et al. (2022) reported that GHG measurements from OSS exhibit highly significant and temporal variations, so the flux results are highly sensitive to measurement time, system configuration, and environmental conditions during sampling. (Manga & Muoghalu, 2024) also asserts that variations in local methods and environmental factors can lead to substantial differences in emission estimates in OSS.

From the perspective of the global emissions inventory, this study's results reinforce the importance of CH_4 as the primary focus of mitigation in OSS. The IPCC states that wastewater can be a source of CH_4 when treated or disposed of under anaerobic conditions, whereas CO_2 from wastewater is generally not included in total national emissions because it comes from biogenic carbon (Jong et al., 2026; Xinyue He, 2025). Therefore, although the CO_2 concentration in this study is statistically significant as an indicator of biological processes within the system, the implications of the national inventory are stronger for CH_4. This is all the more relevant because Manga & Muoghalu (2024) report that CH_4 estimates of OSS based on IPCC guidelines can be substantially lower than field-measured values, underscoring the need for the development of local emission factors based on empirical data. Johnson et al. (2022) also showed that emissions from urban sanitation chains can make a major contribution to urban emissions, especially when faecal sludge storage lasts for extended periods under anaerobic conditions, and the management system is not functioning optimally.

Based on these results, this study contributes to the literature by showing that simple socio-technical variables, namely income level and number of users, can help explain the variation in emissions from OSS systems in tropical urban environments. These findings do not imply that income and the number of users are the only determinants of emissions, but they can serve as initial variables to enrich household activity-based inventory models. For policy applications, facilities with a larger number of users need to be prioritised for monitoring, periodic suction, improvements in containment design, and control of

anaerobic conditions that trigger CH_4 formation. At the same time, differences in income levels need to be considered in intervention planning, as maintenance capacity, access to suction services, and sanitation technology choices can vary across socio-economic groups.

However, these results need to be interpreted as preliminary findings because the number of observations is relatively small (N = 15) and does not include important technical variables such as pH, temperature, BOD, COD, dissolved oxygen, oxidation-reduction potential, septic tank age, suction frequency, tank volume, and groundwater level conditions. Subsequent studies are recommended to use larger samples, longitudinal designs, and repeated measurements to capture temporal variations in gas flux. In addition, a hybrid approach combining field measurements, household activity data, and sanitation system technical parameters will improve the accuracy and relevance of the results for the preparation of local emission factors for on-site sanitation systems in the tropics.

3.2.4. Socio-Technical Dynamics of Sanitation Emissions: Beyond Economic Determinants

Results showed that although emissions from on-site sanitation installations are attributable to infrastructure design and/or technical performance, households' social and economic characteristics directly affect GHG emissions. Such differences in CO_2 and CH_4 are consistent with spatial variations across sample sites and indicate that sanitation infrastructure is part of a larger socioenvironmental system in which user activities, wastewater loading profiles, and maintenance activities interact dynamically. Elevated pollutant concentrations in households with high user intensity and socio-economic status strongly imply that sanitation-related factors are associated with consumption, water-use behaviour, and organic loading in septic tank systems. In this system, user behaviour, wastewater loading profiles, and maintenance practices interact dynamically, influencing gas production and release (Manga & Muoghalu, 2024; Moonkawin et al., 2026). In addition, higher concentrations of pollutants observed in households with greater user intensity and higher socio-economic status suggest that sanitation-related emissions are closely linked to consumption patterns, water-use behaviours, and levels of organic loading entering septic tank systems (Huynh et al., 2021).

Focusing on these considerations, we conclude that sanitation emissions are a behaviourally driven environmental process rather than a naturally occurring engineering phenomenon. Consistent trends have also been observed in decentralised wastewater systems, where lifestyle-induced wastewater production significantly affects microbial degradation and greenhouse gas production. The high prevalence of outlier emissions among low-income segments also underscores the importance of region-specific environmental and infrastructure factors. Microenvironments created by poor ventilation, inappropriately sized septic tanks, and irregular sludge disposal do not discriminate based on socio-economic status, thereby favouring anaerobic methane formation. The implication is that it is important to move beyond income-based environmental beliefs and, in such environments, consider integrated socio-technical assessment schemes available in sanitation emissions studies. Sanitation emissions from the entire sanitation service chain are influenced by waste storage, disposal practices, system conditions, and the environment (Johnson et al., 2022). The wide variability in emissions, including the

presence of outliers among low-income households, further points to the importance of region-specific environmental and infrastructure conditions over purely economic determinants (Manga & Muoghalu, 2024).

In particular, micro-environmental conditions such as inadequate ventilation, improper septic tank size, and irregular sludge disposal create a favourable anaerobic environment that promotes methane formation, regardless of socio-economic status (Huynh et al., 2021). These findings highlight the limitations of income-based assumptions for explaining sanitation emissions and underscore the need for an integrated socio-technical assessment framework to capture better the complex interactions that govern emissions dynamics in on-site sanitation systems (Trimmer et al., 2020). A socio-technical approach is needed to better understand and control emissions from local sanitation systems.

According to this study, a conceptual distinction between “accumulation-driven emissions” (represented by gas concentration) and “process driven emissions” (represented by flux) can be drawn. This distinction not only offers a richer understanding of emission dynamics in decentralised sanitation systems, but also lays the basis for further improvements in measurement approaches of this kind and in new emissions models.

4. Conclusions

The modified closed chamber generates reliable data, offering a novel approach to examining greenhouse gas emissions from on-site sanitation systems utilising individual pit latrines, thereby facilitating straightforward, accurate calculations of greenhouse gas emissions from the wastewater sector. This research effectively assessed GHG emissions from individual septic tanks in tropical urban areas using the modified closed-chamber technique. Emissions exhibited significant variability between homes, determined by user intensity and socio-economic characteristics. Although individual emissions are minimal, their aggregate impact at the district level is substantial. The proposed technique can be used across different urban regions to facilitate comprehensive, inclusive greenhouse gas inventories.

This study shows that greenhouse gas emissions from OSS in tropical urban contexts are highly heterogeneous and are associated with interacting socio-technical factors. There is a positive relationship among users, revenue, gas concentration, and flux, in which CH_4 concentration is the most consistent predictor of CH_4 flux, while CO_2 accounts for almost half of the variance but does not reach the 5% significance threshold.

From the IPCC and global inventory perspectives, CH_4 should be treated as a priority gas for climate-sensitive sanitation assessments. Measured CO_2 remains useful for understanding system processes, but biogenic CO_2 from wastewater is generally excluded from the total national inventory. In contrast, CH_4 from anaerobic sanitation conditions has high climatic relevance, and its conversion to CO_2 equivalents confirms that CH_4 dominates the climate signals of the observed system.

This study suggests a complex interplay of socio-economic, system-related, and environment-dependent driving forces on greenhouse gas emissions from on-site sanitation systems. It showed a strong correlation between CO_2 concentration and income level, and that socio-economic status significantly influenced gas accumulation. On the contrary, CH_4 concentration and emission fluxes show only a moderate correlation with the number of users, confirming the predominant influence of local environmental and technical factors on emission dynamics. A major contribution of this study is the distinction between gas concentration and emission flux as distinct indicators of greenhouse gas behaviour. Concentration represents cumulative system conditions, whereas flux describes dynamic emission processes, underscoring the importance of considering both parameters in emission evaluation. From a methodological perspective, field-based evidence from the modified static closed chamber approach under real tropical urban conditions is presented here, thereby complementing existing empirical data from decentralised sanitation systems. The incorporation of a socio-technical framework conceptually improves our understanding of emission variability beyond conventional approaches. These results have significant implications for greenhouse gas inventory development.

This study provides an important basis for developing more context-specific emissions mitigation strategies. Although the small sample size (n = 15), the study follows an exploratory design to allow a real-world characterisation of field variability and contribute to environmental science and sustainable development by combining field-based gas measurements with socio-economic variables and system usage. The consistency between Spearman correlation results and Regression trends provides indicative evidence of underlying relationships. As such, these findings are merely preliminary empirical evidence that can be further confirmed in large-scale studies. Future measurements should align with IPCC-compatible activity data to enable comparison of local emission factors with national greenhouse gas inventory assumptions.

Declarations

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Figures

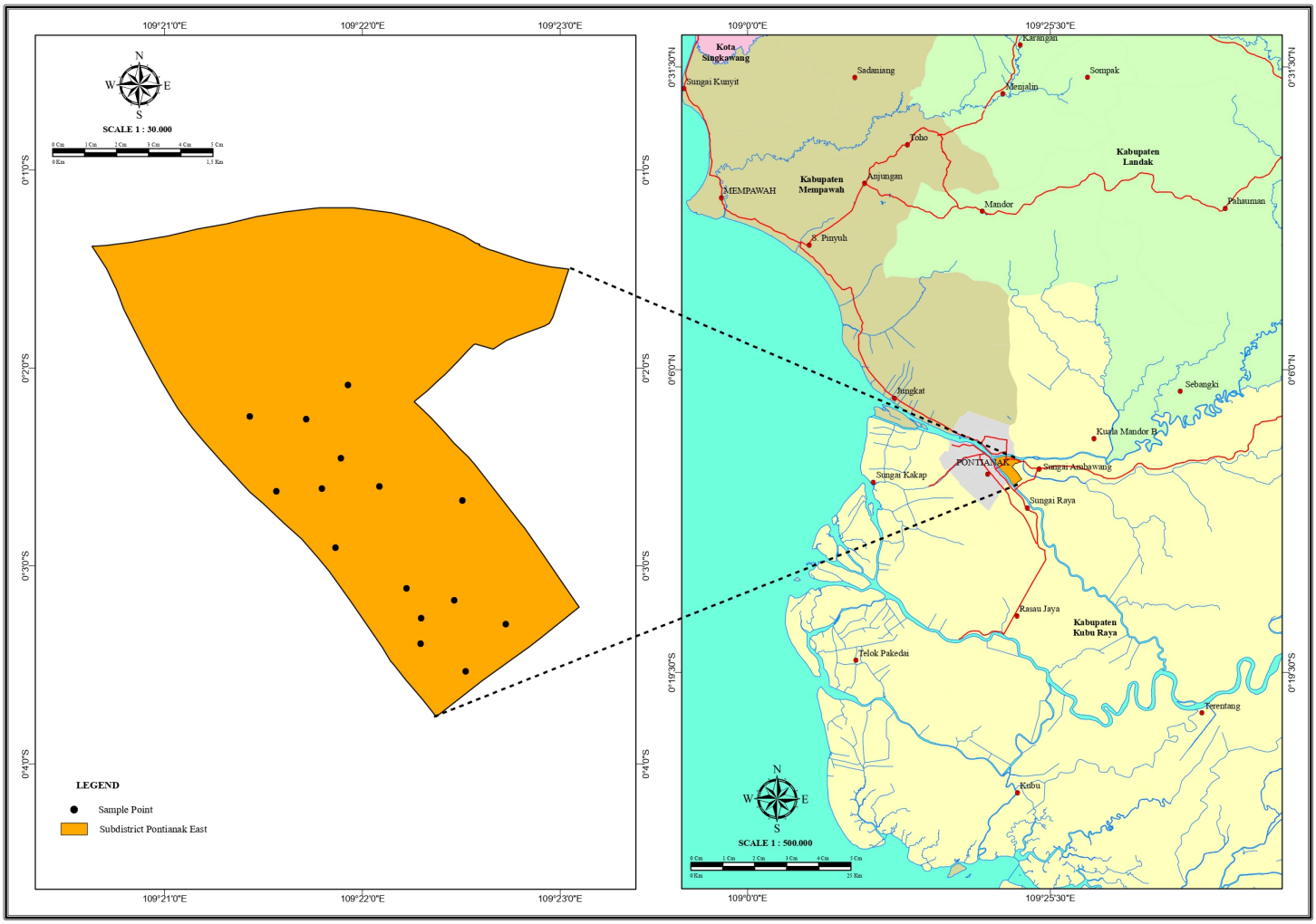


Figure 1

Greenhouse gas sampling points (Arifin, 2023)

a. Top Cover of Latrine Septic tank
b. Manhole / Inspection hole
c. Anchor (rubber gasket) + 1 mm
d. Cover box with 12 Volt DC FAN (12 x 12 cm)
e. Mercury Thermometer
f. Port of gas sampling
g. 5 Kg load
h. Battery 12 V 4,5 AH

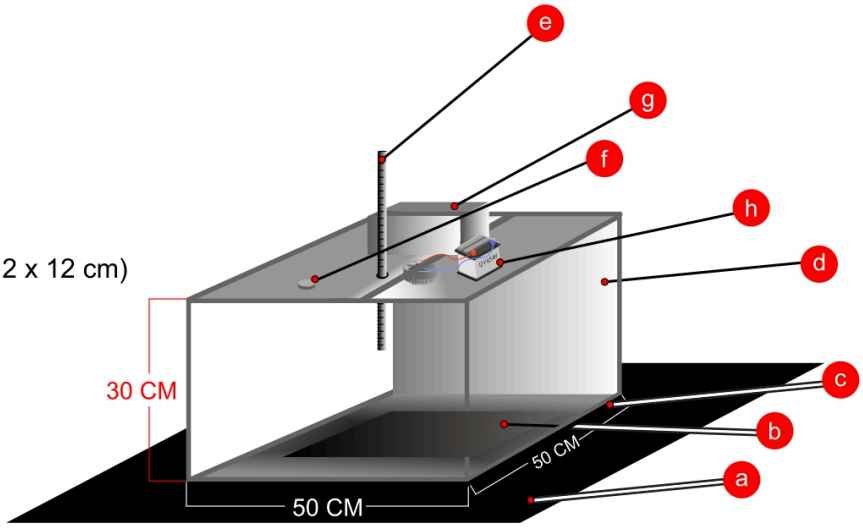


Figure 2

Modified IAEA Closed Chamber (Arifin, 2023)