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Research Paper

Greenhouse gas emissions from container-based sanitation systems in East African cities: a case study in Nairobi, Kenya

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ABSTRACT

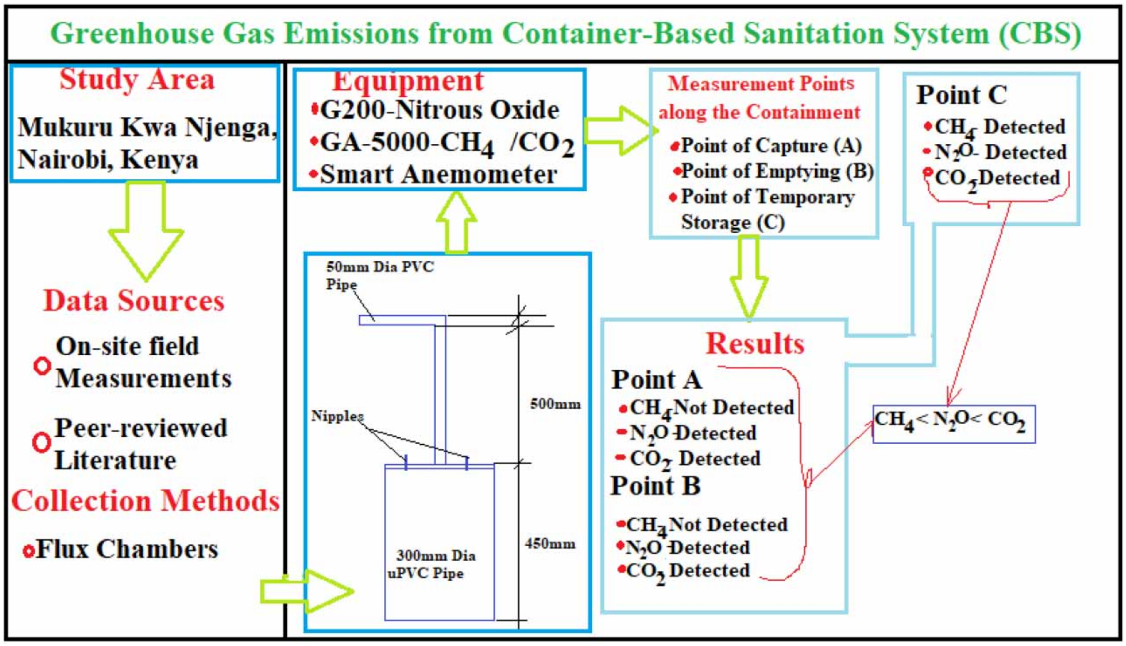
Sanitation systems emit greenhouse gases (GHGs), which are estimated to comprise 3% of global emissions and pose challenges to sustainable development goals (SDGs), specifically SDG 13 and SDG 6.2, which are focused on climate action and sanitation. This study quantified GHG emissions from the containment component of the container-based sanitation (CBS) system, with a specific focus on Fresh Life Toilets (FLTs) in Nairobi, Kenya. Field measurements performed over 10-day studies revealed total GHG emissions of 15.72 kg CO_2 eq/capita/year from faecal matter alone, excluding the emissions from urine. Nuanced variations in emissions were encountered, notably with higher methane production at the point of temporary storage (0.40 kg CO_2 eq/capita/year) compared to values at capture and emptying, which were much below the detection level of the equipment used. This insight underscores the complexities of GHG dynamics within CBS systems, highlighting the ongoing necessity for research to refine and enhance precision in GHG assessments related to CBS. The results of this study contribute to elucidating the impact of climate change on CBS systems.

Key words: container-based sanitation, emissions, greenhouse gases, Nairobi

HIGHLIGHTS

- This is a study on greenhouse gas emissions from Fresh Life Toilets in Nairobi, Kenya.
- The study reveals 15.72 kg CO_2 eq/capita/year from faecal matter alone, highlighting nuances.
- Significantly lower emissions – 73% less methane and 32% less nitrous oxide were elicited compared to previous estimates.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The escalating trend in greenhouse gas (GHG) emissions has become a critical factor in exacerbating the global effects of climate change (UNEP 2021). The consistent rise in GHG emissions poses a significant threat to the goals outlined in the Paris Agreement (United Nations 2015), necessitating immediate and decisive action to avert a substantial deviation.

As of 2023, a staggering 40% of the world population still lacks access to safely managed sanitation systems, representing almost half of the global population (WHO & UNICEF 2024). This deficiency is a substantial impediment to achieving Sustainable Development Goal (SDG) 13, addressing climate action, and SDG 6.2, focusing on sanitation (United Nations General Assembly 2015). The urban slums of Nairobi, characterised by informal settlements and inadequate sanitation and hygiene facilities (Auerbach 2016; Richmond *et al.* 2018), are at the forefront of experiencing the adverse impacts of climate change, including flooding, heavy rainfall, and droughts (Twinomuhangi *et al.* 2021).

Climate change is disrupting the national economies of many low- and middle-income countries (LMICs) (United Nations General Assembly 2015) in various ways, and the destruction of the sanitation infrastructure is the most worst among others (Howard & Bartram 2010). In the CBS system, the faecal waste is hygienically and safely emptied in a sealed container as soon as it fills, reducing the chances of the excreta getting mixed with water during flooding (Mara & Evans 2018; World Bank 2019).

The container-based sanitation (CBS) system is an innovative approach that originated in Bolivia in 1998 and gained global recognition through organisations such as SOIL in Haiti, Sanergy in Kenya, and Clean Team in Ghana (World Bank 2019). The CBS system provides toilets with removable containers to safely dispose of or reuse faecal sludge, effectively separating faeces and urine for more efficient treatment. Within the CBS system, faeces and urine are stored in separate containers for a short duration (3 days to a week) (Auerbach 2016). No water is used for flushing, but rather, cover materials such as sawdust, ash, or lime are sprinkled on the faeces after each defaecation to facilitate drying (Russel *et al.* 2019; World Bank 2019; Russel & Montgomery 2020). This results in dry conditions at the containment of the CBS system, leading to a slower degradation speed and expected lower GHG emissions. Notably, the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) classified CBS as a safely managed sanitation system (Russel *et al.* 2019; World Bank 2019; Russel & Montgomery 2020).

Sanergy's Fresh Life Toilets (FLTs) are examples of CBS systems in East Africa (Riungu 2021). FLT, classified as a dry toilet, segregates urine and faeces in separate cartridges, which are replaced once full. The CBS system sanitation chain comprises containment, emptying, transportation, treatment, and disposal (Russel *et al.* 2019; McNicol *et al.* 2020). The containment involves the separation of the human waste from users and placing it in removable cartridges (World Bank 2019). The cartridges are then emptied, and the content is consolidated and transported to the treatment plant located in Kinanie, approximately 40 km from Nairobi (Riungu 2021). Treatment methods typically involve aerobic composting or the use of black soldier fly larvae (Mertenat *et al.* 2019).

The adoption of CBS systems presents a range of benefits, including reduced GHG emissions, improved privacy, enhanced security, decreased odour, and lower water usage compared to traditional sanitation systems (Reade 2016). Studies have indicated that the CBS system can reduce GHG emissions by up to 79% when replacing pit latrines (Trimmer *et al.* 2020).

Sanitation systems produce 3% of global man-made methane and 2% nitrous gas (Russel & Montgomery 2020). Pit latrines alone produce 1–2% of global methane (Reid *et al.* 2014), and generally by 2020 about 4.7% of anthropogenic methane results from non-sewer sanitation systems (NSSSs) (Cheng *et al.* 2022) Climate-positive sanitation solutions can reduce GHG emissions (Russel *et al.* 2019). In Kampala, poor sanitation management results in 189 kg CO_2/year GHG emissions (Johnson *et al.* 2022). The CBS system reduces emissions through innovative methods such as black soldier fly treatment (Mertenat *et al.* 2019; Parodi *et al.* 2020). Estimated emissions from CBS system containment are 15.4 kg CO_2eq/capita/year for methane and 21.9 kg CO_2eq/capita/year for nitrous oxide (Johnson *et al.* 2022). However, direct quantification of GHGs from CBS system containment is lacking, and IPCC methodology may underestimate emissions by over 53% (Shaw *et al.* 2021). Moreover, a recent study found that the IPCC estimated CH_4 emissions are over seven times the real field measurement (Manga & Muoghalu 2024). Further study is needed to provide accurate field-observed results. Alternative approaches, such as the Container-Based Sanitation Alliance (CBSA) Calculator and flux chamber methodologies, are gaining traction (Huynh *et al.* 2021; Reddy *et al.* 2022; Russel *et al.* 2019). This study addresses the gap in GHG emissions quantification along the CBS system containment, which is crucial for reducing GHG emissions and informing effective climate mitigation strategies.

2. MATERIALS AND METHODS

2.1. Study area

Situated at the geographic coordinates 1 °18′45.7″S and 36 °53′08.9″E, the study area encompasses the sprawling Mukuru (Figure 1), the second-largest informal settlement in Nairobi, Kenya. Nestled within Mukuru is Mukuru Kwa Njenga, a village serving as the focal point for the implementation of the CBS systems by Sanergy, predominantly in the form of FLTs (Larsen

Figure 1 | Mukuru Kwa Njenga in Nairobi, Kenya, East Africa.

et al. 2021) with a population of 113,032 (Corburn *et al.* 2017). The temperature regime, ranging from 10 to 26 °C, contributes to the nuanced environmental conditions. The precipitation pattern follows a bimodal distribution, with long rains prevailing from March to May and short rains from October to December (Aardenne Lisa Van 2017).

2.2. Data sources and collection methods

All the data used in this study were obtained through field measurements and from a peer-reviewed article by Johnson *et al.* (2022) in Kampala. The data from Johnson *et al.* (2022) were used, based on the assumption they were comparable as they were obtained from the model that uses data from one of the East African Cities, Kampala.

2.3. Field measurements for the different GHGs

Each GHG was measured in four replicates at points of capture, emptying, and storage using portable handheld gadgets (Figure 2(a)). The measurements were also done three times daily: morning, afternoon, and evening. The N_2O was measured using a G200 Gas Analyser (QED, Geotech, England). Carbon dioxide and methane were measured using GA 5000 Gas Analyser (QED, Geotech, England). This equipment was connected to the flux chamber through a horse pipe fitted with an external user-changeable 2.0 μm *polytetrafluoroethylene (PTFE)* traps. Variation in the pressure and oxygen level was monitored to be <22% so that the cell of the GA5000 could be operated safely. The unit of measurement for carbon dioxide and methane was in percentage. Still, it is converted to parts per million (ppm) using Equation (1).

$$Q_{\text{ppm}} = \frac{P}{100} \times 1,000,000 \tag{1}$$

where Q_{ppm} is the concentration of gas in parts per million (ppm), and P is the concentration of the gas in percentage. The pressure was recorded in the atmosphere (atm).

The flow velocity and gas flow volumes were measured using a Smart Anemometer (Testo 405i, United States) with a detection level of 0.00001 m^3/s. For this study, the device was inserted through a hole in a 50 mm diameter pipe to measure the flow rate, the volume flows, and the temperature of the gases exiting the flux chamber through the pipe.

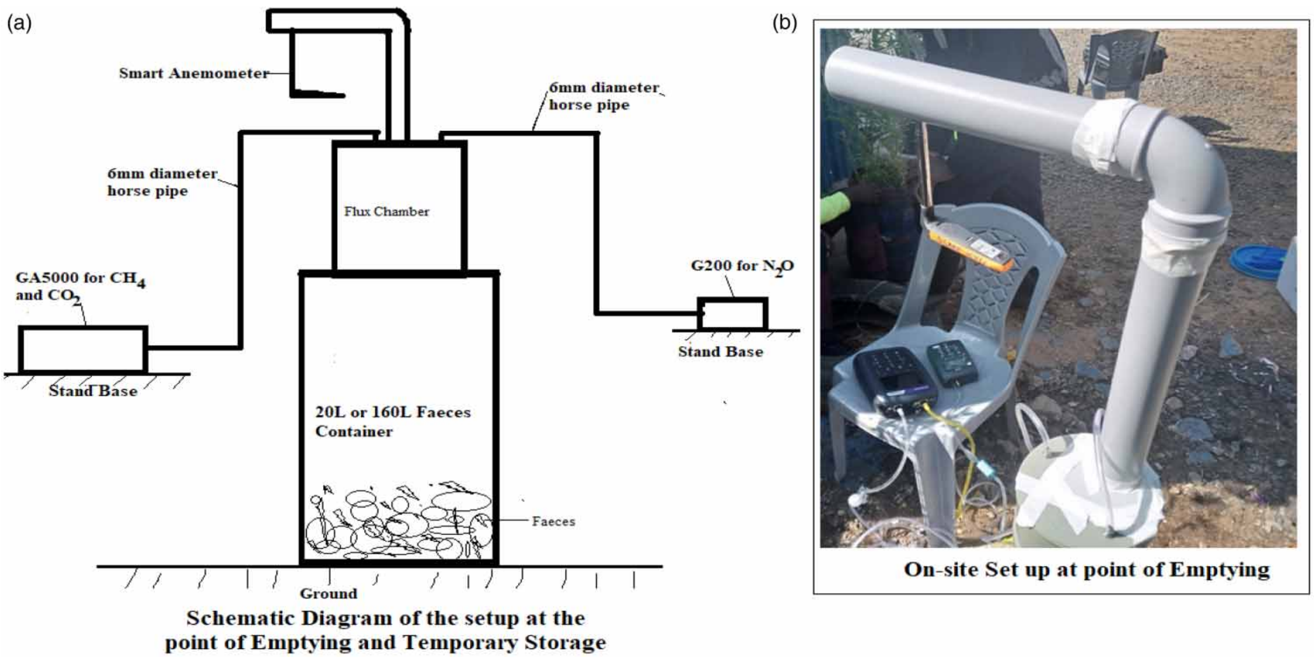


Figure 2 | Setup of the equipment.

2.4. Flux chamber

The design of the flux chamber (Figure 3) originated from Huynh *et al.* (2021), Leverenz *et al.* (2011), and Reddy *et al.* (2022) with some modifications in this study to connect the portable gas analysers through nipples fitted on the top surface of the flux chamber. It was made of a 6-inch (150 mm) PVC pipe fitted with a 50-inch diameter pipe for the outlet and connection of the smart anemometer. The pipe was 350 mm in height with a 45° bend and four sets of flux chambers were constructed for this study and used interchangeably.

2.5. Equipment setup within the CBS system

The containment of the FLTs/CBS system was divided into three points (Figure 4): capture of the waste inside the toilets, point of emptying the waste from the 20-L containers, and temporary storage/consolidation point into 160-L barrels depending on actual daily operation.

The division of the containment was done to allow measurement of the actual activity happening at the consolidation centre as the collected 20-L containers could have been taken directly to the treatment site. At each of these points, GHG emissions measurements were performed separately.

Measurement was carried out in the morning between 8 a.m. and 12 noon, afternoon (12 noon to 3 p.m.), and in the evening between 3 p.m. to 5:30 p.m. every day for 10 days. However, at the emptying point of the containment, measurements were taken only early in the morning as all the containers were emptied and taken back to the toilets.

The storage, after the consolidation centre was temporary, and the faeces took 3 days to a week before transportation to the treatment plant. This strategy was necessary to reduce the costs of transportation. All the sets of data collected were checked for outliers using Microsoft Excel version 2021.

2.5.1. Point of capture

The lead field operator of FLTs identified one FLT within the community for daily study. The identified toilet was then marked out of use for that day. On the morning of the measurement day, the flux chamber was placed on top of the squatting pan of the FLT (Figure 5(a)) leading directly to the faeces container, and the joint between them was sealed with cello tape to prevent air leakage. The smart anemometer was connected and then temperature, flow velocity, and volume readings were recorded after 1 h. Later, GA5000 and G200 were connected and respective readings for methane, pressure and nitrous oxide were recorded. The same steps were followed in the afternoon and evening time.

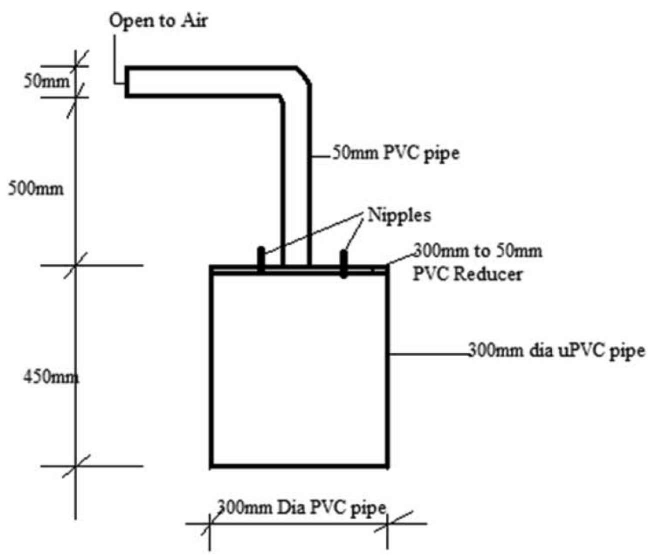


Figure 3 | Schematic diagram of the flux chamber.

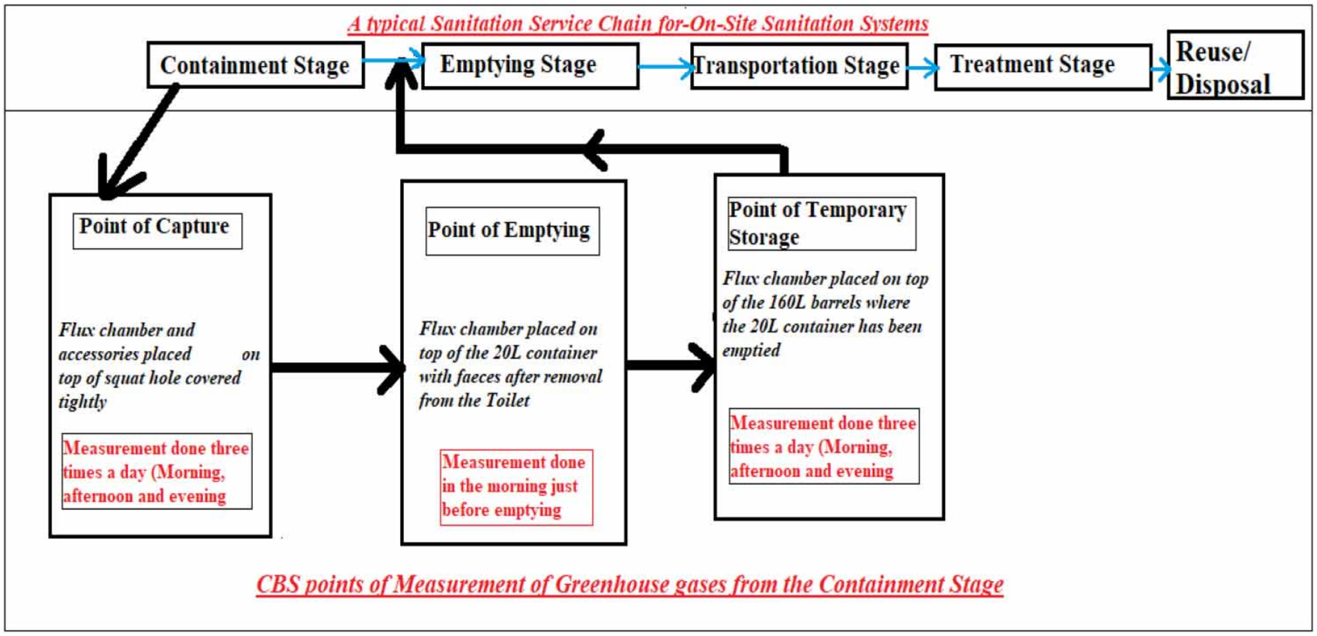


Figure 4 | Sanitation service chain and points of GHG measurement at containment of the CBS system.

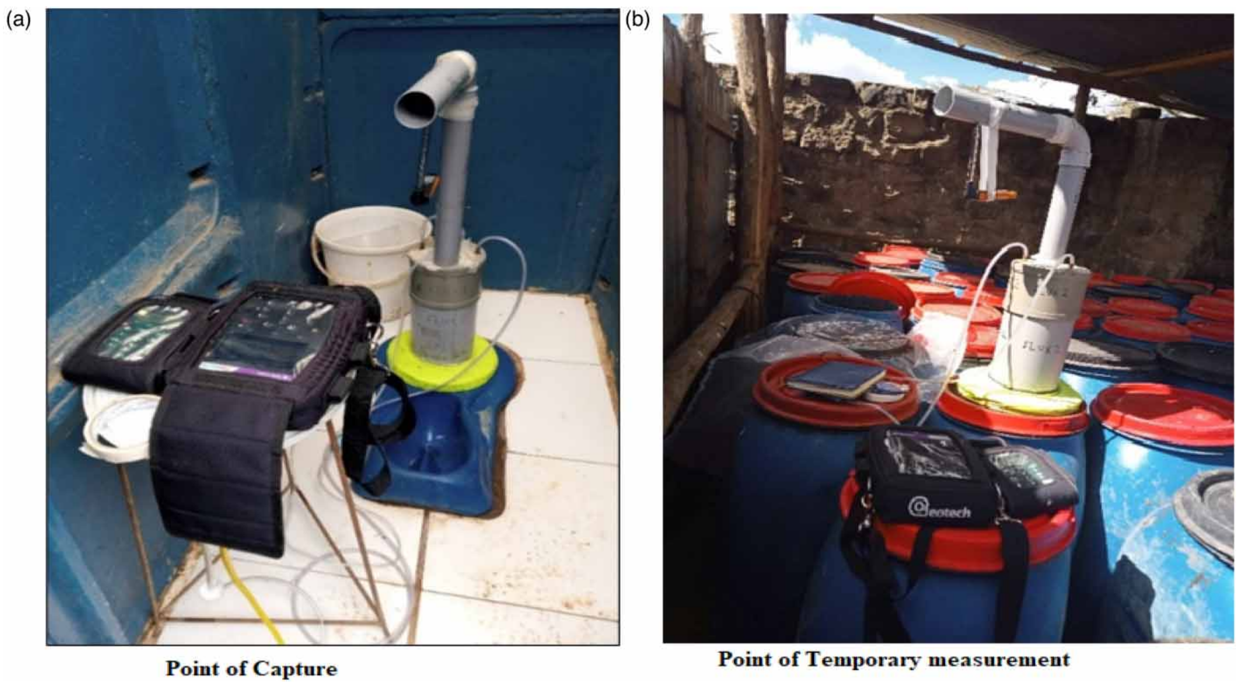


Figure 5 | Setup at the point of capture and temporary storage of the CBS system.

2.5.2. Emptying point

At this point, faeces samples brought in the containers using a *tuk-tuk* (tricycle) or handcart to the consolidation centre were sampled for measurements and the rest were consolidated immediately. The containers and the polyethylene sheets inside were opened and the flux chamber setup was immediately fixed on the top. The polyethylene sheet was used to reduce the exposure risk while handling the faecal matter. The flux chamber base was modified (Figure 2(b)) with a lid that fitted the opening of the faeces container and the edges between the flux chamber and the container were made airtight.

2.5.3. Point of temporary storage

The temporary storage point allowed faeces accumulation in 160-L barrels before transportation to the treatment plant. Sanitation waste (faeces) consolidated in each barrel weighed about 98 kg (Figure 5(b)). The barrel was opened only during filling, and it remained covered in the storage shade until transportation to the treatment plant.

2.6. Emission measurements and calculations

2.6.1. Measurement procedures

Upon connecting the GA 5000, initial readings fluctuated but eventually stabilised, and the recorded values are presented in Table 1. Conversely, the G200 displayed high initial readings that subsequently decreased and normalised to a constant value. The smart anemometer automatically recorded and printed flow velocity and volume flow readings. Notably, the smart anemometer readings were predominantly zero, except for temperature, which was consistently recorded and noted each time when the data were collected from the G200 and GA 5000.

Details of the quantity and origin of the sawdust used were not recorded. However, the amount of the faecal matter (including sawdust collected with it) from each of the 20-L containers was weighed and recorded. This quantity was used to estimate the number of persons using the toilet based on the data from Rose *et al.* (2015) and Oxfam WASH (2017). The quantity of the faeces from the 160-L barrel at the temporary storage was also weighed, however, it was not used to estimate the total number of users as it was purely the consolidated faecal matter from the 20-L containers.

The values of the concentration of the gases were estimated using the gas Equation (2) (Huynh *et al.* 2021):

$$\text{Gas concentration}\left(\frac{\text{mg}}{\text{m}^3}\right) = \left(\frac{C_{\text{ppm}}}{10^6}\right) \times \text{MW} \times \left(\frac{1{,}000\ \text{mg}}{\text{g}}\right) \times \left(\frac{RT}{P}\right) \tag{2}$$

where C_{ppm} is the concentration of gas in parts per million (ppm), MW is the molecular weight of the gas under consideration (g/mol), R is the gas constant (0.000082057 atm m^3/mol K), T is the absolute temperature (K), measured using the smart anemometer, P is the absolute pressure of the gas in the atmosphere (atm), read from the GA 5000 gas analyser.

Upon determination of the gas concentration in mg/m^3, the quantity of gas in g/day was calculated by multiplying the volume flows from the smart anemometer with the gas concentration while converting the seconds to days. As the measurement of the emissions was executed during the day only, an assumption was made to distribute the quantity of the gases

Table 1 | GHGs (ppm) recorded from the equipment

			G200 readings (ppm)	
Date	**Time**	**Container ID**	**Methane**	**Nitrous oxide**
25/11/2021	Morning	F1	0.00 ± 0.00	43 ± 9.8
27/11/2021	Morning	F2	0.00 ± 0.00	42 ± 9.8
30/11/2021	Morning	F3	0.00 ± 0.00	39 ± 9.8
02/12/2021	Morning	F4	0.00 ± 0.00	36 ± 9.8
25/11/2021	Afternoon	F1	0.00 ± 0.00	39 ± 9.8
27/11/2021	Afternoon	F2	0.00 ± 0.00	49 ± 9.8
30/11/2021	Afternoon	F3	0.00 ± 0.00	43 ± 9.8
30/11/2021	Afternoon	F4	0.00 ± 0.00	43 ± 9.8
25/11/2021	Evening	F1	0.00 ± 0.00	37 ± 9.8
27/11/2021	Evening	F2	0.00 ± 0.00	42 ± 9.8
30/11/2021	Evening	F3	0.00 ± 0.00	40 ± 9.8
03/12/2021	Evening	F4	0.00 ± 0.00	40 ± 9.8

throughout 24 h. This was done by multiplying the resulting emission by 28,8000 s (measurement for morning, afternoon, and evening for points of capture and temporary storage) and by 84,6000 s (measurement done in the morning only at the end of emptying). The resulting values were divided by the quantity of the faeces in kilograms measured from each container (20 and 160 L) at the point of capture, emptying and temporary storage (Table 2). The average quantity of faeces obtained during the study per container of 20 L was 5.4 kg.

2.6.2. Carbon dioxide equivalent

The emission value obtained for each gas emitted was converted to carbon dioxide equivalent values using the conversion factor obtained from the IPCC Guidelines 2019 (IPCC 2019). The global warming potential conversion factors considered were 34 for methane, 34 for nitrous oxide, and 1 for carbon dioxide (GWP) (Vallero 2019).

3. RESULTS AND DISCUSSIONS

3.1. Quantity of GHGs emitted from the capture

After summing up the morning, afternoon and evening emissions, methane gas (0.00 g/day/kg of faecal matter) was not detected at the capture point (Table 3). This could have been because there was less biodegradation of the fresh faeces, resulting from the aerobic condition (exposure to full oxygen flow) and cover materials (Niwagaba 2009; Semiyaga *et al.* 2018; Ryals *et al.* 2019). The cover materials absorb most moisture, leaving the faeces dry with little chance of degradation. The emission of nitrous oxide remained almost the same during the day (Figure 6) due to the constant exposure to free oxygen (Shaw *et al.* 2021; Manga & Muoghalu 2024).

At the same time, very little nitrous oxide (0.34 g/day/kg of faeces after summing from morning, afternoon, and evening hours) was detected at the point of capture, resulting from little biodegradation activities (Andersen *et al.* 2010). However, the quantity of nitrous oxide was higher than that of methane due to existing aerobic conditions at the surface of the container (Johnson *et al.* 2022).

3.2. Emissions from the emptying

The quantity of methane (below the detection level) and nitrous oxide (0.34 g/day/kg of faecal) was low due to little biodegradation (Table 3) resulting from high aeration (Osada *et al.* 2000). This is further supported by the theoretical evidence that

Table 2 | Calculation of the emissions per capita

Total emissions from direct measurement at containment		Methane	Nitrous oxide
Values without GWP factor (g/day/kg of faecal matter)		0.16 ± 0.09	0.70 ± 0.11
Cover material	0.1 kg/per person/day (Oxfam WASH 2017)	0.228 kg/person/day and considering 5 days, faeces spent at containment with a total quantity of faeces per toilet of 5.4 kg estimated on average giving 5persons	
Faeces	0.13/per person/day (Rose *et al.* (2015))		
Total emission (g/day/capita)		0.03 ± 0.02	0.14 ± 0.02

Table 3 | Summary of GHG emission at each point of containment of the CBS system

	Total emissions (g/day/kg of the faecal matter)		
Point of measurement	Carbon dioxide	Methane	Nitrous oxide
At the point of capture	4.9 ± 1.1	0.00 ± 0.00	0.34 + 0.02
At the point of emptying	340 ± 25	0.00 ± 0.00	0.34 ± 0.11
At the point of temporary storage	47 ± 14	0.16 ± 0.09	0.03 ± 0.01
Total emission for each gas	400 ± 29	0.16 ± 0.09	0.70 ± 0.11

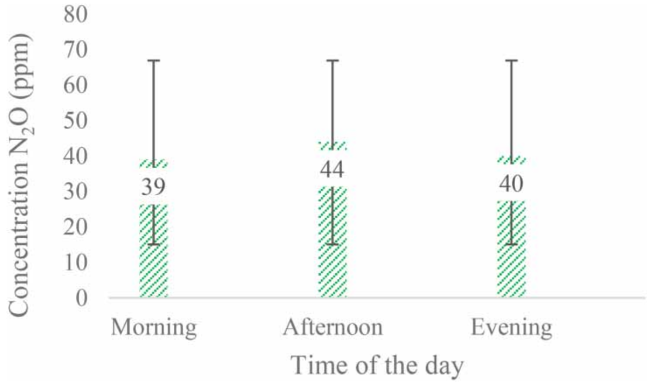


Figure 6 | Variation of the concentration of N_2O during the day.

shows little decomposition of the sanitation waste during emptying arising from the little time (2–3 days) the waste spends in the containment (Hellmann *et al.* 1997; Beck-Friis *et al.* 2001; Andersen *et al.* 2010; World Bank 2019). The fact that fresh sawdust covered the faeces in the containers, there is a higher chance the sawdust could have caused a reduction in the moisture content (Semiyaga *et al.* 2018) resulting in low emissions.

3.3. Emissions from the temporary storage

The highest quantity of methane gas (0.16 g/day/kg of faecal matter) was obtained during the temporary storage, due to the anaerobic digestion in the 160-L barrel covered with the lids (Andersen *et al.* 2010) and due to the larger container sizes of 160 L (Johnson *et al.* 2022). Nitrous oxide (0.03 g/day/kg of faecal matter) was low due to the anaerobic condition in the barrel (Andersen *et al.* 2010). The increase in the quantities of methane could have also contributed to the lower quantities of nitrous oxide (Park *et al.* 2011). Generally, there were higher quantities of the GHGs (Figure 7) obtained at this point due to the longer time and favourable condition of the consolidated amount of the faeces in the 160 L (Hellmann *et al.* 1997; Beck-Friis *et al.* 2001; Chan *et al.* 2011) and probably the depth of the content (Nakagiri *et al.* 2017).

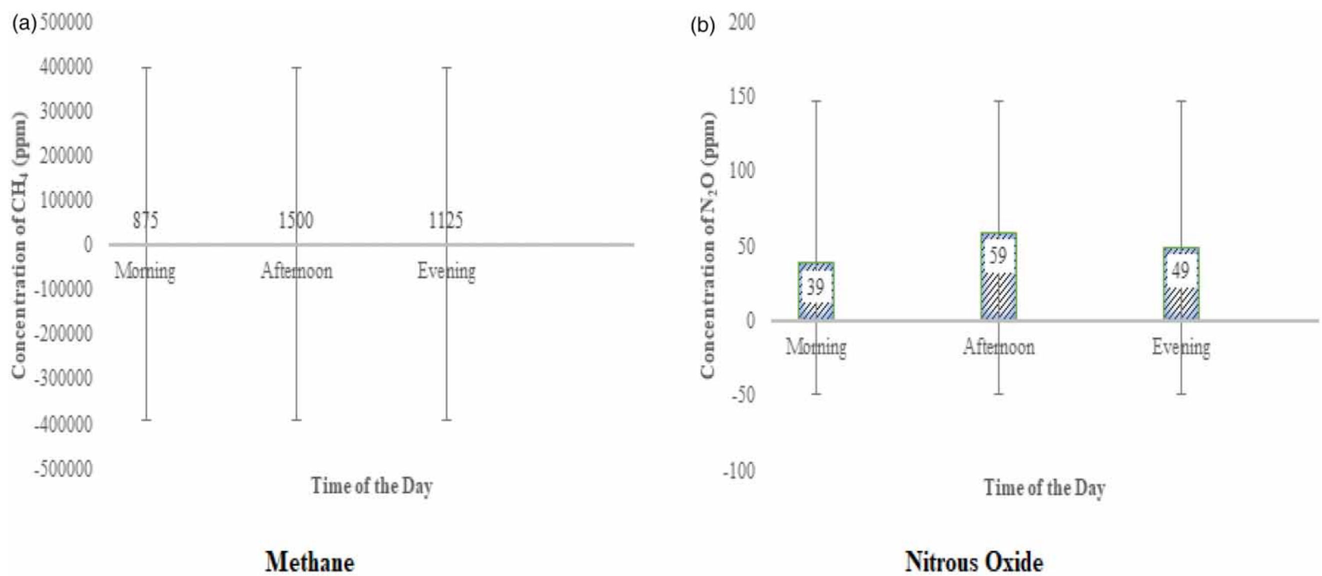


Figure 7 | Variation of GHGs at temporary storage point.

3.4. Comparison of emissions within the containment points of the CBS system

Nitrous oxide was emitted in quantities higher than methane (Figure 8 and Supplementary Table S2) at the points of capturing and emptying (Table 3). This was attributed to the exposure of the containers to open air, which resulted in more aerobic conditions (Johnson *et al.* 2022).

However, at the point of temporary storage, methane was detected due to the presence of anaerobic conditions (Nakagiri *et al.* 2017), resulting from consolidating the faeces in the 160-L barrels before transportation. The unit of measurement for the total quantity of the gases was in g/day/kg of faecal matter to accommodate the differences in the sizes of the containers. The unit was then converted to kg/CO_2eq/day/kg of faecal matter to cater to global warming potential (GWP).

3.5. Comparisons of GHG emissions as CO_2 equivalents

This study calculated methane and nitrous oxide emissions from the CBS system containment, totalling 16 kgCO_2 eq/year/capita (Table 4), significantly lower than the 37 kgCO_2 eq/year/capita estimated by Johnson *et al.* (2022). The discrepancy may be attributed to varying environmental conditions, such as temperature, pressure, and aeration (Huynh *et al.* 2021), and the use of modified emission factors by Johnson *et al.* (2022) that are based on IPCC assumptions (Shaw *et al.* 2021) rather than actual system performance.

Notably, the study's emission values are 73% lower for methane (0.40 kgCO_2 eq/year/capita vs. 15 kgCO_2 eq/capita) and 32% lower for nitrous oxide (15 kgCO_2 eq/year/capita vs. 22 kgCO_2 eq/capita) compared to the estimate values by Johnson *et al.* (2022). The lower emission values may also be because the study does not account for urine-derived emissions, a significant source of nitrous oxide (Reid 2020). Given the limitations and uncertainty in sanitation system emission estimates (Doorn *et al.* 2006), further research is necessary to confirm these findings and provide more accurate data.

Carbon dioxide (79 kgCO_2 eq/year/capita) being biogenic was not considered in estimating the total emissions (Table 4) for the comparison with IPCC methodology since the method does not include it. This is because faecal waste at the containment

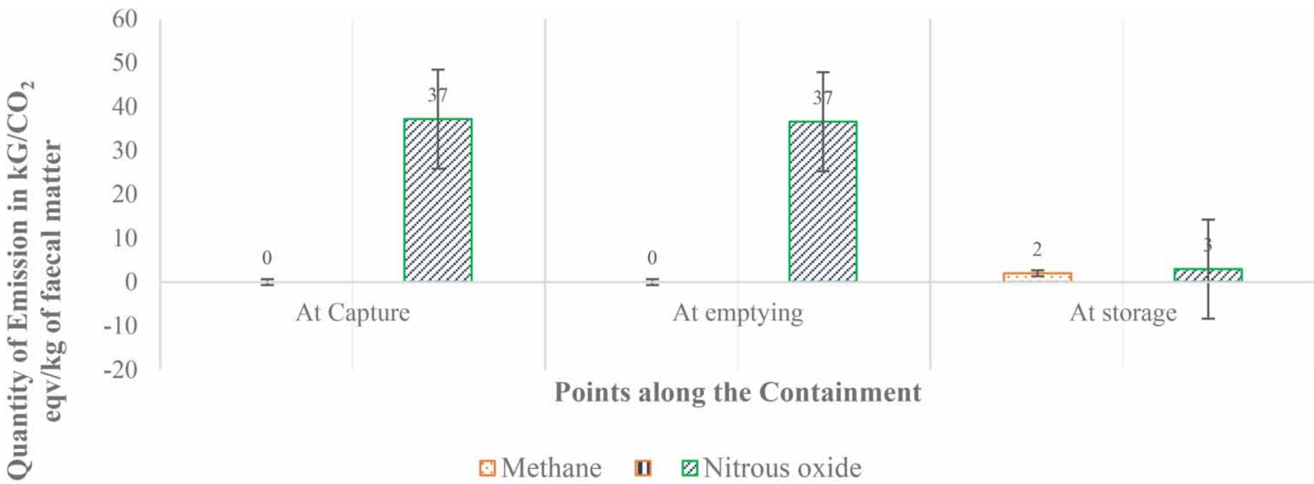


Figure 8 | Quantity of GHG emissions at different points of containment of the CBS system.

Table 4 | Summary of GHG emissions after conversion to carbon dioxide equivalent

Total emissions from direct measurement at containment	Carbon dioxide	Methane	Nitrous oxide
Values without GWP factor (g/day/kg of faecal matter)	400 ± 29	0.16 ± 0.09	0.70 ± 0.11
Total emission (g/day/capita)	79 ± 5.7	0.03 ± 0.02	0.14 ± 0.02
100-year GWP	1	34	300
Values GWP factor (kgCO_2 eq/year/capita)	79 ± 5.7	0.40 ± 0.25	15 ± 2.2
Total emission kgCO_2 eq/capita/year) excluding carbon dioxide		**16 ± 2.2**	

originates from plant tissues and this process allows for the natural carbon cycle flow (Brown *et al.* 2008; Shaw *et al.* 2021; Mehmood *et al.* 2022). Carbon dioxide also has a GWP of only 1 compared to methane (34) and nitrous oxide (300) in the sanitation system (IPCC 2019) and thus, is considered only to have a minimum impact (Shaw *et al.* 2021; Johnson *et al.* 2022).

4. CONCLUSIONS

This study provides new insights into GHG emissions from CBS systems. Methane and nitrous oxide are identified as primary emissions, with nitrous oxide production dominating due to aerobic conditions. Although carbon dioxide is present, its biogenic nature and minimal GWP render it to be a minor contributor. Our findings show significantly lower emissions – 73% less methane and 32% less nitrous oxide – than previous estimates. These results underscore the importance of accurate on-site measurements and improved techniques to inform sustainable strategies for mitigating GHG emissions in urban sanitation.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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