Kathmandu University
Journal of Science, Engineering and Technology

Greenhouse gas emissions from different containment system in Dhulikhel Municipality in Nepal

Prativa Poudel[a,b], Subodh Sharma*[a,b], Prayon Joshi[b], Anish Ghimire[c], and Manish Baidya[b]

[a]Department of Environmental Science and Engineering, Kathmandu University, Nepal.
[b]Aquatic Ecology Centre, School of Science, Kathmandu University, Nepal.
[c]Department of Water Resources and Environmental Engineering, Asian Institute of Technology, Pathum Thani 12120, Thailand.

Abstract

On-site sanitation systems (OSS), are commonly used in low and middle-income countries (LMICs) like Nepal because of their practicality and economic feasibility. These systems are vital for ensuring access to basic sanitation, which is essential for both human health and the environment. However, they can significantly contribute to greenhouse gas (GHG) emissions through the microbial breakdown of faecal sludge via anaerobic and aerobic processes. Onsite containments are responsible for the majority of the GHG emissions occurring in the whole sanitation value chain. Therefore, this study intends to estimate the GHG emissions from different onsite containments prevailing in Dhulikhel Municipality using updated 2019 Intergovernmental Panel on Climate Change (IPCC) Guidelines. It was observed that 2.33 Gg CO_2 eq-per year is being emitted annually from Dhulikhel municipality from the containment systems and open defecation. A total of 2.32 Gg CO_2 eq-per year is contributed by methane (CH_4) emission from containment and rest of from nitrous oxide (N_2O) emissions from the open defecation solely. Similarly, the annual per capita CH_4 and N_2O emissions (from OD) from the onsite containments prevailing in Dhulikhel were computed as 67.52 kg CO_2-eq per person per year and 18.39 kg CO_2-eq per person per year respectively. A comparison of the emission was made between the containments that were emptied once and those which were never emptied. Paired sample t-test showed that emptied containments are likely to emit lesser CH_4 emissions compared to those which are never emptied (p-value<0.05). Similarly, a comparison of emissions was conducted between sealed and unsealed containment systems. Sealed containment systems were found to produce significantly lower GHG emissions compared to unsealed systems (p-value < 0.05). The design and typology of containment structures play a critical role in influencing emissions from different systems. However, our national statistics and other reports do not include precise and clear typological definition which have underestimated the emission originating from different kind of containment units.

Keywords: Methane; Carbon dioxide; Nitrous oxide; Greenhouse gas emission; Containments.

1. Introduction

Globally, 43% of people worldwide use onsite sanitation system (OSS), which have several benefits over sewered systems, such as being less expensive and less complicated infrastructure needs [1]. However, because of their ability to emit greenhouse gases (GHG), these systems have lately drawn attention for their implications on the environment [2]. Significant amount of methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) is produced by non-sewered technologies, depending on whether they are working in anaerobic or aerobic conditions [3–5].

Current global estimates indicate that the sanitation sector contributes approximately 1.3% of global GHG emissions [6]. Though this emission from sanitation seems small in percentages, other studies have suggested that the variation of the emission can be contextual. For instance, data from Kampala research show that the sanitation sector's emissions might likely account for nearly 50% of the city's total emissions [7]. A meta-analysis further suggests that as much as 5% of anthropogenic methane emissions are linked to non-sewered sanitation systems[8]. Additionally, onsite sanitation systems, such as pit latrines, are estimated to be responsible for 1–2% of global GHG emissions [9]. These figures underscore the significance of sanitation as a source of emissions, particularly CH_4 and N_2O, which has a global warming potential (GWP) of 27 and 273 times greater than CO_2 over a 100 years period [10]. However, CO_2 is not included by intergovernmental panel for climate change (IPCC) as it is considered as biogenic emission [11]. Though, these scattered literature indicate that GHG emission from sanitation are in larger scale, there are very scarce datasets to actually guide on the mitigating option from sanitation sector [2].

Various methodologies, including modeling, empirical approaches, and laboratory-based estimations, are available for quantifying emissions [6, 12, 13]. However, accurately estimating emissions from onsite sanitation systems remains challenging due to the diverse nature of sludge characteristics [14]. Empirical methods face additional challenges, such as limited adaptability to different geographical contexts and the high cost of gas sample analysis [13]. Moreover, there is a significant lack of comprehensive data covering emissions across the entire sanitation value chain. A study conducted in Kampala, Uganda sought to address this gap by quantifying emissions from the containment stage to faecal sludge treatment plant (FSTP) utilization. The findings indicated that containment systems alone accounted for 49% of total emissions along the sanitation chain [7]. However, emissions from containment systems can vary significantly depending on factors such as sludge

*Corresponding author. Email: subodh.sharma@ku.edu.np

conditions (wet or dry, influenced by groundwater (GW) inundation), whether containments are emptied or not, and user parameters [13, 15]. Although some evidences are available, it remains insufficient to draw definitive conclusions about emissions from each specific containment typology.

Despite the fact that the emissions from sanitation are real, research on GHG emissions from sanitation systems remains limited, particularly in low- and middle-income countries (LMICs), where resource constraints often sanitation sector is less prioritized [13]. Additionally, this lack of data and evidence is a major challenge for understanding the true scale of emissions and identifying effective mitigation strategies [2, 16]. Addressing this research gap is crucial, as the sanitation sector holds considerable potential for contributing to global emission reduction targets.

Nepal is a country where the majority of the population relies on onsite sanitation systems. Following its declaration as an open defecation-free country in 2019, the number of sanitation containments, such as septic tanks and pit latrines, has significantly increased [17]. As a party to the Paris Agreement, Nepal is committed to lowering greenhouse gas (GHG) emissions to net zero and mitigating the consequences of climate change. In line with this commitment, Nepal has submitted three National Communications to the United Nations Framework Convention on Climate Change (UNFCCC) in 2004, 2014, and 2021, respectively [18, 19]. Despite these efforts, emissions from decentralized wastewater systems, including onsite sanitation, have been calculated using broad categories such as "pit latrines" and "septic tanks". This approach overlooks the variations in emission factors (EF) and methane correction factors (MCF) associated with different types of containment systems. IPCC has acknowledged these differences and provided guidelines for EF and MCF based on parameters like the number of toilet users and GW inundation [11]. However, Nepal's National communications to the UNFCCC have relied on generalized emission factors, potentially underestimating emissions from onsite sanitation systems.

With the gaps identified, this specific research aims to compute and estimate the CH_4 and N_2O emission from various containment system that exist in the Dhulikhel municipality of Nepal by utilizing IPCC 2019 improved approach for GHG inventory.

2. Materials and methods

2.1. Study area

This study was carried out in Dhulikhel Municipality of Kavrepalanchowk district situated southeast of Kathmandu, Nepal (Fig. 1). Dhulikhel is one of the municipalities where the United Cities and Local Governments Asia-Pacific (UCLG ASPAC)'s project "Municipalities Network Advocacy in Sanitation in South Asia" is being implemented [20]. In Dhulikhel, the majority of the population (around 84%) relies on onsite sanitation systems, while 2% still practice open defecation. According to a shit flow diagram (SFD) report by ENPHO (2021), 51% of the excreta in Dhulikhel is safely managed, leaving 49% unsafely managed [21].

2.2. Data collection

The data on containment typology was sourced from the Shit Flow Diagram (SFD) of Dhulikhel Municipality, prepared by ENPHO in 2021[21]. Total population of the Municipality was taken from census 2021[22]. Methane conversion factor (MCF) and the Emission factor (EF) were taken from default values from IPCC [11]. For the MCF that was not listed, were either searched from literature review or assumption made based on expert opinion [7].

Table 1: Parameters for methane emission.

Parameters	Units	Values	Remarks
S_j	–	0	No sludge removal mechanism in the containment
R_j	–	0	No mechanism for the methane capture present
BOD_5	g/capita/day	40	From IPCC [11]
I_j	–	1	No additional BOD_5 in the treatment
GWP	CO_2 eq-	27	Based on IPCC AR6 [10]

2.3. CH_4 emission calculations

The method used for the computation of the emission was - 2019 refinement to 2006 IPCC recommendations for National Greenhouse Gas Inventories. CH_4 emissions from treatment/discharge pathway or system, j, in inventory year, kg CH_4/yr is computed using Eq. 1 [11].

$$\text{CH}_4 \text{ Emission} = [(TOW_j - S_j) \times EF_j - R_j] \tag{1}$$

TOW_j: total organics in wastewater system in inventory year, kg BOD_5/yr

S_j: organic component removed from wastewater in inventory year (kg BOD_5/yr)

j: treatment/discharge pathway or system

EF_j: emission factor for treatment/discharge pathway or system (kg CH_4/kg BOD_5).

R_j: amount of CH_4 recovered or flared from treatment/discharge pathway or system, j, in inventory year (kg CH_4/yr), the default value is zero.

The parameters and their respective values used in the calculation of the CH_4 emissions are tabulated in Table 1.

Total organics in domestic wastewater by treatment pathway is calculated as in Eq. 2.

$$TOW_j = \Sigma\,[TOW \times U_j \times T_{ij} \times I_j] \tag{2}$$

TOW_j: total organics in wastewater in inventory year, kg BOD_5/yr, for income group i and treatment/discharge pathway or system.

TOW: total organics in wastewater in inventory year, kg BOD_5/yr.

U_j: fraction of population in income group i in inventory year.

T_{ij}: degree of utilization of treatment/discharge pathway or system, j, for each income group fraction

I_j: correction factor for additional industrial BOD_5 discharged into treatment/discharge pathway or system j.

Total organically degradable material in domestic wastewater is calculated by Eq. 3.

$$TOW = P \times BOD \times 0.001 \times 365 \tag{3}$$

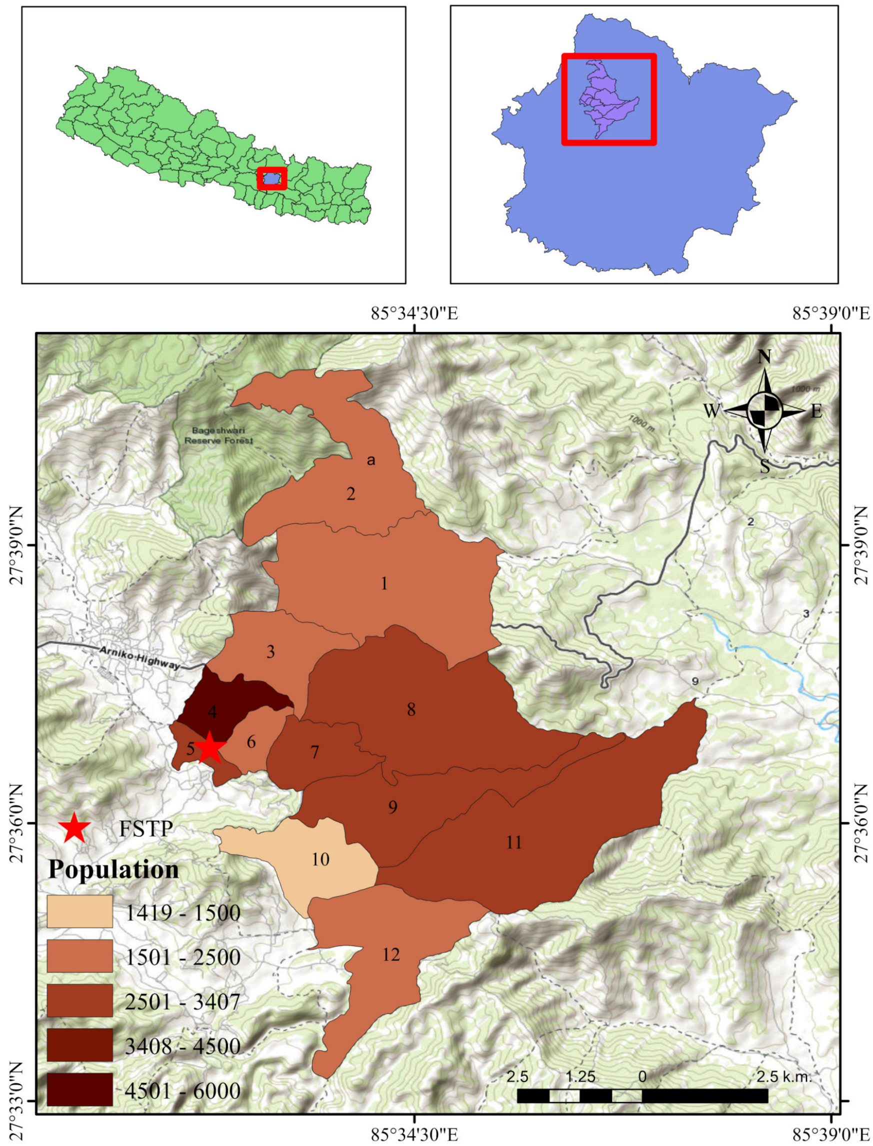

Figure 1: Map of Nepal showing Kavrepalanchowk district (top-left); Kabhrepalanchowk district showing ward level map of Dhulikhel Municipality (top-right); and ward level map of Dhulikhel Municipality showing population distribution and location of faecal sludge treatment plant (FSTP) (bottom).

TOW: total organics in wastewater in inventory year, kg BOD_5/yr

P: country population in inventory year, (person)

BOD: country-specific per capita BOD in inventory year, g/person/day.

0.001: conversion from grams BOD to kg BOD

For a wastewater treatment and discharge system, the methane conversion factor (MCF) the maximal methane-producing potential (B_0) define the emission factor (EF)[11]. This relationship is represented by Eq. 4.

$$EF = MCF \times B_0 \quad (4)$$

EF: Emission factor for methane emissions from each treatment or discharge pathway/system (kg CH_4 per kg BOD).

B_0: Maximum CH_4-producing capacity (kg CH_4 per kg BOD).

MCF: Methane Conversion Factor, representing the fraction of degradable organic material converted to methane under specific treatment or discharge conditions (dimensionless).

2.4. N_2O calculations

The estimation of N_2O emissions require specific activity data, including the nitrogen content in wastewater effluents, the population of the country, and the average annual per capita protein production (measured in kg/person/year). Protein production per capita encompasses both consumed protein, as reported by the Food and Agriculture Organization (FAO), and adjustments for unconsumed protein and industrial protein discharges into sewer systems.

The estimation of protein consumed is calculated using Eq. 5 [11].

$$\text{Protein supply} = \text{Protein} \times FPC \quad (5)$$

Protein supply: annual per capita protein supply, kg protein/person/yr

FPC: Fraction of protein consumed. The default value for Asia is 0.96.

N_2O emissions from domestic wastewater treatment plants is calculated using Eq. 6 [11].

Table 2: Value of EF suggested by IPCC [11].

Containment type	EF (kg N_2O-N/kg N)
Septic tank	0
Pit latrines	0
Open Defecation	0.008

$$N_2O \text{ plants} = [\Sigma (U_j \times T_{ij} \times EF_j)] \times TN_{DOM} \times \frac{44}{28} \quad (6)$$

N_2O plants: N_2O emissions from domestic wastewater treatment plants in inventory year, kg N_2O/yr

TN_{DOM}: total nitrogen in domestic wastewater in inventory year, kg N/yr.

U_j: fraction of population in income group i in inventory year.

T_{ij}: degree of utilization of treatment/discharge pathway or system j, for each income group fraction i in inventory year.

i: income group: rural, urban high income and urban low-income

j: each treatment/discharge pathway or system

EF_j = emission factor for treatment/discharge pathway or system j, kg N_2O-N/kg N

The EF suggested by IPCC is tabulated in Table 2. The EF for all type of containment system is considered 0 in the calculations. The EF for open defecation was considered 0.008 kg N_2O-N/kg N from Johnson et al. [7] assuming that the open defecation is done in open ground and disposed in soil.

Total nitrogen in domestic wastewater by treatment pathway is calculated using Eq. 7.

$$TN_{DOM_j} = P_{treatment_j} \times \text{Protein} \times F_{NPR} \times N_{HH} \times F_{NON-CON} \times F_{IND-COM} \quad (7)$$

TN_{DOM_j}: total annual amount of nitrogen in domestic wastewater for treatment pathway j, kg N/yr

$P_{treatment_j}$: human population who are served by the treatment pathway j, person/yr $Protein$ = annual per capita protein consumption, kg protein/person/yr

F_{NPR}: fraction of nitrogen in protein, default = 0.16 kg N/kg protein

$F_{NON_{CON}}$: factor for nitrogen in non-consumed protein disposed in sewer system, kg N/kg N.

$F_{IND_{COM}}$: factor for industrial and commercial co-discharged protein into the sewer system, kg N/kg N

N_{HH}: additional nitrogen from household products added to the wastewater

The parameters and their respective values used in the calculation of the N_2O emissions are tabulated in Table 3.

2.5. Global warming potential

The total GHG emission is calculated in CO_2 equivalent by using the global warming potential (GWP) for CH_4 as 27 and that for N_2O as 273 for 100-year time horizon [10].

Table 3: Parameters for nitrous oxide emission.

Parameters	Units	Values	Remarks
Population	Individuals	31596	Active population based on SFD, 2021 of Dhulikhel
Protein consumption	g/ day/ person	82.96	From IPCC [11]
Conversion factor	–	1.57	Equivalent to 44/28. Conversion factor between N_2 (M.W. 28) to N_2O (M.W. 44)
GWP	CO_2 eq-	273	Based on IPCC AR6 [10]
Gg to kg	–	1000000	Factor for unit conversion

2.6. Statistical analysis

Descriptive statistical analysis was done in MS Excel (Ver. 2016). The descriptive analysis, graphical representation and inferential analysis were done using Python Environment using Jupyter Notebook with packages namely matplotlib, pandas, NumPy, and sci-kit learn. Inferential analyses like paired sample t-tests and independent sample t-tests, were conducted to assess the significance of the emission rates from different containment types.

3. Results and discussion

3.1. Distribution of sanitation technology, MCF and EF

The sanitation system in Dhulikhel was dominated by OSS which accounts for 83% of the total sanitation coverage (Fig. 2). These on-site systems include fully lined tank (49.40%), lined tanks (14.46%), lined pits (15.46%), unlined pit (26.66%) and septic tanks (6.02%) [21]. These numbers and percentages imply that the municipality dependence on decentralized sanitation solutions. The differences in tank types and pit demonstrate various construction methods and containment approaches within the community.

For the calculation of emissions, the SFD categories were further subdivided into emptied and never-emptied, as well as sealed and unsealed categories. This categorization was done based on the description of the containment that was present in SFD. The details of the type of containment and the categorization and the respective MCF and EF are presented in Table 4 [21].

3.2. Greenhouse gas emission from different containment type

Calculated per capita CH_4 emission is presented in Fig. 3. The emission from unlined pit latrine was found higher compared to other type of the containments in Dhulikhel. The average per capita CH_4 emission from unlined pits, lined pits, lined tanks, septic tank, fully lined tank and open defecation were 134.81 ± 33.02, 112.34± 24.61, 87.85 ± 9.30,76.86 ± 6.32,74.89 ± 6.10, and 23.65 kg CO_2 eq-per person per year respectively (Fig. 3). Unlined pit latrine has the potential for GW inundation and percolation of the liquid from the surrounding, leading to increase in the moisture favoring anaerobic conditions [4, 9, 15]. This increases the chance of CH_4 emission [9, 15, 16]. This result is similar to the study done by Johnson et al. [7]. Johnson et al. [7] did whole system analysis of the citywide sanitation in Kampala, Uganda reporting that unlined pits have higher emission ranging from 38.556 – 107.95 kg CO_2 eq-per person per year. Similarly, a study conducted by Reddy

Table 4: Categories and classification of the different containment prevalent in Dhulikhel Municipality.

Containment type from SFD [21]	Categorization	Emptying	Sealing	MCF[a]	Assumption/ References
Septic tank connected to centralized combined sewer	Septic Tank	n/a	Sealed	0.3	No inundation and no accumulation[b]
Septic tank connected to soak pit	Septic Tank	Emptied	Sealed	0.3	No chance of inundation and limited accumulation thus less emission[b]
Septic tank connected to soak pit	Septic Tank	Not Emptied	Sealed	0.35	No chance of inundation but accumulation due to no emptying[b]
Septic tank connected to open drain or storm sewer	Septic Tank	Emptied	Sealed	0.3	No chance of inundation and limited accumulation thus less emission[b]
Septic tank connected to open drain or storm sewer	Septic Tank	Not Emptied	Sealed	0.35	No chance of inundation but accumulation due to no emptying[b]
Septic tank connected to 'don't know where'	Septic Tank	Emptied	Sealed	0.3	No chance of inundation and limited accumulation thus less emission[b]
Septic tank connected to 'don't know where'	Septic Tank	Not Emptied	Sealed	0.35	No chance of inundation but accumulation due to no emptying[b]
Fully lined tank (sealed) connected to centralized combined sewer	Fully Lined Tank	n/a	Sealed	0.3	No inundation and no accumulation[b]
Fully lined tank (sealed), no outlet or overflow	Fully Lined Tank	Emptied	Sealed	0.3	No chance of inundation and limited accumulation thus less emission[b]
Fully lined tank (sealed), no outlet or overflow	Fully Lined Tank	Not Emptied	Sealed	0.35	No chance of inundation but accumulation due to no emptying[b]
Fully lined tank (sealed) connected to soak pit	Fully Lined Tank	n/a	Sealed	0.3	No chance of inundation and limited accumulation[b]
Fully lined tank (sealed) connected to open ground	Fully Lined Tank	Emptied	Sealed	0.3	No inundation and aerobic conditions in open ground[b]
Fully lined tank (sealed) connected to open ground	Fully Lined Tank	Not Emptied	Sealed	0.35	No inundation and anaerobic conditions due to accumulation[b]
Lined tank with impermeable walls and open bottom, connected to centralized combined sewer	Lined Tank	n/a	Unsealed	0.4	[b]
Lined tank with impermeable walls and open bottom, no outlet or overflow	Lined Tank	Emptied	Unsealed	0.3	[b]
Lined tank with impermeable walls and open bottom, no outlet or overflow	Lined Tank	Not Emptied	Unsealed	0.4	[b]
Lined tank with impermeable walls and open bottom, connected to soak pit	Lined Tank	Emptied	Unsealed	0.35	[b]
Lined tank with impermeable walls and open bottom, connected to soak pit	Lined Tank	Not Emptied	Unsealed	0.4	[b]
Lined tank with impermeable walls and open bottom, connected to open ground	Lined Tank	Emptied	Unsealed	0.35	[b]
Lined tank with impermeable walls and open bottom, connected to open ground	Lined Tank	Not Emptied	Unsealed	0.4	[b]
Lined pit with semipermeable walls and open bottom, no outlet or overflow	Lined Pit	Emptied	Unsealed	0.35	[b]
Lined pit with semipermeable walls and open bottom, no outlet or overflow	Lined Pit	Not Emptied	Unsealed	0.45	[b]
Unlined pit, no outlet or overflow	Unlined Pit	Emptied	Unsealed	0.45	[b]
Unlined pit, no outlet or overflow	Unlined Pit	Not Emptied	Unsealed	0.4	[b]
Containment failed, damaged, collapsed or flooded	Unlined Pit	n/a	Unsealed	0.7	Risk of GW Inundation [11]
Open defecation	Others	n/a	Others	0.1	[11]
Septic tank to soak pit, risk of GW pollution	Septic Tank	n/a	Sealed	0.35	[b]
Lined pit, semipermeable walls, risk of GW pollution	Lined Pit	Emptied	Unsealed	0.5	[b]
Lined pit, semipermeable walls, risk of GW pollution	Lined Pit	Not Emptied	Unsealed	0.6	Chance of inundation but accumulation due to no emptying

Note: [a] for CH_4; [b] Limited references, taking value between IPCC [11] and Diaz Valbuena et al. [3]; n/a: not available

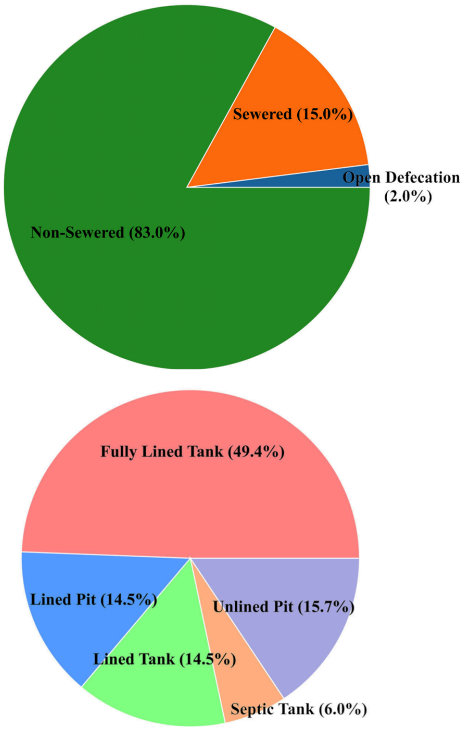

Figure 2: Distribution of the sanitation system in Dhulikhel Municipality [21].

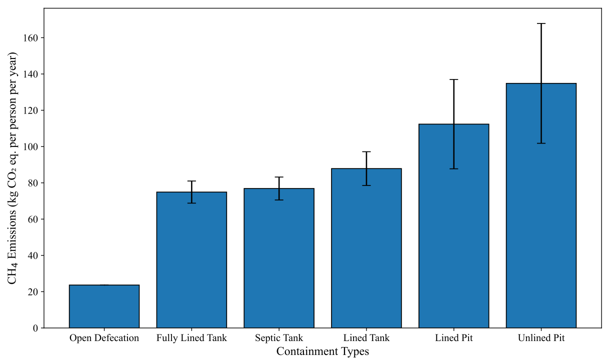

Figure 3: Average per capita CH_4 emission in kg CO_2 eq-per person per year of each containment type in Dhulikhel Municipality.

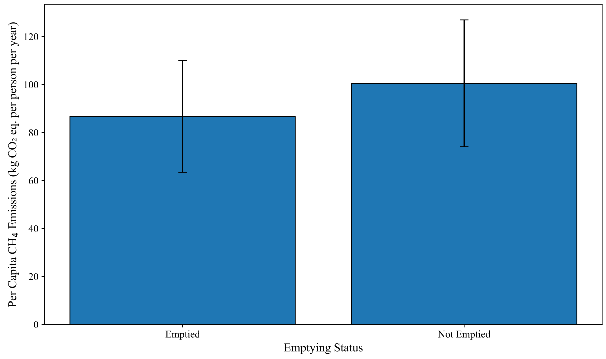

Figure 4: Variation of the emission between emptied and not emptied containments.

et al. [15] reported that emissions from pit latrines in Senegal were 33.65 kg CO_2 eq-per person per year. Our findings indicate higher emissions compared to those reported by Reddy et al. [15]. The result from our study was compared to the other similar studies done globally. The results are tabulated in Table 5.

Unlike unlined pit latrines, the CH_4 emission by the open defecation (OD) was minimum i.e 23.65 kg CO_2 eq-per person per year. During OD, sludge is exposed to air, creating aerobic conditions that inhibit the methanogenesis process. Although open defecation contributes minimally to GHG compared to other improved sanitation systems, addressing it is crucial to safeguard public health and improve the quality of life [2].

Similarly, the average per capita N_2O emissions for containment was calculated as 0 kg CO_2eq-per year. N_2O from open defecation was calculated as 18.39 kg CO_2eq-per year. Human excreta or sludge that contain nitrogen interact with the environment with varied environmental conditions like, temperature and presence of nitrifying/denitrifying bacteria that might have enhanced the emissions. However, since the N_2O is of major concern with GWP of 273 which is more potent than CO_2. Our finding was similar to Johnson et al. (2022) that calculated the N_2O emission from OD as 18.59 kg CO_2 eq-per year [7].

3.3. Emptied vs not emptied containments

The comparison of emissions between the emptied containment and not emptied containment shows that the emission was higher for containments which were not emptied (Fig. 4). Containments that were not emptied had sludge accumulation over the period of time leading to higher emission. The average per capita total emissions from emptied containment was 86.72 ± 26.44 kg CO_2 eq-per year and per capita emission for not emptied was 100.52 ±23.29 kg CO_2 eq- per year. Paired sampled t- test was done to compare if the emptying plays significant role on GHG emission. Result signified that the emission was significantly varied depending on the emptying practices (*p- value <0.05*). A similar result was observed in the study by Feng et al. (2022), where the authors compared CH_4 emissions across different emptying frequencies. The findings from Feng et al. (2022) study highlight that more frequent emptying can reduce emission activity, resulting in lower overall emissions [24].

Similarly, a study done by Moonkawin et al. [25] found that the increased emptying intervals increase the sludge height and hence BOD and Chemical oxygen demand (COD) increase compromising the dissolved oxygen and the Oxidation reduction potential (ORP). This led to the anaerobic condition favoring CH_4 emissions [25]. Similarly, research by Huynh et al. [26] found that CH_4 emission rates from septic tanks storing septage for more than five years were significantly higher than those from tanks storing septage for 0–5 years ($p = 0.016$). This suggests that prolonged storage durations, combined with lower ORP and higher levels of biodegradable carbon, are key contributors to CH_4 emissions [26]. The obtained result signifies that emptying can be one of the mitigations of GHG emissions from the containment systems.

3.4. Sealed vs unsealed containments

The results showed that the emissions were higher in unsealed containments. Total emission from unsealed containment was 108.65 kg CO_2 eq- per person per year and while the total emission from sealed containment was 76.02 kg CO_2 eq- per person per year (Fig. 5). Sealing is linked with primarily CH_4 emissions. Unsealed containment can allow the infiltration of the liquid and create an anaerobic condition. Technological intervention of the sealed technology over unsealed can be an option for the reduction of the emission from the containment units. An independent sample t-test was done to verify if sealing of the containment played an important role in the emissions. The result signifies that the emission was significantly higher in the unsealed containments compared to sealed containments. (p-value <0.05).

Table 5: Comparison of this study finding with literature.

Authors	Country	Scope	Total GHG emissions (kg CO_2 eq-per person per year)
Johnson et al. [7]	Kampala Uganda	Containments	73.76
Reddy et al. [15]	Senegal	Pit latrines	33.68
Poudel et al. [16]	Nepal	Septic tanks	104.6
Poudel et al. [16]	Nepal	Pit latrines	93.5
Poudel et al. [16]	Nepal	Non sewered sanitation system	198.1
Shrestha et al. [23]	Nepal	Decentralized wastewater treatment system	131.38
This study	Dhulikhel, Nepal	Containment system (excluding OD)	97.35

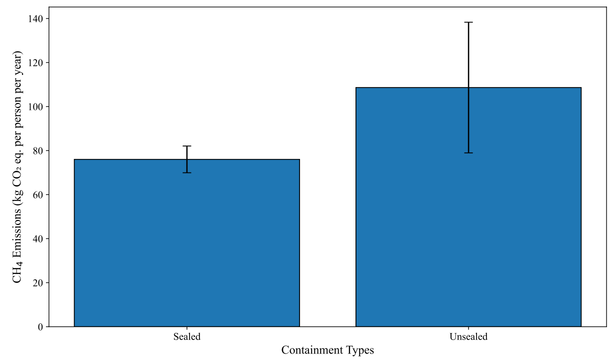

Figure 5: Variation of the emission between sealed and unsealed containments.

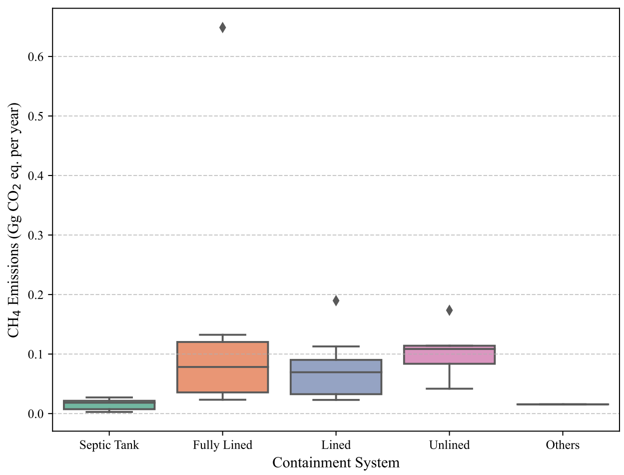

Figure 6: Total CH_4 emission from various containment type in Dhulikhel.

3.5. Total GHG emission

The total emissions from the containment systems along with the open defecation is estimated to be 2.33 Gg CO_2 eq- annually. Further breaking down, the N_2O emissions from OD contribute to 0.011 Gg CO_2 eq- annually, while the CH_4 contributes 2. 32 Gg CO_2 eq- annually (Fig. 6). These results imply that the CH_4 emissions from containments are of major concern. However, this emission varies between containment types as well. Though the per capita emission of CH_4 was higher for unlined pit, the total emission was higher from fully lined tanks, 0.948 Gg CO_2 eq. in total a large emission from the fully lined tank can be accounted for by the population using such containment system i.e. nearly 13,000 individuals.

4. Conclusion

This study quantifies emissions from various containment systems prevalent in Dhulikhel Municipality, Nepal. Existing data on the sanitation system was used to calculate CH_4 and N_2O emissions. Our results conclude that GHG emission from the containment can be of major concern. GHG emission varies with the design and construction of the containment combined with the management of the sludge, often linked to the emptying practices. The unlined pit structures of the containment that can be linked to GW inundation can emit higher emissions compared to sealed containment that are often emptied. The emptied containment emit lesser emission compared to those that are not emptied, suggesting that emptying can be one of the option for GHG mitigation from sanitation sector.

However, this study focused on the SFD of a specific municipality, but such data is currently unavailable at the national level. Reliable data and clear containment typologies are essential for accurate emission quantification. Future efforts should prioritize improving data collection to ensure that emission estimations for sanitation systems are both accurate and reliable.

Acknowledgments

We would like to recognize Sanitation and Climate: evaluating resilience and emissions (SCARE) initiative which is financed by the University of Bristol. We would also like to thank Aquatic Ecology Centre, Kathmandu University for providing us with the essential tools for communication.

References

[1] World Health Organization (WHO) and the United Nations Children's Fund (UNICEF). Progress on household drinking water, sanitation and hygiene 2000-2020: five years into the SDGs. Tech. rep. (2021).

[2] Shaw K, Kennedy C & Dorea C C, Non-sewered sanitation systems' global greenhouse gas emissions: Balancing sustainable development goal tradeoffs to end open defecation, *Sustainability*, 13(21) (2021) 11884. ISSN 2071-1050. https://doi.org/10.3390/su132111884.

[3] Diaz-Valbuena L R, Leverenz H L, Cappa C D, Tchobanoglous G, Horwath W R & Darby J L, Methane, carbon dioxide, and nitrous oxide emissions from septic tank systems, *Environmental Science & Technology*, 45(7) (2011) 2741–2747. ISSN 1520-5851. https://doi.org/10.1021/es1036095.

[4] van Eekert M H A, Gibson W T, Torondel B, Abilahi F, Liseki B, Schuman E, Sumpter C & Ensink J H J, Anaerobic digestion is the dominant pathway for pit latrine decomposition

and is limited by intrinsic factors, *Water Science and Technology*, 79(12) (2019) 2242–2250. ISSN 1996-9732. https://doi.org/10.2166/wst.2019.220.

[5] van Eekert M H A, Gibson W T, Torondel B, Abilahi F, Liseki B, Schuman E, Sumpter C & Ensink J H J, Rebuttal to dominant decomposition pathways in pit latrines: a commentary, *Water Science and Technology*, 80(7) (2019) 1395–1398. ISSN 1996-9732. https://doi.org/10.2166/wst.2019.385.

[6] Lambiasi L, Ddiba D, Andersson K, Parvage M & Dickin S, Greenhouse gas emissions from sanitation and wastewater management systems: a review, *Journal of Water and Climate Change*, 15(4) (2024) 1797–1819. ISSN 2408-9354. https://doi.org/10.2166/wcc.2024.603.

[7] Johnson J, Zakaria F, Nkurunziza A G, Way C, Camargo-Valero M A & Evans B, Whole-system analysis reveals high greenhouse-gas emissions from citywide sanitation in Kampala, Uganda, *Communications Earth & Environment*, 3(1) (2022) 1. ISSN 2662-4435. https://doi.org/10.1038/s43247-022-00413-w.

[8] Cheng S, Long J, Evans B, Zhan Z, Li T, Chen C, Mang H P & Li Z, Non-negligible greenhouse gas emissions from non-sewered sanitation systems: A meta-analysis, *Environmental Research*, 212 (2022) 113468. ISSN 0013-9351. https://doi.org/10.1016/j.envres.2022.113468.

[9] Reid M C, Guan K, Wagner F & Mauzerall D L, Global methane emissions from pit latrines, *Environmental Science & Technology*, 48(15) (2014) 8727–8734. ISSN 1520-5851. https://doi.org/10.1021/es501549h.

[10] Intergovernmental panel for climate change (IPCC). Sixth assessment report: Climate change 2023. Tech. rep. (2023).

[11] Intergovernmental Panel on Climate Change (IPCC). 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories: Wastewater treatment and discharge. Tech. Rep. 2019, IPCC, Geneva (2019). URL https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/5_Volume5/19R_V5_6_Ch06_Wastewater.pdf.

[12] Manga M & Muoghalu C C, Greenhouse gas emissions from on-site sanitation systems: A systematic review and meta-analysis of emission rates, formation pathways and influencing factors, *Journal of Environmental Management*, 357 (2024) 120736. https://doi.org/10.1016/j.jenvman.2024.120736.

[13] Poudel P, Ghimire A, Howard G, Evans B, Camargo-Valero M A, Mills F, Reddy O, Sharma S, Tuladhar S, Geremew A, Okurut K, Ngom B, Baidya M & Dangol S, Field-based methods for measuring greenhouse gases emissions from on-site sanitation systems: A systematic review of published literature, *Heliyon*, 9(9) (2023) e19947. ISSN 2405-8440. https://doi.org/10.1016/j.heliyon.2023.e19947.

[14] Strande L, Integrating recent scientific advances to enhance non-sewered sanitation in urban areas, *Nature Water*, 2(5) (2024) 405–418. ISSN 2731-6084. https://doi.org/10.1038/s44221-024-00240-7.

[15] Reddy O, Rahman M, Nijhawan A, Pregnolato M & Howard G, Infiltrated pits: Using regional groundwater data to estimate methane emissions from pit latrines, *Hydrology*, 10(5) (2023) 114. ISSN 2306-5338. https://doi.org/10.3390/hydrology10050114.

[16] Poudel P, Joshi P, Tuladhar S, Ghimire A, Baidya M, Howard G & Sharma S, Groundwater implications on methane emission from non-sewered sanitation systems in Nepal, *Environmental Pollution*, 356 (2024) 124248. ISSN 0269-7491. https://doi.org/10.1016/j.envpol.2024.124248.

[17] Sharma S, Baidya M, Poudel P, Panthi S R, Pote-Shrestha R R, Ghimire A & Pradhan S P, Drinking water status in Nepal: an overview in the context of climate change, *Journal of Water, Sanitation and Hygiene for Development*, 11(6) (2021) 859–866. ISSN 2408-9362. https://doi.org/10.2166/washdev.2021.045.

[18] Government of Nepal. Second nationally determined contribution (NDC) Nepal. Tech. rep. (2020).

[19] Ministry of Forest and Environment. Third national communication to United National Framework Convention on Climate Change. Tech. rep. (2021).

[20] Shrestha J & Bajracharya B. *Sanitation Situation Report of Dhulikhel Municipality* (2019).

[21] Environment and Public Health Organisation. SFD promotion initiative Dhulikhel Nepal, (2021). Tech. rep.

[22] Government of Nepal. *National Population and Housing Census 2021-National Report* (2021).

[23] Shrestha A, Bhattarai T N, Ghimire S, Mainali B, Treichel H & Paudel S R, Estimation of greenhouse gases emission from domestic wastewater in Nepal: A scenario-based analysis applicable for developing countries, *Chemosphere*, 300 (2022) 134501. ISSN 0045-6535. https://doi.org/10.1016/j.chemosphere.2022.134501.

[24] Feng L, Bonne Guldberg L, Jørgen Hansen M, Ma C, Vinther Ohrt R & Bjarne Møller H, Impact of slurry removal frequency on CH_4 emission and subsequent biogas production; a one-year case study, *Waste Management*, 149 (2022) 199–206. ISSN 0956-053X. https://doi.org/10.1016/j.wasman.2022.06.024.

[25] Moonkawin J, Huynh L T, Schneider M Y, Fujii S, Echigo S, Nguyen L P H, Hoang T H T, Huynh H T & Harada H, Challenges to accurate estimation of methane emission from septic tanks with long emptying intervals, *Environmental Science & Technology*, 57(43) (2023) 16575–16584. ISSN 1520-5851. https://doi.org/10.1021/acs.est.3c05724.

[26] Huynh L T, Harada H, Fujii S, Nguyen L P H, Hoang T H T & Huynh H T, Greenhouse gas emissions from blackwater septic systems, *Environmental Science Technology*, 55(2) (2021) 1209–1217. ISSN 1520-5851. https://doi.org/10.1021/acs.est.0c03418.