

Methane emissions from onsite sanitation containment units in Indonesia: an empirical study at the household level

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SUPPORTING INFORMATION

SI-1 CHARACTERISTICS OF HOUSEHOLD SANITATION CONTAINMENT UNITS

Table SI-1. Sanitation containment unit characteristics

Sanitation unit ID	Location	Total number of chambers	Type of influent	Filter media	Walls	Base	Top	Vent pipe	Infiltration pit	Outlet	Aeration	Aerated chambers	Aeration frequency	Number of connected households	People connected	Classification
BA-1	Bandung	1	Black	No	Sealed	Sealed	Sealed	Yes	Yes	Yes	No	N.A.	N.A.	1	4	Type A
BA-2	Bandung	1	Black	No	Lined	Open	Closed	No	No	No	No	N.A.	N.A.	2	9	Type E
BA-3	Bandung	1	Black	No	Lined	Open	Closed	Yes	No	No	No	N.A.	N.A.	1	4	Type E
BA-4	Bandung	1	Black	No	Lined	Open	Sealed	Yes	No	No	No	N.A.	N.A.	1	4	Type E
BA-7	Bandung	1	Black	No	Lined	Open	Sealed	No	No	No	No	N.A.	N.A.	1	5	Type E
BA-8	Bandung	1	Black	No	Lined	Lined	Sealed	Yes	No	No	No	N.A.	N.A.	1	6	Type E
BA-9	Bandung	1	Black	No	Lined	Open	Closed	Yes	Yes	Yes	No	N.A.	N.A.	1	2	Type D
BA-10	Bandung	1	Black	No	Lined	Open	Sealed	No	No	No	No	N.A.	N.A.	1	2	Type E
BP-1	Balikpapan	1	Black	No	Lined	Lined	Open	Yes	Yes	Yes	No	N.A.	N.A.	1	2	Type D
BP-2	Balikpapan	2	Black	No	Sealed	Sealed	Sealed	Yes	No	Yes	No	N.A.	N.A.	1	2	Type B
BP-3	Balikpapan	1	Black	No	Sealed	Sealed	Sealed	No	No	Yes	No	N.A.	N.A.	1	4	Type A
BP-4	Balikpapan	1	Black	No	Lined	Open	Closed	No	No	No	No	N.A.	N.A.	1	4	Type E
BP-5	Balikpapan	1	Black	No	Sealed	Open	Open	Yes	No	Yes	No	N.A.	N.A.	2	5	Type F

Table SI-1. Sanitation containment unit characteristics

Sanitation unit ID	Location	Total number of chambers	Type of influent	Filter media	Walls	Base	Top	Vent pipe	Infiltration pit	Outlet	Aeration	Aerated chambers	Aeration frequency	Number of connected households	People connected	Classification
BP-6	Balikpapan	1	Black	No	Sealed	Open	Open	Yes	No	Yes	No	N.A.	N.A.	2	8	Type F
JA-3	Jakarta	6	Mixed	Yes	Sealed	Sealed	Closed	Yes	No	Yes	Yes	Chambers 4 and 5	2 hours/day	3	18	Type C
JA-4	Jakarta	6	Black	Yes	Sealed	Sealed	Closed	Yes	No	Yes	Yes	Chambers 4 and 5	2 hours/day	3	18	Type C
JA-5	Jakarta	1	Black	No	Sealed	Sealed	Closed	Yes	No	Yes	No	N.A.	N.A.	1	7	Type A
JA-7	Jakarta	2	Black	Yes	Sealed	Sealed	Closed	Yes	No	Yes	No	N.A.	N.A.	2	4	Type B
JA-8	Jakarta	3	Black	Yes	Sealed	Sealed	Closed	Yes	No	Yes	No	N.A.	N.A.	3	13	Type B
MA-1	Manggarai	1	Black	No	Lined	Open	Closed	No	No	No	No	N.A.	N.A.	1	8	Type E
MA-2	Manggarai	1	Black	No	Lined	Open	Closed	No	No	No	No	N.A.	N.A.	1	5	Type E
MB-1	Manggarai Barat	1	Black	No	Lined	Sealed	Sealed	Yes	Yes	Yes	No	N.A.	N.A.	1	5	Type D
MB-2	Manggarai Barat	2	Black	No	Sealed	Sealed	Closed	Yes	Yes	Yes	No	N.A.	N.A.	1	2	Type B
MB-3	Manggarai Barat	1	Black	No	Lined	Open	Sealed	Yes	No	No	No	N.A.	N.A.	1	5	Type E
MB-4	Manggarai Barat	1	Black	No	Open	Open	Sealed	Yes	No	No	No	N.A.	N.A.	1	7	Type F
MB-5	Manggarai Barat	1	Black	No	Open	Open	Open	No	No	No	No	N.A.	N.A.	1	6	Type F
MB-6	Manggarai Barat	1	Black	No	Open	Open	Open	No	No	No	No	N.A.	N.A.	2	10	Type F

SI-2 STATIC FLUX CHAMBER METHOD AND METHANE EMISSIONS

The static flux chamber method utilises a closed headspace above a specific target area to capture gas emitted through it over time (Figure SI-1a). Changes in methane gas concentration in the headspace over time are used to calculate the mass flux of methane emitted from the liquid column below the flux chamber (Figure SI-1b). This method is simple, replicable, transferable to different local settings, highly sensitive compared to other methods and does not require gas flow rates to be measured, which makes it suitable for low and variable emission rates typically observed from sanitation containments.

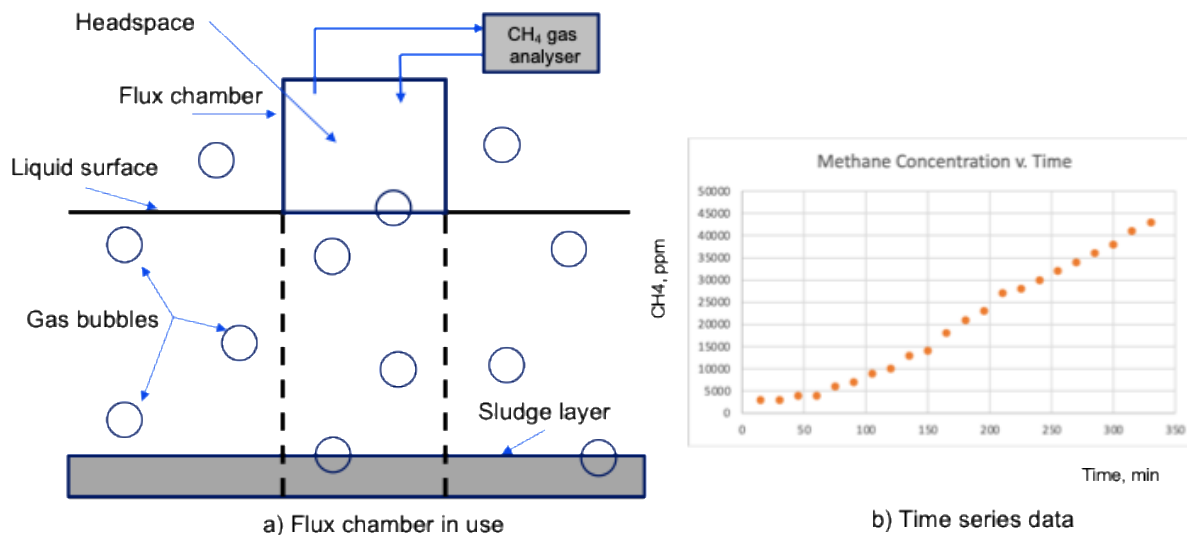


Figure SI-1. Static flux chamber principles in onsite containment unit sampling. a) schematics of a static flux chamber in use; b) methane concentration in the chamber's headspace over time.

We standardised the flux chamber design to a frustum-shaped bucket with a base diameter of 260 mm, an upper diameter of 230 mm, and a predefined submersion depth of 50 mm to maintain a constant headspace volume (9.8 L). To collect and analyse samples of the emitted gas from the headspace, we modified the flux chamber by connecting four tubes on top (Figure 2a). One tube was connected to a manometer (Testo 511, Testo SE & Co.) to record changes in absolute pressure; a second tube in the middle of the chamber was used to measure temperature inside the flux chamber using a temperature sensor probe (UT325F 4-Channel Thermometer, Uni-Trend Technology Co., Ltd.); a third tube was used to collect and transport the gas sample into a portable gas analyser (Geotech GA5000 or Biogas 5000, Geotech QED Environment) for methane, carbon dioxide and oxygen analysis; and finally, a fourth tube was used to return the gas sample from the portable gas analyser to the flux chamber to induce mixing in the headspace. We selected the Geotech GA5000 and Biogas 5000 gas analysers because of their compact design, portability, long battery life, and affordability, making them suitable for the local field conditions. We tested the design of the flux chamber and gas analyser setup at the School of Civil Engineering's environmental laboratory at the University of Leeds using pit slurry to confirm that the system was operating correctly and that the gas readings were appropriate.

To maximise the gas analyser's efficiency when we needed measurements from more than one chamber, we installed a 3-way Luer valve (Figure 2b) to simultaneously measure gas

concentrations from two chambers. When one chamber was being measured, the valve closed the line to the other chamber, fully isolating its headspace. To ensure consistency, the total length and diameter of the tubes remained the same across all measurements (3 m in length and 8 mm in diameter). The portable gas analysers could pump 550 mL gas/min, with the pump operated for 90 seconds at each reading to flush all gases from the tubing. At this length and diameter, the residual gas volume remaining in the tubing after switching chambers was negligible compared to the headspace volume, effectively preventing cross-chamber gas exchange. The flux chamber was carefully positioned over the containment units using a tripod, ensuring 50 mm submersion for an airtight seal and a 9.8 L headspace. Once secured, tubes were connected to the gas analyser, pressure meter and thermometer. Measurements commenced immediately, with gas mixing for 90 seconds before the initial and subsequent recordings, which were taken every 10 minutes across a 180-minute cycle. Each reading noted CH₄, CO₂, O₂, temperature and pressure.

Once raw data were collected in the field, methane concentration readings were transformed from percentages (v/v) to ppm (v/v) and then to mg m⁻³ using **Error! Reference source not found.**

$$C = \frac{\left(\frac{C \text{ ppm}}{10^6}\right) * MW * 1000}{\frac{R * T}{P}} \quad \text{Equation SI-1}$$

where:

C: Methane concentration (mg m⁻³)

C ppm: Methane concentration in ppm (v/v)

10⁶: Factor to convert methane concentrations into mole fractions

MW: Methane molecular weight (16.04 g mol⁻¹)

1000: Factor to convert grams into milligrams

R: Universal gas constant (0.000082057 Atm m³ mol⁻¹ K⁻¹)

T: Temperature within the flux chamber (K)

P: Absolute pressure within the flux chamber (Atm)

Methane concentrations (mg m⁻³) were plotted against accumulated time (min) to calculate the corresponding methane accumulation rate in the headspace (MAR, mg m⁻³ min⁻¹) as the slope of the linear regression of the field data. The resulting coefficient of determination, *R-squared* (*R*²), was used to assess overall model fit.

According to the technical specifications for the Geotech GA5000 and Biogas 5000 gas analysers, the corresponding accuracy for methane gas analysis between 0 and 70% (v/v) is ±0.5%, and between 70 and 100% (v/v), it is ± 1.5%. This information was used to calculate their quantification level, which corresponded to 1% (v/v). For that reason, all methane concentrations in the headspace below 1% (v/v) were reported as below the lower limit of quantification. This information was used to determine the quantification level for *MAR* values, accounting for the specific characteristics of the static flux chamber methodology. Therefore, for methane readings below 1% (v/v) over the sampling cycle (up to 3 hours in some cases),

the level of quantification for *MAR* values was calculated as the maximum detectable increment in concentration (based on equipment accuracy = 0.5%) over the sampling time (**Error! Reference source not found.**). When all methane concentrations in the headspace were zero throughout the sampling cycle, *MARs* were reported as true zeros.

$$MAR = \frac{\Delta C}{\Delta t} \quad \text{Equation SI-2}$$

where:

MAR: Methane accumulation rate in the headspace (mg m⁻³ min⁻¹)

ΔC : The maximum increment in concentration based on equipment accuracy (0.5% v/v) over the sampling period (mg m⁻³)

Δt : Sampling period calculated as the difference between the end and start of the sampling cycle (min)

Once *MAR* values were determined, we calculated methane mass fluxes, as the rate at which the methane gas escapes from the liquid to the atmosphere through the cross-sectional area of the flux chamber, using **Error! Reference source not found.**

$$J_{CH_4} = \frac{MAR * 1,440 * V_{FC}}{A_{FC} * 1000} \quad \text{Equation SI-3}$$

where:

J_{CH₄}: Methane mass flux (g m⁻² day⁻¹)

MAR: Methane accumulation rate in the headspace (mg m⁻³ min⁻¹)

1,440: Factor to convert minutes to days

V_{FC}: Volume of the flux chamber headspace (m³)

A_{FC}: Area of the flux chamber (m²)

1,000: Factor to convert milligrams to grams

Then, we calculated the methane emission rate (*ER*) for each cycle (**Error! Reference source not found.**). If the onsite sanitation unit consists of a single chamber, this *ER* value corresponds to the methane emissions from the entire unit. In cases where the onsite sanitation unit comprises multiple chambers, the *ER* value will be representative of the unit's chamber where the sampling was conducted – i.e., in a septic tank with two chambers, *i* = 1 for the first chamber and 2 for the second.

$$ER_{CH_4-Chamber\ i} = J_{CH_4 - chamber\ i} * A_{chamber\ i} \quad \text{Equation SI-4}$$

where:

$ER_{CH_4-Chamber\ i}$: Methane emission rate from each cycle and unit chamber i (g day⁻¹)

J_{CH_4} : Methane flux (g m⁻² day⁻¹)

$A_{chamber\ i}$: Surface area for unit chamber i (m²)

When the onsite sanitation unit has more than one chamber, the total methane emission rate is the sum of the rates from each unit chamber (**Error! Reference source not found.**). In our research, we included six multichambered sanitation containment units, which have between two and six chambers; two of these containment units are hybrid, meaning that some intermediate chambers are aerated intermittently (every 2 hours per day). Due to this complexity, the calculation of the total emission rate from the multichambered containment units followed a different procedure, which we explain in the Section SI-3.

$$Total\ ER_{CH_4-Sanitation\ unit} = \sum_{i=1}^{i=n} ER_{CH_4-Chamber\ i} \quad \text{Equation SI-5}$$

where:

$Total\ ER_{CH_4 - Sanitation\ unit}$: Total methane emission rate for multichambered units (g day⁻¹)

$ER_{CH_4-Chamber\ i}$: Methane emission rate from each cycle and unit chamber i (g day⁻¹)

i : Chamber unit

n : Total number of chambers in the multichambered sanitation unit

Finally, to be able to compare methane emission rates among containment units in our study and with other rates reported in the published literature, we normalised ER values by dividing them by the nominal number of users in the household(s) connected to the corresponding onsite sanitation containment unit (**Error! Reference source not found.**).

$$NER_{CH_4-Sanitation\ unit} = \frac{Total\ ER_{CH_4-Sanitation\ unit}}{N} \quad \text{Equation SI- 6}$$

$NER_{CH_4 - Sanitation\ unit}$: Normalised methane emission rate (g cap⁻¹ day⁻¹) of the onsite sanitation containment unit

$Total\ ER_{CH_4 - Sanitation\ unit}$: Total methane emission rate from the onsite sanitation unit (g day⁻¹)

N : Nominal number of users connected to the onsite sanitation unit (capita)

SI-3 METHODOLOGY TO CALCULATE NERs FROM MULTICHAMBERED SANITATION CONTAINMENT UNITS

At sampling sites where onsite sanitation containment units had more than one chamber (some with up to six chambers per unit), methane emission rates were assessed using a mixed-method approach combining empirical and modelling methods. This approach was adopted because we were unable to measure methane emissions directly from each unit chamber in some of these containment units due to several challenges, including sealed lids, limited gas analysers, and constrained staff availability. These adaptations reflect the need to balance methodological rigour with practical field constraints.

The methodology for calculating NERs in multichambered containment units involves modelling soluble COD decay within unit chambers using lab data and regression analysis and calculating emission factors from soluble COD removals and directly measured emission rates in selected unit chambers. In our study, each sanitation unit has unique configurations, such as hybrid setups with aerated chambers or varying numbers of chambers, requiring tailored regression models (linear or exponential).

The following is the general procedure for calculating nominal methane emission rates (NERs) in multichambered containment units, considering the particular conditions in sanitation units BP-2, JA-3, JA-4, JA-7, JA-8 and MB-2, as described in **Table SI-2**.

1. Determining a regression model of soluble COD within the chambers from inlet to outlet.
2. In sanitation containment units where some intermediate chambers are aerated (hybrid units), we determined two regression models: before and after the aerated chambers.
3. Calculating the soluble COD decay in each chamber (including the feeding chamber (chamber zero) as a representation for raw wastewater characteristics), by applying regression models.
4. Calculating the soluble COD removed between chambers.
5. Calculating the soluble COD load removed between chambers by multiplying the in soluble COD removed between chambers by the flow rate of the sanitation unit.
6. Calculating the emission factor from all sampled unit chambers and cycles by dividing the emission rate determined by direct measurements in the field by the removed COD load.
7. Determining the average methane emission factor.
8. Calculating the methane emission rates from non-sampled chambers by multiplying the average methane emission factor by the removed COD load in the respective unit chamber.
9. Determining the normalised methane emission rates (NERs) per cycle for the entire sanitation unit by adding up the emission rates obtained by direct measurements in the field, to the estimated emission rates from unit chamber with no direct measurements and dividing by the number of nominal users connected to the sanitation unit.

Table SI-2. Conditions to calculate NERs in each sanitation unit.

Sanitation Unit	Considerations for ER calculation
BP-2	Type of regression model for soluble COD: linear The same linear regression was used in both S1 and S2.
JA-3	Hybrid system Type of regression model for soluble COD: exponential Considering that chambers 4 & 5 are aerated 2 h/day, methane emissions could originate from dissolved methane produced in previous anoxic chambers (aeration) or from actual methane production in these chambers (no aeration). Since no aeration is the prevalent operational condition, the emission rate was calculated by applying emission factors to the dissolved COD removed in these chambers.
JA-4	Hybrid system Type of regression model for soluble COD: linear Two linear regressions: before and after the aerated chambers Considering that chambers 4 & 5 are aerated 2 h/day, methane emissions could originate from dissolved methane produced in previous anoxic chambers (aeration) or from actual methane production in these chambers (no aeration). Since no aeration is the prevalent operational condition, the emission rate was calculated by applying emission factors to the dissolved COD removed in these chambers.
JA-7	Type of regression model for soluble COD: linear
JA-8	Type of regression model for soluble COD: linear
MB-2	Direct methane measurements were taken from both chambers in this system, in both sampling campaigns.

SI-4 NER COMPARISON WITH IPCC-GUIDED EMISSION RATES

To facilitate comparison of the normalised methane emission rates (NERs; g CH₄ cap⁻¹ day⁻¹) derived in this study with emissions rates derived using IPCC methodologies, we integrated Equations 6.1, 6.2 and 6.3c from the 2019 IPCC Guidelines. As a result, Equation SI-7 was used to estimate daily methane emissions from onsite sanitation containment units (septic tanks and pit latrines) treating the nominal quantity of waste produced by a single individual.

$$NER = (TOW * (1 - 0.5 * F)) * Bo * MCF \quad \text{Equation SI-7}$$

where:

NER: Normalised methane emission rate from containment unit (g CH₄ cap⁻¹ day⁻¹)

TOW: total organic load contribution per person per day (g COD cap⁻¹ day⁻¹)

Bo: maximum methane producing capacity (0.25 g CH₄ g COD⁻¹)

MCF: methane correction factor (fraction)

F: fraction of the population managing their containment unit in compliance with the corresponding sludge removal instructions

0.5: fraction of organics removed in sludge when the containment unit is managed in accordance with the corresponding desludging instructions

IPCC-guided methane emission rates for septic tanks and pit latrines were calculated for ranges based on typical lower and upper values of the variables in Equation SI-7 (Table SI-3). We assume that the IPCC category entitled 'Septic tank' aligns most closely with containment units with lined or sealed walls and bases, while the 'Latrine' category aligns with containment units where either the walls or the base are unlined, as described in our study. *MCF* values were taken from Table 6.3 of the IPCC guidelines. *F* values are reported based on responses to questionnaires administered to households in Indonesia, from which we estimated that 9% of the population empties their septic tanks at regular intervals, while sludge in pit latrines is not removed at all (0%). The *TOW* values reported in g COD cap⁻¹ day⁻¹ were calculated by multiplying typical figures reported in g BOD cap⁻¹ day⁻¹ by 2.2 (assumed COD:BOD = 2.2). The lower value of BOD contributions per capita was obtained from recommended figures for Asia – i.e., 35 g BOD cap⁻¹ day⁻¹, Table 6.4 of the IPCC guidelines (IPCC, 2019). The upper BOD bound was 40 g BOD cap⁻¹ day⁻¹, as reported in the latest GHG emission inventory by the Indonesian government (Ministry of Environment and Forestry et al., 2024). *Bo* values were taken from Table 6.2 of the IPCC guidelines.

Table SI-3. Values of parameters to calculate the IPCC-guided methane NERs

Sanitation containment unit*	Default Bo*, g CH ₄ g COD ⁻¹	MCF*, fraction	EF*, g CH ₄ cap ⁻¹ day ⁻¹	TOW**, g COD cap ⁻¹ day ⁻¹	F
Septic tank (alone or with land dispersal field)	0.25	0.40 – 0.72	0.10 – 0.18	77 - 88	0.09
Latrine (wet climate)	0.25	0.70 – 1.00	0.18 – 0.25	77 - 88	0.00

*IPCC (2019)

**Ministry of Environment and Forestry et al. (2024)

A one-at-a-time (OAT) sensitivity analysis was conducted to evaluate the influence of key input parameters on estimated methane emissions. The model was first assessed under baseline conditions for septic tanks, defined as the midpoint of the plausible range for each parameter. Each parameter (*TOW*, *MCF*, and *F*) was then varied independently within its defined lower and upper bounds, while holding the remaining parameters at baseline values. For each parameter, methane emissions (*NERs*) were computed at evenly spaced values across its range to characterise the response curve. In addition, a range-based impact metric (ΔE) was calculated as the difference between emissions at the maximum (E_{max}) and minimum (E_{min}) parameter values ($\Delta E = E_{max} - E_{min}$). This metric quantifies the total variation in methane emissions attributable to parameter uncertainty or variability and enables ranking parameters by their practical influence on model outputs. Per cent changes relative to the baseline emission were also computed to facilitate interpretation and comparison across parameters.

SI-5 STATISTICAL ANALYSIS OF METHANE NER AND ADDITIONAL PHYSICOCHEMICAL AND ENVIRONMENTAL PARAMETERS

SI-5.1 Q-Q PLOT FOR TESTING METHANE NER DATA NORMALITY

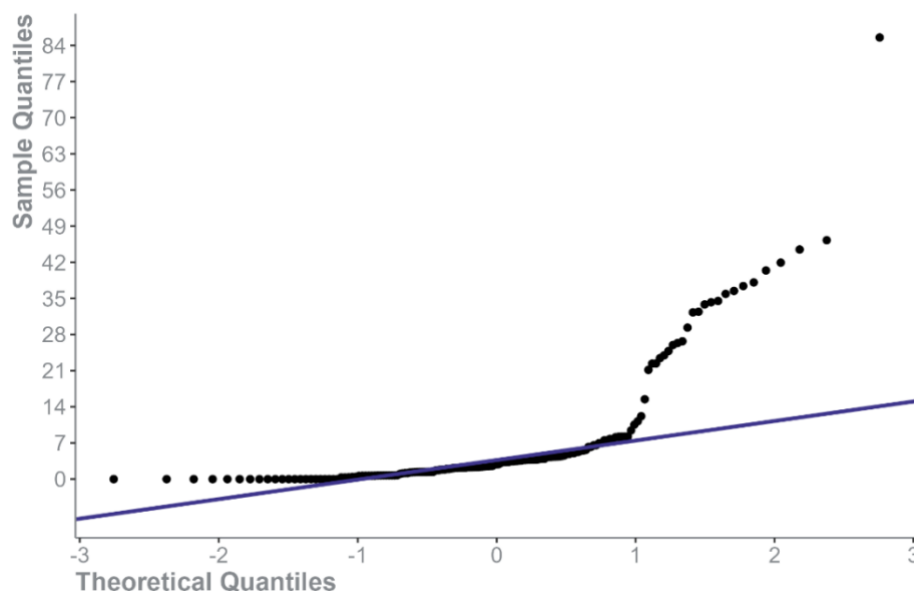


Figure SI-2. Normality test of all methane NERs from onsite sanitation containment units. Methane NERs from surveyed sanitation containment units in Indonesia are not normally distributed. Shapiro-Wilk test, $p = 5.16 \times 10^{-19}$

SI-5.2 DETAILED RESULTS OF THE GENERALISED LINEAR MIXED MODEL FOR A MULTIVARIATE ANALYSIS OF METHANE NER

SI-5.2.1 Fixed effects

Table SI-4. Fixed Effects (Gamma GLMM with log link)

Predictor	Rate ratio ($\exp \beta$)	Confidence interval		p
		2.5%	97.5%	
(Intercept)	13.18	2.53	68.69	0.002
Walls - Lined	0.44	0.10	1.90	0.274
Walls - Open	1.39	0.21	9.18	0.736
Base - Lined	0.40	0.06	2.57	0.333
Base - Open	0.79	0.22	2.86	0.721
Outlet - Yes	0.27	0.07	1.08	0.064
Aeration - Yes	0.30	0.07	1.36	0.119

The GLMM was fitted using a Gamma distribution with a log link. In this formulation, model coefficients are estimated on the logarithmic scale. Exponentiating the coefficients yields rate ratios, which represent multiplicative changes in the response variable¹. A rate ratio of 1 indicates no effect relative to the reference category.

¹ McCullagh, P., Cox, D.R., Reid, N., Isham, V., Tibshirani, R.J., Louis, T.A., Tong, H., Keiding, N., 2019. Generalized Linear Models. CRC Press.

- A rate ratio < 1 indicates a decrease in methane emissions.
- A rate ratio > 1 indicates an increase in methane emissions.

For ease of interpretation, rate ratios were also expressed as per cent changes. For example, a rate ratio of 0.27 indicates approximately a 73% reduction in methane emissions relative to the reference category.

For exponentiated coefficients (rate ratios), the null value is 1, not 0².

- If the 95% confidence interval includes 1, the effect is not statistically significant at the 5% level.
- If the entire confidence interval lies below 1, the predictor is associated with a statistically significant reduction in emissions.
- If the entire confidence interval lies above 1, the predictor is associated with a statistically significant increase.

Importantly, wide confidence intervals indicate high uncertainty, which may arise from limited sample size, high variability, or overlap among predictors.

SI-5.2.2 Random effects

Table SI-5. Random Effects (Variance Components)

Grouping factor	Component	Estimate	Confidence interval	
			2.5%	97.5%
Unique identifier of each system (Basic system name)	SD (Intercept)	0.823	0.984	1.226

The interpretation of the random effect analysis is based on the proximity to zero of the confidence interval³. That is to say, if the lower confidence interval bound is close to zero, clustering is weak or uncertain. In the opposite case, clustering is strong or well-supported.

Due to back-transformation from the variance scale, confidence intervals are asymmetric in this study.

SI-5.2.3 Variance partitioning

Table SI-6. Variance Partitioning and Model Performance

Metric	Value
Adjusted ICC	0.461
Unadjusted ICC	0.344
Marginal R ²	0.253
Conditional R ²	0.598

² Gelman, A., Hill, J., 2007. Data Analysis Using Regression and Multilevel/Hierarchical Models. Cambridge University Press.

³ Zuur, A.F., Leno, E.N., Walker, N., Saveliev, A.A., Smith, G.M., 2009. Mixed effects models and extensions in ecology with R, 1st ed. Springer.

The intraclass correlation coefficient (ICC) measures the proportion of total variance attributable to clustering. In this case, the differences between sanitation containment units indicate strong clustering (adjusted ICC \approx 0.30–0.50).

Marginal R^2 represents the variance explained by fixed effects alone, and the conditional R^2 represents the variance explained by both fixed and random effects. In our study, a marginal R^2 of 0.25 indicates that typology variables explain about 25% of the variance. A conditional R^2 of 0.60 suggests that including system-level random effects substantially improves explanatory power. The significant difference between marginal and conditional R^2 and the adjusted ICC further highlights the importance of unmeasured system-level processes⁴.

SI-5.2.4 Model performance

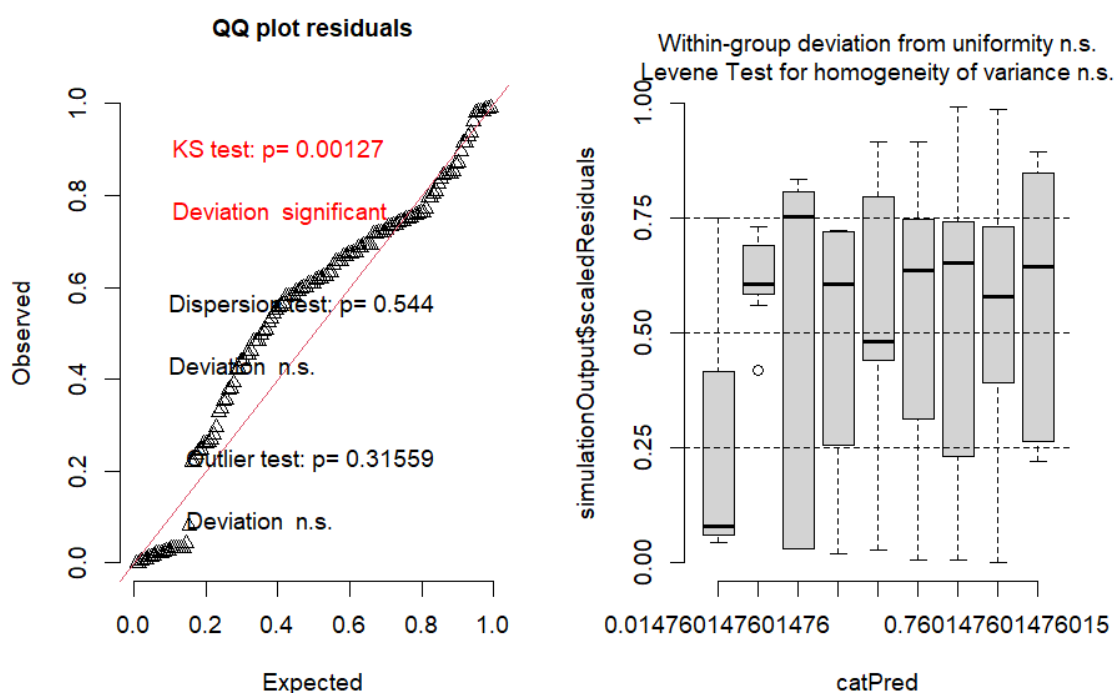


Figure SI-3. DHARMA analysis results

To interpret the DHARMA analysis results, p-values are used for diagnostic purposes and not for hypothesis testing.

The DHARMA residual diagnostics, implemented in R⁵, indicate that, while the residuals deviate slightly from the ideal uniform distribution expected for a perfectly fitting GLMM ($p < 0.05$), the Gamma GLMM does not exhibit overdispersion ($p > 0.05$), and no problematic extreme values were detected ($p > 0.05$). The model demonstrates a good fit in the tails of the distribution, and the residuals show no systematic bias across the categorical predictors (Walls, Base, Outlet, Aeration). Variances across typology categories are also homogeneous. Nonetheless, the model does not fully capture the overall shape of the data distribution, a

⁴ Nakagawa, S., Johnson, P., Schielzeth, H., 2017. The coefficient of determination R^2 and intra-class correlation coefficient from generalized linear mixed-effects models revisited and expanded. *J R Soc Interface* 14. <https://doi.org/10.1098/rsif.2017.0213>.

⁵ Hartig, F., 2024. DHARMA: residual diagnostics for hierarchical (multi-level/mixed) regression models.

common feature of Gamma GLMMs when the data are highly skewed or zero-inflated, even after adding a small constant.

SI-6 DATA DISTRIBUTION OF ADDITIONAL PHYSICOCHEMICAL AND ENVIRONMENTAL PARAMETERS

SI-6.1 Total COD

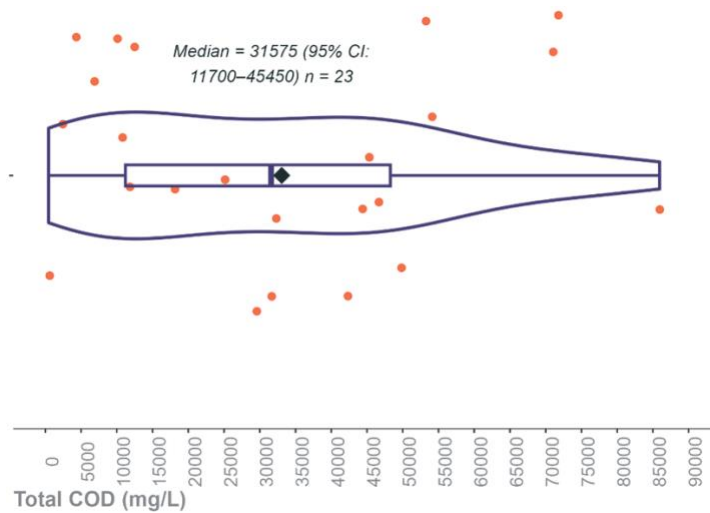


Figure SI-4. Total COD in the liquid-sludge mixture stored in the first chamber of 27 sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamond indicates the mean, vertical line marks the median, the box indicates the interquartile range, and the violin shows the data distribution.

SI-6.2 ORP

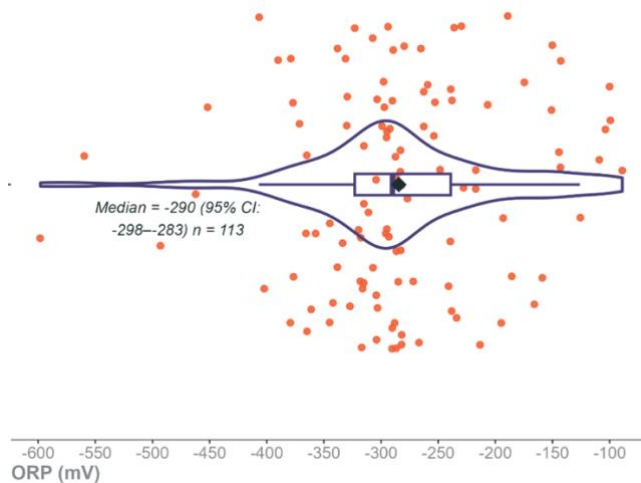


Figure SI-5. Redox potential in the liquid-sludge mixture stored in 27 sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamond indicates the mean, vertical line marks the median, the box indicates the interquartile range, and the violin shows the data distribution.

SI-6.3 Dissolved oxygen

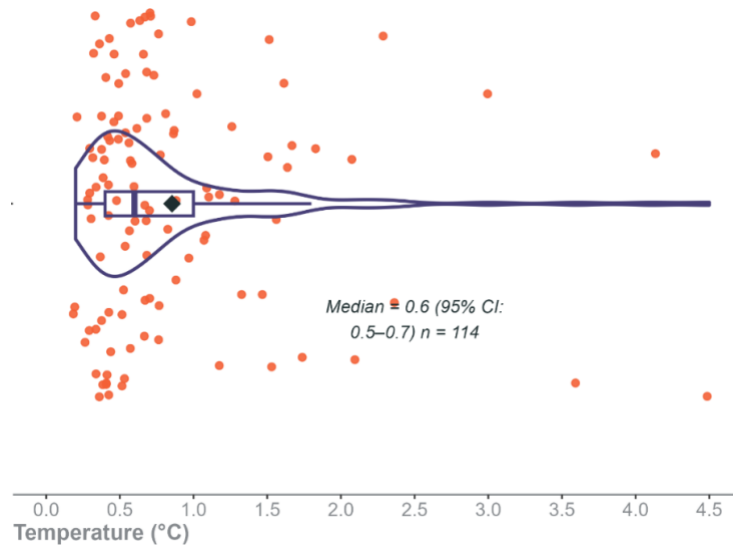


Figure SI-6. Dissolved oxygen in the liquid-sludge mixture stored in 27 sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamond indicates the mean, vertical line marks the median, the box indicates the interquartile range, and the violin shows the adjusted data distribution.

SI-6.4 Temperature

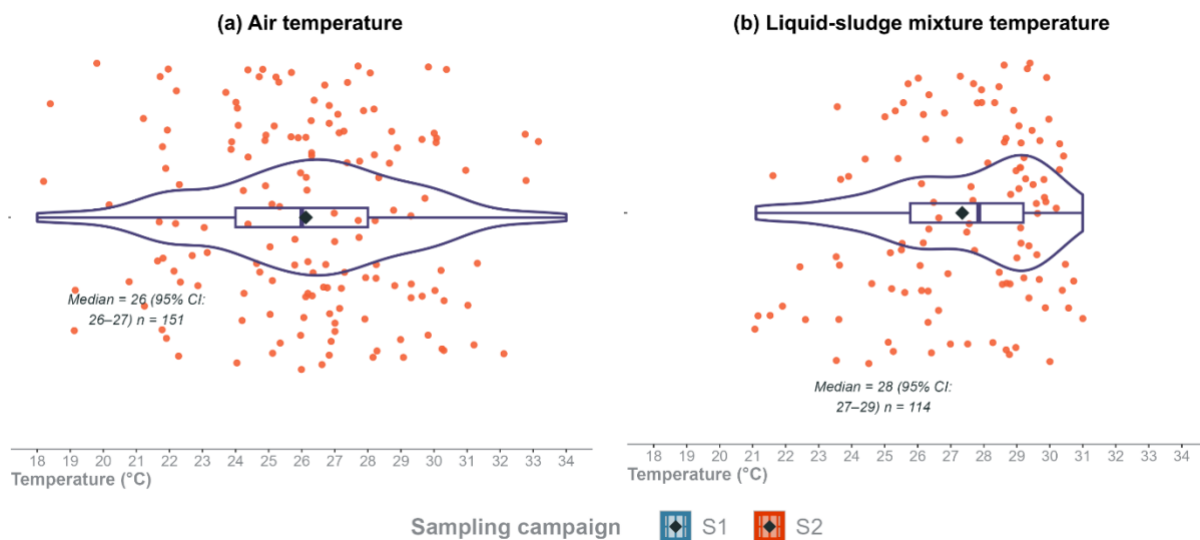


Figure SI-7. Air and liquid-sludge mixture temperature monitored as part of the study of 27 sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamond indicates the mean, vertical line marks the median, the box indicates the interquartile range, and the violin shows the adjusted data distribution. (a) Air temperature. (b) Liquid-sludge mixture temperature.

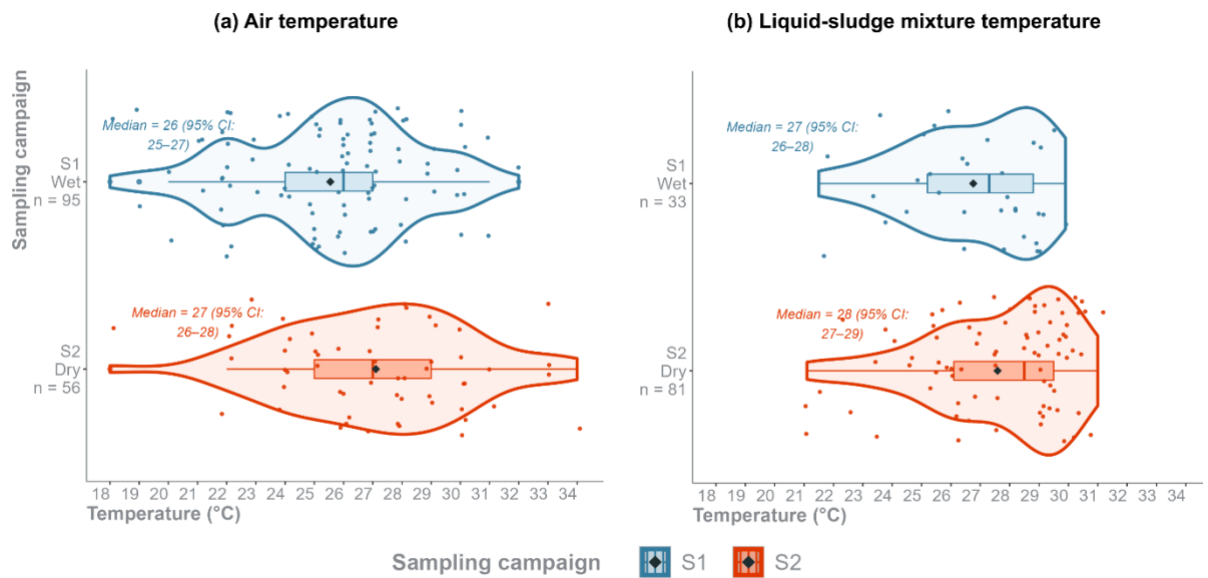


Figure SI-8. Air and liquid-sludge mixture temperature monitored as part of the study of 27 sanitation containment units in Indonesia, observed during two seasons (S1 and S2) between November 2024 and August 2025. Diamond indicates the mean, vertical line marks the median, the box indicates the interquartile range, and the violin shows the adjusted data distribution. (a) Air temperature. (b) Liquid-sludge mixture temperature.

SI-6.5 pH

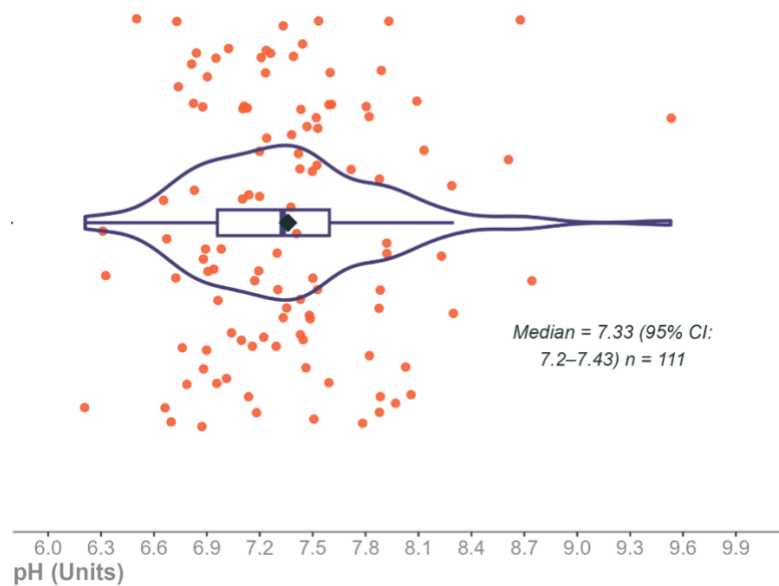


Figure SI-9. pH in the liquid-sludge mixture stored in 27 sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamond indicates the mean, vertical line marks the median, the box indicates the interquartile range, and the violin shows the adjusted data distribution.

SI-7 RAW DATA OF ADDITIONAL PHYSICOCHEMICAL AND ENVIRONMENTAL PARAMETERS

SI-7.1 Total and soluble COD

Table SI-7. Total and soluble COD measured in liquid and sludge samples during S2

System ID	Sampling date	Sampling point	Sample type (1)	Sample type (2)	COD (mg/L)
S2_JA-3	27/05/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	32450
S2_JA-3	27/05/2025	Chamber 2	Liquid-sludge mixture	Unfiltered	38200
S2_JA-3	27/05/2025	Chamber 3	Liquid-sludge mixture	Unfiltered	17200
S2_JA-3	27/05/2025	Chamber 4	Liquid-sludge mixture	Unfiltered	10450
S2_JA-3	27/05/2025	Chamber 5	Liquid-sludge mixture	Unfiltered	6075
S2_JA-3	27/05/2025	Chamber 6	Liquid-sludge mixture	Unfiltered	1220
S2_JA-4	27/05/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	6825
S2_JA-4	27/05/2025	Chamber 2	Liquid-sludge mixture	Unfiltered	8288
S2_JA-4	27/05/2025	Chamber 3	Liquid-sludge mixture	Unfiltered	970
S2_JA-4	27/05/2025	Chamber 4	Liquid-sludge mixture	Unfiltered	700
S2_JA-4	27/05/2025	Chamber 5	Liquid-sludge mixture	Unfiltered	470
S2_JA-4	27/05/2025	Chamber 6	Liquid-sludge mixture	Unfiltered	91.0
S2_JA-7	19/05/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	4450
S2_JA-7	19/05/2025	Chamber 2	Liquid-sludge mixture	Unfiltered	1325
S2_JA-8	20/05/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	53350
S2_JA-8	20/05/2025	Chamber 3	Liquid-sludge mixture	Unfiltered	16290
S2_BA-1	12/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	10700
S2_BA-2	10/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	12325
S2_BA-3	11/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	11700
S2_BA-4	11/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	25200
S2_BA-7	12/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	18020
S2_BA-8	10/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	29700
S2_BA-9	16/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	9950
S2_BA-10	16/06/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	450
S2_BP-1	22/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	44325
S2_BP-2	22/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	46700
S2_BP-2	22/07/2025	Chamber 2	Liquid-sludge mixture	Unfiltered	14075
S2_BP-3	23/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	71200
S2_BP-4	23/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	42200
S2_BP-5	24/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	45450
S2_BP-6	24/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	49825
S2_MB-1	10/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	54200
S2_MB-2	09/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	2345
S2_MB-2	09/07/2025	Chamber 2	Liquid-sludge mixture	Unfiltered	395
S2_MB-3	03/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	31575
S2_MB-4	03/07/2025	Chamber 1 (*)	Sludge	Unfiltered	71625
S2_MB-5	04/07/2025	Chamber 1 (*)	Sludge	Unfiltered	264500
S2_MB-6	04/07/2025	Chamber 1 (*)	Sludge	Unfiltered	219000
S2_MA-1	07/07/2025	Chamber 1	Liquid-sludge mixture	Unfiltered	85950
S2_JA-3	27/05/2025	Chamber 1	Liquid-sludge mixture	Filtered	647
S2_JA-3	27/05/2025	Chamber 2	Liquid-sludge mixture	Filtered	347
S2_JA-3	27/05/2025	Chamber 3	Liquid-sludge mixture	Filtered	230

System ID	Sampling date	Sampling point	Sample type (1)	Sample type (2)	COD (mg/L)
S2_JA-3	27/05/2025	Chamber 4	Liquid-sludge mixture	Filtered	64.5
S2_JA-3	27/05/2025	Chamber 5	Liquid-sludge mixture	Filtered	67.0
S2_JA-3	27/05/2025	Chamber 6	Liquid-sludge mixture	Filtered	49.5
S2_JA-4	27/05/2025	Chamber 1	Liquid-sludge mixture	Filtered	410
S2_JA-4	27/05/2025	Chamber 2	Liquid-sludge mixture	Filtered	685
S2_JA-4	27/05/2025	Chamber 3	Liquid-sludge mixture	Filtered	210
S2_JA-4	27/05/2025	Chamber 4	Liquid-sludge mixture	Filtered	277
S2_JA-4	27/05/2025	Chamber 5	Liquid-sludge mixture	Filtered	97.0
S2_JA-4	27/05/2025	Chamber 6	Liquid-sludge mixture	Filtered	54.5
S2_JA-7	19/05/2025	Chamber 1	Liquid-sludge mixture	Filtered	475
S2_JA-7	19/05/2025	Chamber 2	Liquid-sludge mixture	Filtered	33.3
S2_JA-8	20/05/2025	Chamber 1	Liquid-sludge mixture	Filtered	535
S2_JA-8	20/05/2025	Chamber 3	Liquid-sludge mixture	Filtered	160
S2_BA-1	12/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	99.5
S2_BA-2	10/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	228
S2_BA-3	11/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	325
S2_BA-4	11/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	815
S2_BA-7	16/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	410
S2_BA-8	10/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	811
S2_BA-9	16/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	695
S2_BA-10	16/06/2025	Chamber 1	Liquid-sludge mixture	Filtered	4.5
S2_BP-1	22/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	407
S2_BP-2	22/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	195
S2_BP-2	22/07/2025	Chamber 2	Liquid-sludge mixture	Filtered	133
S2_BP-3	23/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	366
S2_BP-4	23/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	45.0
S2_BP-5	24/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	45.0
S2_BP-6	24/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	340
S2_MB-1	10/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	120
S2_MB-2	09/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	95.8
S2_MB-2	09/07/2025	Chamber 2	Liquid-sludge mixture	Filtered	102
S2_MB-3	03/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	40.8
S2_MA-1	07/07/2025	Chamber 1	Liquid-sludge mixture	Filtered	471

(*) A sludge sample was taken from a pit without Liquid-sludge mixture in it

SI-7.2 Redox potential, dissolved oxygen, pH and temperature

Table SI-8. Redox potential, dissolved oxygen, pH, and temperature measured in Liquid-sludge mixture-sludge mixture samples during S1 and S2

System ID	Sampling date	Sampling time	Sampled chamber	ORP (mV)	Dissolved oxygen (mg/L)	pH (Units)	Liquid-sludge mixture temperature (°C)	Sampling depth below water surface (m)
S1_BA-1	17/01/2025	07:00	1	-345	4.1	7.42	25.1	N.A.
S1_BA-2	17/01/2025	10:20	1	-560	0.8	8.68	25.6	N.A.
S1_BA-3	21/01/2025	10:20	1	-365	4.5	7.16	26.1	N.A.
S1_BA-4	21/01/2025	07:30	1	-342	1.7	8.06	23.6	N.A.
S1_BA-7	25/01/2025	07:01	1	-379	0.9	7.82	23.5	N.A.
S1_BA-8	25/01/2025	10:24	1	-150	3.6	8.74	26.2	N.A.
S1_BA-9	31/01/2025	06:30	1	-598	1.6	7.80	24.5	N.A.
S1_BA-10	31/01/2025	09:45	1	-462	1.3	8.09	25.0	N.A.
S1_BP-1	13/02/2025	07:45	1	-109	1.3	7.72	25.2	N.A.
S1_BP-2	13/02/2025	07:20	1	-338	0.7	9.53	23.6	N.A.
S1_BP-3	15/02/2025	07:30	1	-452	0.8	8.61	27.8	N.A.
S1_BP-4	15/02/2025	05:19	1	-493	1.1	8.13	27.3	N.A.
S1_BP-5	18/02/2025	06:35	1	N.A.	1.8	8.23	25.5	N.A.
S1_BP-6	18/02/2025	05:40	1	-402	1.2	6.96	26.4	N.A.
S1_MA-1	14/03/2025	08:30	1	-320	1.1	8.30	21.9	N.A.
S1_MA-2	14/03/2025	09:03	1	-195	2.1	6.72	21.5	N.A.
S1_MB-1	07/03/2025	09:00	1	-377	0.7	7.50	27.9	N.A.
S1_MB-2	07/03/2025	09:10	1	-379	1.2	7.88	28.1	N.A.
S1_MB-2	07/03/2025	09:20	2	-299	1.5	7.88	28.3	N.A.
S1_MB-3	11/03/2025	07:30	1	-323	0.7	7.20	28.6	N.A.
S1_MB-4	11/03/2025	08:00	1	-357	0.7	7.43	26.3	N.A.
S1_MB-5	12/03/2025	08:20	1	-365	0.6	7.59	26.3	N.A.
S1_MB-6	12/03/2025	08:30	1	-298	0.6	6.98	28.3	N.A.
S1_JA-3	04/12/2024	10:05	3	-293	0.3	7.61	29.0	N.A.
S1_JA-3	04/12/2024	10:24	5	-288	0.4	7.47	28.8	N.A.
S1_JA-3	04/12/2024	10:35	6	-272	1.5	7.50	29.1	N.A.
S1_JA-4	27/11/2024	10:20	3	-290	1.0	7.38	29.0	N.A.
S1_JA-4	27/11/2024	10:40	6	-283	0.6	7.33	29.1	N.A.
S1_JA-5	11/01/2025	09:20	1	-407	1.6	7.88	27.7	N.A.
S1_JA-7	25/04/2025	07:58	1	-295	0.8	6.88	29.9	N.A.
S1_JA-7	25/04/2025	08:01	2	-330	0.9	6.89	29.4	N.A.
S1_JA-8	14/03/2025	08:15	1	-345	0.6	7.46	29.3	N.A.
S1_JA-8	14/03/2025	08:30	3	-334	0.5	7.23	29.2	N.A.
S2_BA-1	12/06/2025	15:30	1	-207	0.9	7.78	30.7	N.A.
S2_BA-1	12/06/2025	15:35	1	-189	0.8	7.59	27.0	N.A.
S2_BA-1	12/06/2025	15:40	1	-144	0.4	7.10	27.3	N.A.
S2_BA-2	10/06/2025	16:20	1	-317	0.7	7.88	26.2	N.A.
S2_BA-3	11/06/2025	15:25	1	-259	0.7	7.04	29.8	0.00
S2_BA-3	11/06/2025	15:25	1	-290	0.6	7.43	30.4	1.36
S2_BA-3	11/06/2025	15:25	1	-338	0.4	7.10	30.5	2.72
S2_BA-4	11/06/2025	16:05	1	-307	1.1	7.39	25.7	0.00

System ID	Sampling date	Sampling time	Sampled chamber	ORP (mV)	Dissolved oxygen (mg/L)	pH (Units)	Liquid-sludge mixture temperature (°C)	Sampling depth below water surface (m)
S2_BA-4	11/06/2025	16:05	1	-304	0.4	7.38	25.4	0.53
S2_BA-4	11/06/2025	16:05	1	-265	0.3	7.35	25.2	1.06
S2_BA-7	12/06/2025	16:48	1	-311	0.7	7.14	26.3	0.00
S2_BA-7	12/06/2025	16:40	1	-234	1.0	7.29	26.1	0.88
S2_BA-7	12/06/2025	16:30	1	-304	0.5	7.14	26.3	1.75
S2_BA-8	10/06/2025	17:01	1	-238	0.4	7.17	25.3	N.A.
S2_BA-9	16/06/2025	16:45	1	-236	0.5	N.A.	26.0	1.20
S2_BA-9	16/06/2025	16:50	1	-289	0.7	N.A.	25.5	0.60
S2_BA-9	16/06/2025	17:00	1	-315	0.7	N.A.	25.3	0.00
S2_BA-10	16/06/2025	16:35	1	-267	0.7	7.30	28.5	0.00
S2_BA-10	16/06/2025	16:37	1	-241	0.6	7.44	26.1	0.70
S2_BA-10	16/06/2025	16:40	1	-230	0.4	7.48	25.6	1.40
S2_BP-1	22/07/2025	15:57	1	-159	0.2	6.33	29.5	N.A.
S2_BP-2	22/07/2025	16:14	1	-307	0.8	8.03	30.0	0.00
S2_BP-2	22/07/2025	16:14	1	-315	0.7	7.97	29.4	0.35
S2_BP-2	22/07/2025	16:14	1	-316	0.6	7.60	29.8	0.69
S2_BP-3	23/07/2025	16:17	1	-315	0.3	7.43	28.5	0.00
S2_BP-3	23/07/2025	16:20	1	-296	0.3	6.70	27.6	0.30
S2_BP-3	23/07/2025	16:22	1	-287	0.5	6.94	27.5	0.59
S2_BP-4	23/07/2025	15:54	1	-297	0.8	7.52	31.0	0.00
S2_BP-4	23/07/2025	16:00	1	-285	0.4	7.45	30.6	0.70
S2_BP-4	23/07/2025	16:04	1	-294	0.3	7.41	30.4	1.30
S2_BP-5	24/07/2025	16:04	1	-217	0.4	6.50	28.7	0.00
S2_BP-5	24/07/2025	16:10	1	-228	0.2	6.21	29.0	0.60
S2_BP-5	24/07/2025	16:20	1	-193	0.2	6.31	28.7	1.19
S2_BP-6	24/07/2025	16:17	1	-303	0.3	6.84	29.4	0.00
S2_BP-6	24/07/2025	16:20	1	-282	0.3	6.82	28.9	0.57
S2_BP-6	24/07/2025	16:22	1	-263	0.4	6.73	29.1	1.14
S2_MA-1	07/07/2025	16:30	1	-287	1.5	8.29	21.1	0.00
S2_MA-1	07/07/2025	16:30	1	-248	0.5	7.53	21.2	0.62
S2_MA-1	07/07/2025	16:30	1	-213	0.4	7.24	21.6	1.23
S2_MA-2	08/07/2025	16:13	1	-100	0.4	7.01	23.9	0.00
S2_MA-2	08/07/2025	16:13	1	-126	2.4	7.20	22.6	0.90
S2_MA-2	08/07/2025	16:13	1	-143	2.3	7.19	22.4	1.80
S2_MB-1	10/07/2025	15:27	1	-327	0.3	7.49	27.7	0.00
S2_MB-1	10/07/2025	15:30	1	-318	0.3	7.43	27.6	0.20
S2_MB-1	10/07/2025	15:34	1	-292	0.3	7.10	27.9	0.40
S2_MB-2	09/07/2025	16:30	1	-186	0.3	7.93	26.5	0.00
S2_MB-2	09/07/2025	16:30	1	-166	0.4	7.92	26.6	0.59
S2_MB-2	09/07/2025	16:30	1	-175	0.4	7.82	26.6	1.17
S2_MB-2	09/07/2025	16:38	2	-217	0.4	7.92	26.8	0.00
S2_MB-2	09/07/2025	16:38	2	-151	0.4	7.89	26.9	0.44
S2_MB-2	09/07/2025	16:38	2	-143	0.7	7.88	26.2	0.87
S2_MB-3	03/07/2025	17:40	1	-89	1.1	6.65	23.7	0.00
S2_MB-3	03/07/2025	17:49	1	-104	0.7	6.76	23.6	0.32
S2_MB-3	03/07/2025	17:53	1	-99	0.5	6.66	23.5	0.63

System ID	Sampling date	Sampling time	Sampled chamber	ORP (mV)	Dissolved oxygen (mg/L)	pH (Units)	Liquid-sludge mixture temperature (°C)	Sampling depth below water surface (m)
S2_MB-4	03/07/2025	17:40	1	-239	0.4	7.53	24.4	N.A.
S2_MB-5	04/07/2025	16:51	1	-239	0.6	7.51	27.5	N.A.
S2_MB-6	04/07/2025	16:50	1	-238	0.4	7.13	24.6	N.A.
S2_JA-3	27/05/2025	14:30	1	-295	0.4	6.88	29.9	1.18
S2_JA-3	27/05/2025	14:35	2	-290	0.4	6.79	29.2	1.18
S2_JA-3	27/05/2025	16:35	3	-287	0.4	6.90	29.1	0.95
S2_JA-3	27/05/2025	15:23	4	-303	0.5	7.26	29.6	0.95
S2_JA-3	27/05/2025	15:28	5	-254	0.6	6.90	29.1	0.85
S2_JA-3	27/05/2025	16:38	6	-331	0.5	7.33	28.6	0.90
S2_JA-4	27/05/2025	14:47	1	-318	0.5	6.67	29.5	0.97
S2_JA-4	27/05/2025	14:53	2	-304	0.5	6.74	29.1	0.97
S2_JA-4	27/05/2025	16:51	3	-282	0.3	6.81	28.8	0.90
S2_JA-4	27/05/2025	15:46	4	-277	0.5	6.95	29.6	0.98
S2_JA-4	27/05/2025	15:52	5	-263	0.5	7.22	29.6	0.95
S2_JA-4	27/05/2025	16:45	6	-283	0.5	6.87	28.7	0.94
S2_JA-5	14/05/2025	17:55	1	-253	2.1	7.52	27.7	N.A.
S2_JA-7	19/05/2025	17:20	1	-330	0.7	6.83	29.7	0.00
S2_JA-7	19/05/2025	17:20	1	-280	1.0	7.02	29.3	0.50
S2_JA-7	19/05/2025	17:20	1	-287	0.9	6.91	29.1	1.00
S2_JA-7	19/05/2025	17:30	2	-283	1.5	6.88	28.6	1.00
S2_JA-7	19/05/2025	17:30	2	-282	1.7	6.96	28.8	0.00
S2_JA-8	20/05/2025	16:19	1	-361	0.3	7.30	29.7	N.A.
S2_JA-8	20/05/2025	16:19	1	-377	0.4	7.24	29.9	N.A.
S2_JA-8	20/05/2025	16:19	1	-371	0.6	7.18	30.0	N.A.
S2_JA-8	20/05/2025	15:50	3	-366	3.0	7.21	30.3	N.A.
S2_JA-8	20/05/2025	15:50	3	-295	1.3	7.53	30.3	N.A.
S2_JA-8	20/05/2025	15:50	3	-390	1.6	7.11	30.2	N.A.

SI-7.3 Air temperature

Table SI-9. Air temperature measured in Liquid-sludge mixture and sludge samples during S1 and S2

System ID	Measurement date	Measurement time	Air temperature (°C)
S1_BA-1	16/01/2025	11:16	26
S1_BA-2	16/01/2025	11:16	29
S1_BA-3	1/20/2025	13:00	23
S1_BA-3	1/20/2025	20:00	22
S1_BA-3	1/20/2025	02:00	21
S1_BA-3	1/21/2025	08:00	23
S1_BA-4	20/01/2025	10:00	26
S1_BA-7	24/01/2025	09:50	26
S1_BA-7	24/01/2025	15:50	26
S1_BA-7	24/01/2025	21:50	22
S1_BA-7	25/01/2025	03:50	19
S1_BA-8	24/01/2025	13:22	28
S1_BA-8	24/01/2025	19:24	23
S1_BA-8	24/01/2025	01:34	21
S1_BA-8	25/01/2025	07:10	22
S1_BA-9	30/01/2025	15:35	22
S1_BA-9	30/01/2025	21:30	22
S1_BA-9	31/01/2025	03:30	20
S1_BA-10	30/01/2025	12:10	25
S1_BA-10	30/01/2025	18:15	24
S1_BA-10	31/01/2025	00:15	22
S1_BA-10	31/01/2025	06:15	20
S1_BP-1	12/02/2025	09:21	27
S1_BP-1	12/02/2025	15:27	27
S1_BP-1	12/02/2025	20:45	26
S1_BP-1	13/02/2025	03:20	24
S1_BP-2	12/02/2025	09:30	28
S1_BP-2	12/02/2025	15:25	29
S1_BP-2	12/02/2025	20:20	27
S1_BP-2	13/02/2025	03:20	24
S1_BP-3	14/02/2025	08:18	27
S1_BP-3	14/02/2025	14:18	31
S1_BP-3	14/02/2025	20:36	27
S1_BP-3	15/02/2025	02:26	25
S1_BP-4	14/02/2025	08:25	27
S1_BP-4	14/02/2025	14:15	32
S1_BP-4	14/02/2025	20:05	28
S1_BP-4	15/02/2025	01:35	25
S1_BP-5	17/02/2025	09:21	26
S1_BP-5	17/02/2025	15:23	30
S1_BP-5	17/02/2025	21:23	26
S1_BP-5	18/02/2025	03:29	25
S1_BP-6	17/02/2025	08:57	27
S1_BP-6	17/02/2025	14:55	30
S1_BP-6	17/02/2025	20:45	26
S1_BP-6	18/02/2025	02:35	24
S1_MA-1	13/03/2025	10:00	25
S1_MA-1	13/03/2025	16:15	22
S1_MA-1	13/03/2025	22:00	22
S1_MA-1	14/03/2025	04:10	19

System ID	Measurement date	Measurement time	Air temperature (°C)
S1_MA-2	13/03/2025	11:08	24
S1_MA-2	13/03/2025	17:00	25
S1_MA-2	13/03/2025	23:00	22
S1_MA-2	14/03/2025	05:00	18
S1_MB-1	06/03/2025	09:00	27
S1_MB-1	06/03/2025	15:00	30
S1_MB-1	06/03/2025	21:50	27
S1_MB-1	07/03/2025	03:00	25
S1_MB-2	06/03/2025	08:40	27
S1_MB-2	06/03/2025	14:45	30
S1_MB-2	06/03/2025	21:00	27
S1_MB-2	07/03/2025	03:00	25
S1_MB-3	10/03/2025	10:20	28
S1_MB-3	10/03/2025	16:20	26
S1_MB-3	10/03/2025	22:25	22
S1_MB-3	11/03/2025	04:20	25
S1_MB-4	10/03/2025	10:32	27
S1_MB-4	10/03/2025	16:42	25
S1_MB-4	10/03/2025	22:42	25
S1_MB-4	11/03/2025	04:30	21
S1_MB-5	11/03/2025	10:52	28
S1_MB-5	11/03/2025	17:00	26
S1_MB-5	11/03/2025	23:00	22
S1_MB-5	12/03/2025	05:08	26
S1_MB-6	10/03/2025	10:51	28
S1_MB-6	10/03/2025	17:02	27
S1_MB-6	10/03/2025	22:59	24
S1_MB-6	11/03/2025	05:20	22
S1_JA-3	12/03/2024	11:45	30
S1_JA-3	12/03/2024	17:45	27
S1_JA-3	12/03/2024	23:06	25
S1_JA-3	12/04/2024	05:46	26
S1_JA-4	12/03/2024	11:47	30
S1_JA-4	12/03/2024	17:54	27
S1_JA-4	12/03/2024	23:11	25
S1_JA-4	12/04/2024	05:46	26
S1_JA-5	11/01/2025	N.A.	30
S1_JA-7	24/04/2025	09:50	31
S1_JA-7	24/04/2025	16:17	29
S1_JA-7	24/04/2025	21:52	27
S1_JA-7	25/04/2025	03:58	26
S1_JA-8	28/04/2025	09:47	29
S1_JA-8	28/04/2025	15:45	28
S1_JA-8	28/04/2025	21:51	26
S1_JA-8	29/04/2025	03:47	28
S2_BA-1	12/06/2025	08:30	24
S2_BA-1	12/06/2025	12:20	29
S2_BA-2	10/06/2025	08:43	24
S2_BA-2	10/06/2025	13:00	26
S2_BA-3	11/06/2025	08:35	22
S2_BA-3	11/06/2025	12:15	27
S2_BA-4	11/06/2025	08:00	22

System ID	Measurement date	Measurement time	Air temperature (°C)
S2_BA-4	11/06/2025	12:13	27
S2_BA-7	12/06/2025	08:45	22
S2_BA-7	12/06/2025	13:00	30
S2_BA-8	10/06/2025	08:40	24
S2_BA-8	10/06/2025	13:40	27
S2_BA-9	16/06/2025	08:45	25
S2_BA-9	16/06/2025	13:10	27
S2_BA-10	16/06/2025	09:10	26
S2_BA-10	16/06/2025	13:00	30
S2_BP-1	22/07/2025	08:30	28
S2_BP-1	22/07/2025	13:37	30
S2_BP-2	22/07/2025	08:23	28
S2_BP-2	22/07/2025	12:32	30
S2_BP-3	23/07/2025	08:23	28
S2_BP-3	23/07/2025	12:28	30
S2_BP-4	23/07/2025	08:20	28
S2_BP-4	23/07/2025	12:30	30
S2_BP-5	24/07/2025	08:10	28
S2_BP-5	24/07/2025	12:26	31
S2_BP-6	24/07/2025	08:10	28
S2_BP-6	24/07/2025	12:26	31
S2_MA-1	07/07/2025	10:00	25
S2_MA-1	07/07/2025	16:15	22
S2_MA-2	08/07/2025	08:00	18
S2_MA-2	08/07/2025	11:51	23
S2_MB-1	10/07/2025	07:54	24
S2_MB-1	10/07/2025	11:25	28
S2_MB-2	06/03/2025	08:40	27
S2_MB-2	06/03/2025	14:45	30
S2_MB-2	06/03/2025	21:00	27
S2_MB-2	07/03/2025	03:00	25
S2_MB-3	03/07/2025	09:20	24
S2_MB-3	03/07/2025	13:49	26
S2_MB-4	03/07/2025	09:23	26
S2_MB-4	03/07/2025	13:49	26
S2_MB-5	04/07/2025	09:30	24
S2_MB-5	04/07/2025	13:48	25
S2_MB-6	04/07/2025	09:32	24
S2_MB-6	04/07/2025	13:10	26
S2_JA-3	27/05/2025	08:58	29
S2_JA-3	27/05/2025	13:08	34
S2_JA-4	27/05/2025	09:20	29
S2_JA-4	27/05/2025	13:40	33
S2_JA-5	14/05/2025	09:30	29
S2_JA-5	14/05/2025	14:00	28
S2_JA-7	19/05/2025	09:00	29
S2_JA-7	19/05/2025	14:00	33
S2_JA-8	20/05/2025	09:13	29
S2_JA-8	20/05/2025	13:10	33

SI-7.4 Water column and sludge thickness within chambers

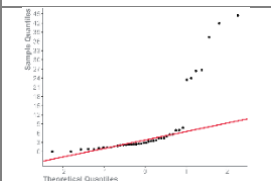
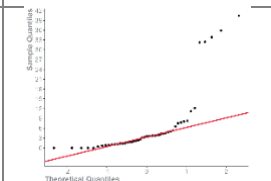
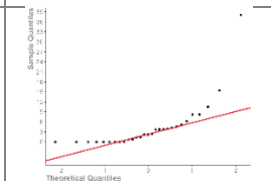
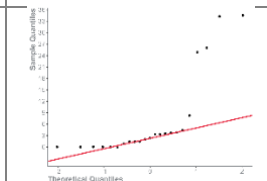
Table SI-10. Water column and sludge thickness within chambers during S1 and S2

System ID	Sampling date	Time	Sampled chamber	Water column (cm)	Sludge thickness (cm)
S1_BA-1	17/01/2025	07:00	1	117	32
S1_BA-2	17/01/2025	10:20	1	74	40
S1_BA-3	21/01/2025	10:20	1	74	75
S1_BA-4	21/01/2025	07:30	1	20	75
S1_BA-7	25/01/2025	07:01	1	66	92
S1_BA-8	25/01/2025	10:24	1	20	6
S1_BA-9	31/01/2025	06:30	1	66	18
S1_BA-10	31/01/2025	09:45	1	79	31
S1_BP-1	13/02/2025	07:45	1	5	112
S1_BP-2	13/02/2025	07:20	1	43	8
S1_BP-3	15/02/2025	07:30	1	29	40
S1_BP-4	15/02/2025	05:19	1	56	54
S1_BP-5	18/02/2025	06:35	1	66	55
S1_BP-6	18/02/2025	05:40	1	53	56
S1_MA-1	14/03/2025	08:30	1	58	45
S1_MA-2	14/03/2025	09:03	1	127	63
S1_MB-1	07/03/2025	09:00	1	69	25
S1_MB-2	07/03/2025	09:10	1	106	19
S1_MB-2	07/03/2025	09:20	2	113	12
S1_MB-3	11/03/2025	07:30	1	80	70
S1_MB-4	11/03/2025	08:00	1	0	60
S1_MB-5	12/03/2025	08:20	1	50	50
S1_MB-6	12/03/2025	08:30	1	0	52
S1_JA-3	04/12/2024	10:05	3	86	10
S1_JA-3	04/12/2024	10:24	5	86	6
S1_JA-3	04/12/2024	10:35	6	86	9
S1_JA-4	27/11/2024	10:20	3	77	11
S1_JA-4	27/11/2024	10:40	6	88	2
S1_JA-5	11/01/2025	09:20	1	40	30
S1_JA-7	25/04/2025	07:58	1	79	22
S1_JA-7	25/04/2025	08:01	2	90	17
S1_JA-8	14/03/2025	08:15	1	32	30
S1_JA-8	14/03/2025	08:30	3	54	15
S2_BA-1	12/06/2025	15:30	1	126	14
S2_BA-2	10/06/2025	16:20	1	110	20
S2_BA-3	11/06/2025	15:25	1	142	130
S2_BA-4	11/06/2025	16:05	1	70	36
S2_BA-7	12/06/2025	16:48	1	100	75
S2_BA-8	10/06/2025	17:01	1	19	8
S2_BA-9	16/06/2025	16:45	1	104	16
S2_BA-10	16/06/2025	16:35	1	100	40
S2_BP-1	22/07/2025	15:57	1	10	111
S2_BP-2	22/07/2025	16:14	1	37	32
S2_BP-3	23/07/2025	16:17	1	16	43
S2_BP-4	23/07/2025	15:54	1	60	70
S2_BP-5	24/07/2025	16:04	1	19	90
S2_BP-6	24/07/2025	16:17	1	52	62
S2_MA-1	07/07/2025	16:30	1	61	62
S2_MA-2	08/07/2025	16:13	1	108	72

System ID	Sampling date	Time	Sampled chamber	Water column (cm)	Sludge thickness (cm)
S2_MB-1	10/07/2025	15:27	1	30	10
S2_MB-2	09/07/2025	16:30	1	97	20
S2_MB-2	09/07/2025	16:38	2	62	25
S2_MB-3	03/07/2025	17:40	1	43	20
S2_MB-4	03/07/2025	17:40	1	0	35
S2_MB-5	04/07/2025	16:51	1	0	50
S2_MB-6	04/07/2025	16:50	1	0	35
S2_JA-3	27/05/2025	14:30	1	88	30
S2_JA-3	27/05/2025	14:35	2	71	47
S2_JA-3	27/05/2025	16:35	3	55	40
S2_JA-3	27/05/2025	15:23	4	85	10
S2_JA-3	27/05/2025	15:28	5	76	9
S2_JA-3	27/05/2025	16:38	6	83	7
S2_JA-4	27/05/2025	14:47	1	22	45
S2_JA-4	27/05/2025	14:53	2	62	35
S2_JA-4	27/05/2025	16:51	3	52	38
S2_JA-4	27/05/2025	15:46	4	88	10
S2_JA-4	27/05/2025	15:52	5	88	7
S2_JA-4	27/05/2025	16:45	6	86	8
S2_JA-5	14/05/2025	17:55	1	20	50
S2_JA-7	19/05/2025	17:20	1	66	37
S2_JA-7	19/05/2025	17:30	2	84	23
S2_JA-8	20/05/2025	16:19	1	35	30
S2_JA-8	20/05/2025	15:50	3	49	20

SI-8 DESCRIPTIVE STATISTICS OF METHANE NORMALISED EMISSION RATES PER CYCLE

Table SI-1. Descriptive statistics of methane NERs per cycle

Descriptor / Test	Value per cycle (g CH ₄ capita ⁻¹ day ⁻¹)			
	Morning	Afternoon	Evening	Night
Median	42	49	29	23
Minimum	0.00	0.00	0.00	0.00
Maximum	44.48	40.42	38.10	34.51
Quartile 1	1.90	1.34	0.00	0.41
Quartile 3	5.64	5.29	4.60	4.07
Skewness	2.05	2.34	3.41	1.72
n	42	49	29	23
Shapiro-Wilk test, <i>p</i>	2.86x10 ⁻⁹	2.2410 ⁻¹⁰	1.90x10 ⁻⁸	1.86x10 ⁻⁶
Q-Q plot				

SI-9 DESCRIPTIVE STATISTICS OF METHANE NORMALISED EMISSION RATES - ALL DATA SET

Table SI-12. Descriptive statistics of methane NERs – All data set

Descriptor	Value (g CH ₄ capita ⁻¹ day ⁻¹)
Median	2.89
95% Confidence Interval (CI)	2.31 – 3.70 (bootstrap)
Geometric Mean	1.78
Geometric Standard Deviation	8.51
Range based on the Geometric SD	0.21 – 15.15
Minimum	0.00
Maximum	44.48
Quartile 1	1.23
Quartile 3	5.27
Skewness	2.29
n	143
Arithmetic Mean (*)	6.54
Standard Deviation (*)	10.26

(*) SD is higher than the arithmetic mean because the data are not normally distributed. These descriptors are shown here for information purposes only.

SI-10 KRUSKAL-WALLIS TEST OF METHANE NER FOR SANITATION CONTAINMENT UNITS WITH THREE DIFFERENT BASE CHARACTERISTICS

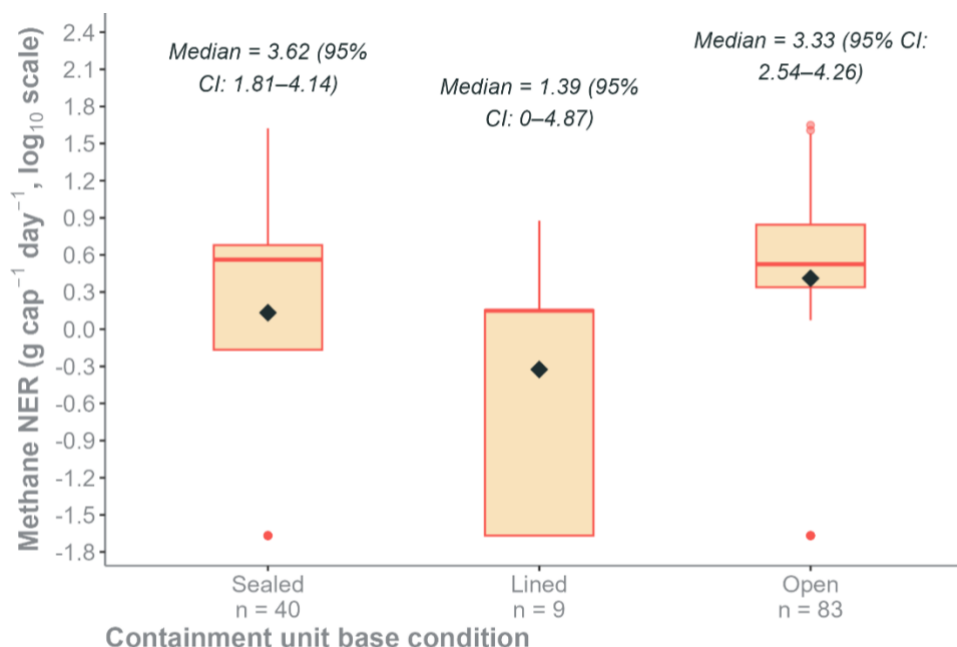


Figure SI-1. Methane NERs for sealed (Types A, B and some D), lined (some Types D & E), and open base (some Types D, E & F) of sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamonds indicate the mean, horizontal lines mark the median, and the box indicates the interquartile range. Kruskal-Wallis test $p = 0.052$

SI-11 DESCRIPTIVE STATISTICS OF METHANE NORMALISED EMISSION RATES PER TYPOLOGY OF SANITATION CONTAINMENT UNITS

Table SI-13. Descriptive statistics of methane NERs – Six typologies for sanitation containment units

Descriptor	Value (g CH ₄ capita ⁻¹ day ⁻¹)					
	Type A	Type B	Type C	Type D	Type E	Type F
System type	Type A	Type B	Type C	Type D	Type E	Type F
Median	3.73	4.35	0.82	1.11	3.61	3.41
95% Confidence Interval	0.66 – 3.77	1.81 – 7.79	0.81 – 1.32	0.00 – 2.31	2.41 – 4.28	2.55 – 12.17
Geometric Mean	0.81	2.09	0.91	0.34	2.29	3.8
Geometric Standard Deviation	9.12	13.8	1.41	9.77	6.31	8.51
Range based on the Geometric SD	0.09 – 7.39	0.15 – 28.84	0.65 – 1.28	0.03 – 3.32	0.36 – 14.45	0.45 – 32.34
Minimum	0.00	0.00	0.43	0.00	0.00	0.00
Maximum	5.67	41.94	1.37	2.35	37.40	44.48
Quartile 1	0.66	1.75	0.81	0.00	1.44	2.23
Quartile 3	3.77	11.63	1.31	2.31	6.39	24.58
n	13	23	11	13	55	28
Arithmetic Mean (*)	2.44	9.82	0.97	1.20	5.58	12.29
Standard Deviation (*)	2.13	12.65	0.31	1.08	7.67	14.94

(*) SD is higher than the arithmetic mean in some cases because the data are not normally distributed. These descriptors are shown here for information purposes only.

SI-12 WILCOXON TEST OF METHANE NER FOR SANITATION CONTAINMENT UNITS WITH AND WITHOUT AERATION

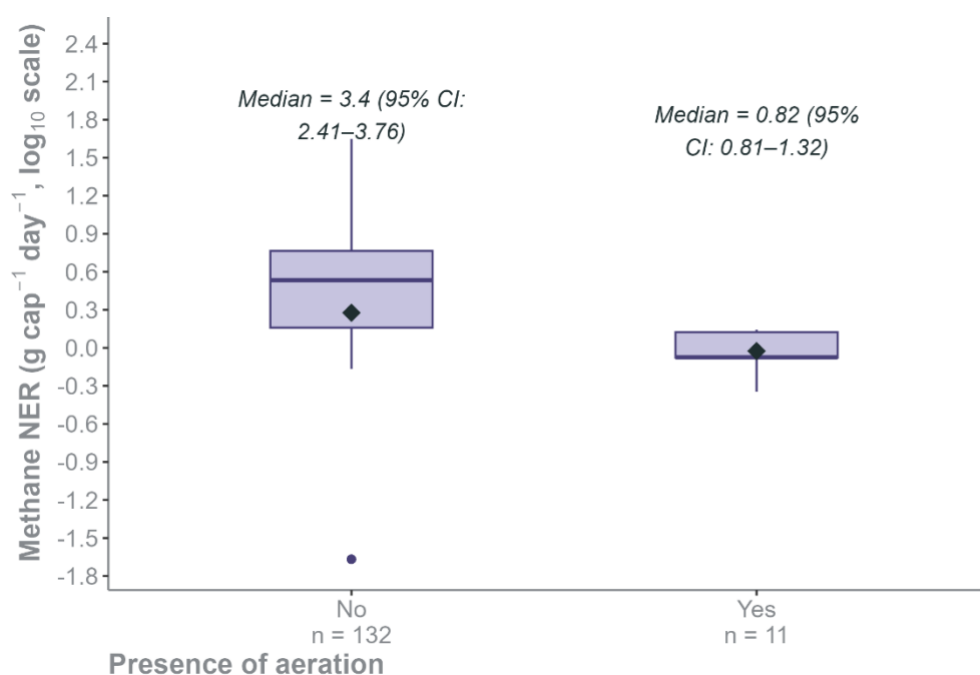


Figure SI-11. Methane NERs for 27 sanitation containment units with and without aeration in Indonesia, observed between November 2024 and August 2025. Diamonds indicate the mean, horizontal lines mark the median, and the box indicates the interquartile range.

SI-13 WILCOXON TEST OF METHANE NER FOR SINGLE- AND MULTICHAMBERED SANITATION CONTAINMENT UNITS

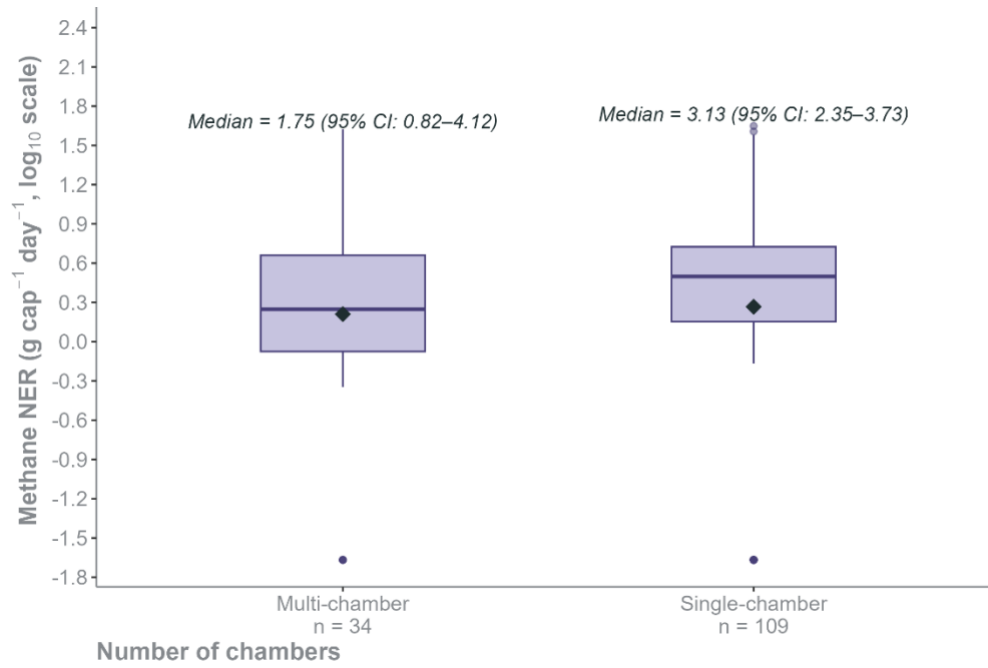


Figure SI-12. Methane NERs for single and multichambered sanitation containment units in Indonesia, observed between November 2024 and August 2025. Diamonds indicate the mean, horizontal lines mark the median, and the box indicates the interquartile range.

SI-14 SPEARMAN CORRELATIONS BETWEEN NERS AND SLUDGE-RELATED PARAMETERS PER FOUR SYSTEM TYPES (SINGLE-CHAMBER SANITATION CONTAINMENT UNITS)

SI-14.1 All data – Single-chamber sanitation containment units

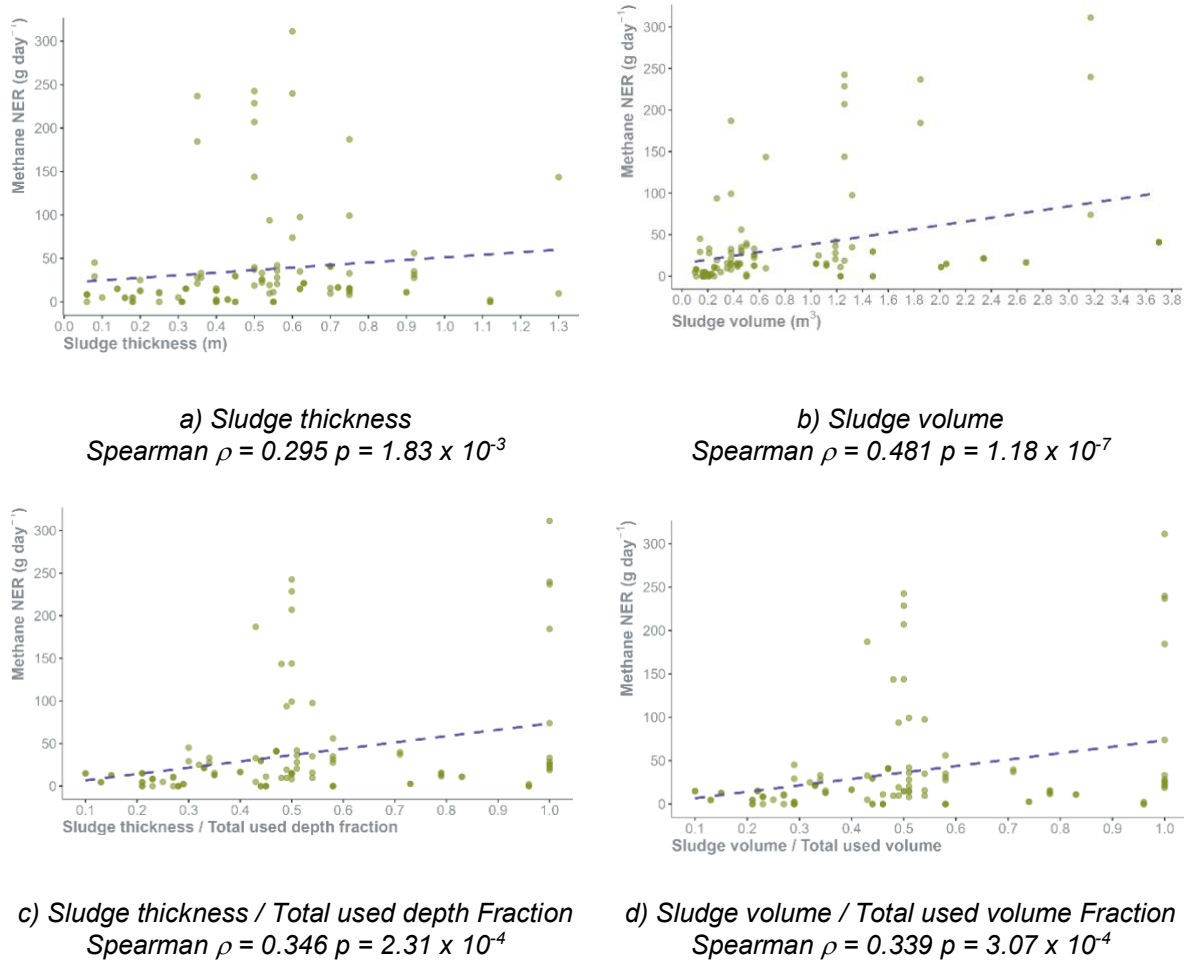
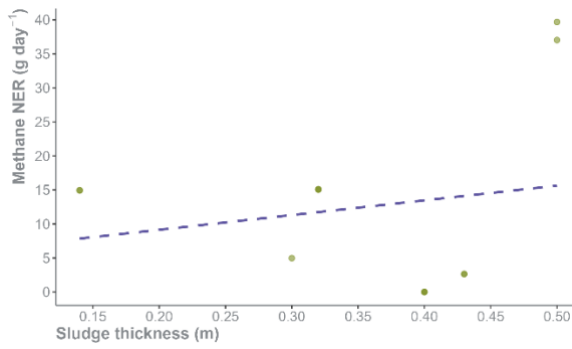
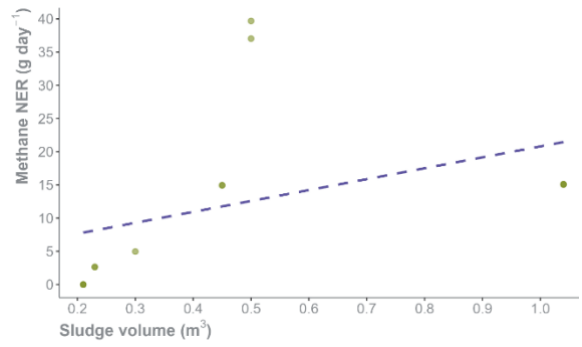


Figure SI-13. Spearman correlations between methane emission rates and sludge parameters for 27 sanitation containment units in Indonesia, observed between November 2024 and August 2025. Dotted lines reflect the direction of the trend. (a) Sludge thickness, (b) Sludge volume, (c) Sludge thickness / Total used depth fraction, (d) Sludge volume / Total used volume fraction.

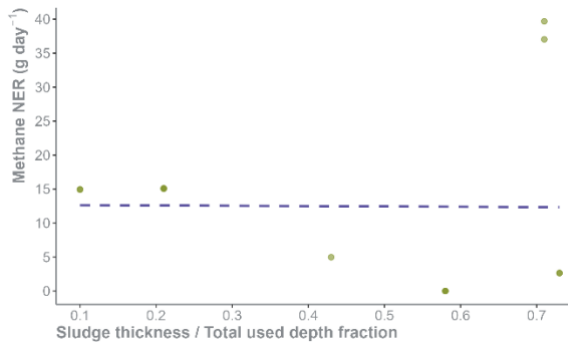
SI-14.2 Type A



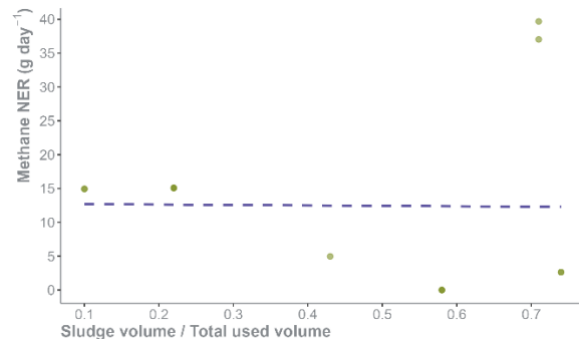
a) Sludge thickness
Spearman $\rho = 0.048$, $p = 0.877$



b) Sludge volume
Spearman $\rho = 0.907$, $p = 1.85 \times 10^{-5}$



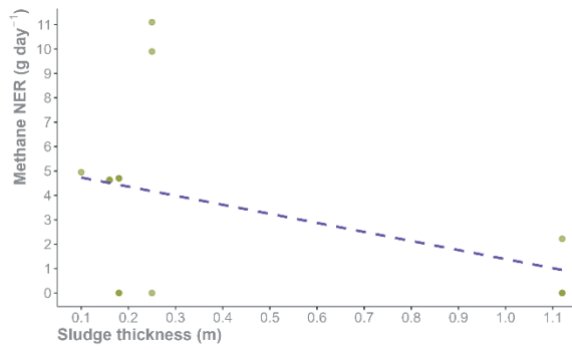
c) Sludge thickness / Total used depth Fraction
Spearman $\rho = -0.199$, $p = 0.514$



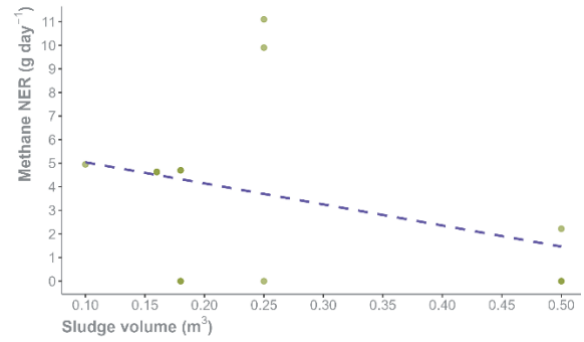
d) Sludge volume / Total used volume Fraction
Spearman $\rho = -0.199$, $p = 0.514$

Figure SI-14. Spearman correlations between several sludge parameters and methane emission rates – Type A

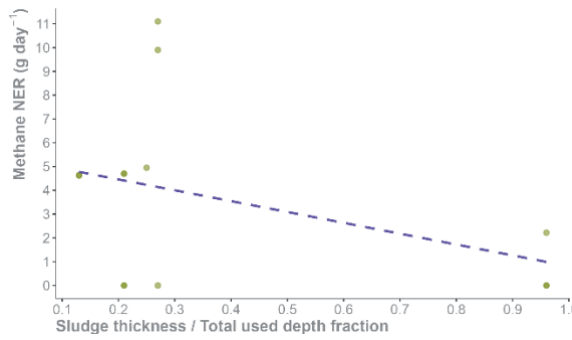
SI-14.3 Type D



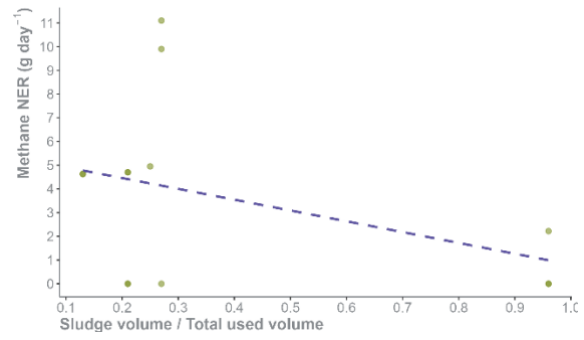
a) Sludge thickness
Spearman $\rho = -0.320$, $p = 0.287$



b) Sludge volume
Spearman $\rho = -0.320$, $p = 0.287$



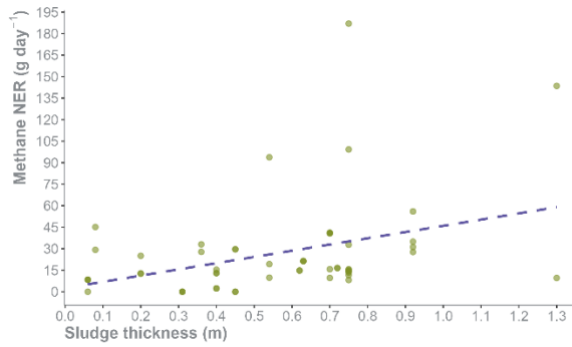
c) Sludge thickness / Total used depth Fraction
Spearman $\rho = -0.169$, $p = 0.582$



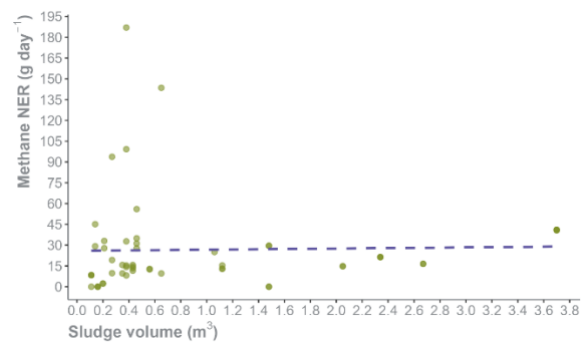
d) Sludge volume / Total used volume Fraction
Spearman $\rho = -0.169$, $p = 0.582$

Figure SI-15. Spearman correlations between several sludge parameters and methane emission rates – Type D

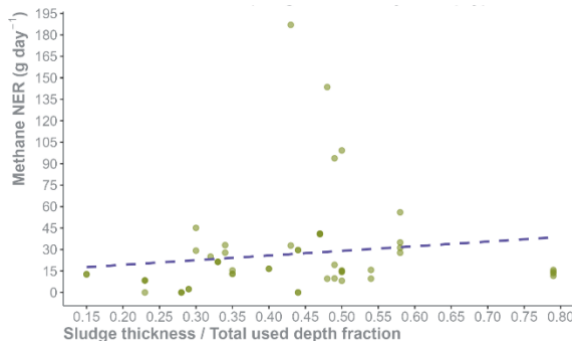
SI-14.4 Type E



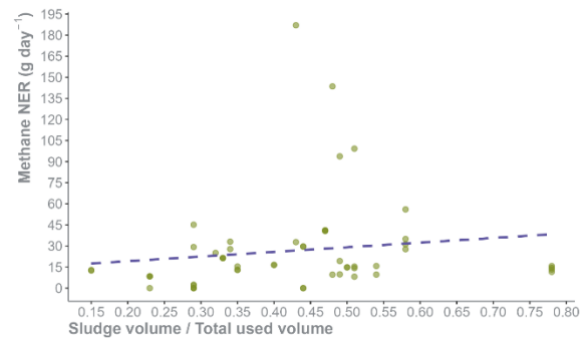
a) Sludge thickness
Spearman $\rho = 0.409$, $p = 1.96 \times 10^{-3}$



b) Sludge volume
Spearman $\rho = 0.338$, $p = 1.15 \times 10^{-2}$



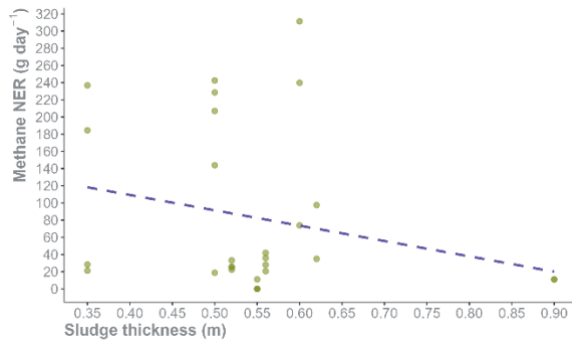
c) Sludge thickness / Total used depth Fraction
Spearman $\rho = 0.317$, $p = 1.85 \times 10^{-2}$



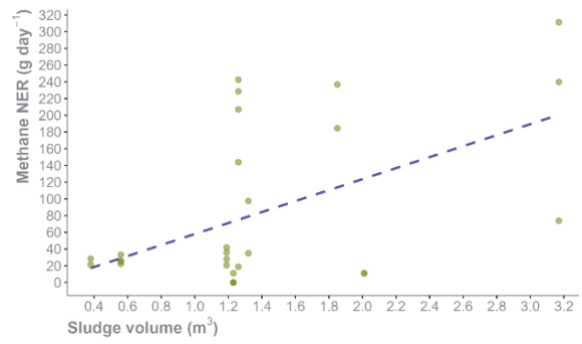
d) Sludge volume / Total used volume Fraction
Spearman $\rho = 0.303$, $p = 2.48 \times 10^{-2}$

Figure SI-16. Spearman correlations between several sludge parameters and methane emission rates – Type E

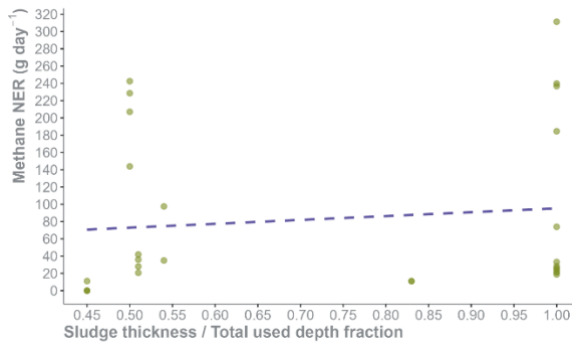
SI-14.5 Type F



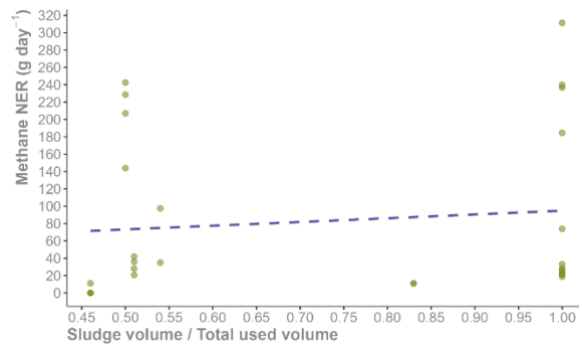
a) Sludge thickness
Spearman $\rho = -0.179$, $p = 0.363$



b) Sludge volume
Spearman $\rho = 0.392$, $p = 3.9 \times 10^{-2}$



c) Sludge thickness / Total used depth Fraction
Spearman $\rho = 0.246$, $p = 0.207$



d) Sludge volume / Total used volume Fraction
Spearman $\rho = 0.246$, $p = 0.207$

Figure SI-17. Spearman correlations between several sludge parameters and methane emission rates – Type F

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