

**Prediction of greenhouse gas emissions along
sanitation service chains**

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ABSTRACT

In 2020, the population served by on-site sanitation worldwide exceeded for the first time the one relying on sewer connections. It is evident that connecting all urban areas to centralized wastewater treatment plants (WWTPs) will not be possible or desirable in the foreseeable future. Typically, sanitation in low- and middle-income countries is a combination of on-site (pre-) treatment facilities (i.e., septic tanks) and centralized WWTPs. While improvement of the provision of adequate sanitation with safe water environments has been prioritized, greenhouse gas (GHG) emissions produced within sanitation service chains (SSCs) are often overlooked. As a result, relatively little research has been focused on the estimation of GHG from on-site treatment facilities, especially on primary data collection. Inadequacy of field data hinders the accurate the estimation of GHG emissions from on-site treatment facilities and thus limited understanding of GHG emissions from such facilities. Therefore, quantification of GHG emissions from sanitation service chains remain a global challenge, and requires investigation from an entire service chain to further develop mitigation strategies.

The thesis involves three main goals which sequentially clarifies the importance and challenges of GHG emissions estimation and mitigation for a typical example of SSC in low- and middle-income countries, the Truc Bach drainage area, Hanoi, Vietnam.

The first goal of this thesis is to assess the impact of long emptying intervals of septic tanks on pollutants (e.g., biological oxygen demand (BOD) removal efficiencies and methane (CH_4) emission rates, and determine the association between CH_4 emission rates and pollutant removal efficiencies. Data from 15 different septic tanks were collected in winter, including septage composition, influent and effluent characteristics, and CH_4 emission rates. Further, the data was combined with the data in summer from a previous study in the same study area. The results show that longer emptying intervals significantly reduced the pollutant removal efficiencies while they increased the CH_4 emission rate from septic tanks. Furthermore, the negative correlation between BOD removal efficiency and CH_4 emission rates indicated that the CH_4 emission estimation based on BOD removal efficiency might not reflect the actual emission for septic tanks with long emptying interval. For better estimation, alternative factors for CH_4 emission are suggested, including emptying intervals, sludge depth, and CH_4 emission factors per capita reflecting long emptying intervals.

The second goal is to estimate GHG emissions from operations along a sanitation service chain, considering the complexity and multiplicity of SSCs to provide a systemic GHG emissions estimation. With the same study area, the scope was expanded from septic tanks to the entire SSC to include not only septic tanks but also sewers, vacuum trucks, WWTP, and fecal sludge treatment plant (FSTP). GHG emissions from each component were estimated based on the current state of the SSC. The results obtained in the first goal was used to estimate GHG emissions from septic tanks. Emissions from sewers and FSTP were estimated by using the Intergovernmental Panel on Climate Change (IPCC)'s methods. Emission from WWTP was obtained from GPS-X software by using a whole plant model. Lastly, emissions from vacuum trucks were estimated based on fuel emission factors. The results identified that the primary contributors to GHG emissions along the SSCs were direct CH₄ emissions from septic tanks and sewers. CH₄ production from anaerobic conditions of septic tanks and sewers was significant, especially when they were inadequately maintained and designed. Thus, the different potential mitigation should be explored for the whole SSC in order to determine the most effective mitigation scenario.

The third goal is to explore potential GHG emissions mitigation of the SSC by quantifying the GHG emissions of three mitigation scenarios and compared with the current GHG emissions for the Truc Bach drainage area in Hanoi. The three mitigation scenarios were developed under the different fates of septic tanks either their operational conditions (i.e., increase frequency of emptying) or existence (i.e., removing of septic tanks from the SSC), and the improvement of sewer conditions. The main findings show that shortening septic tanks' emptying intervals could be an initiative to effectively reduce overall GHG emissions along the SSC because the implementation does not require a substantial transformation of existing built environment. Moreover, the most effective mitigation to reduce GHG emissions was under the scenario that septic tanks were removed and wastewater was treated at a centralized WWTP.

In conclusion, the thesis provides insightful findings on GHG emissions of septic tanks, as well as their city-wide and systemic estimation by including all components in the SSC. These findings could prove beneficial in addressing the challenges associated with GHG emissions estimation and mitigation, thereby ensuring the sustainability of sanitation service chains, and improving overall quality of life.

Keywords: climate change; fecal sludge management; sanitation services; GHG emissions; mitigation

Chapter 1 Introduction

1.1 Challenges of sanitation service chains in an urbanizing world

The global urban population is expected to increase by 2.5 billion between 2018 and 2050, with nearly 90% of new urban residents concentrated in Asia and Africa (United Nations, 2019). As a result, many cities continue to experience the growth of population that far exceeds the ability to provide adequate infrastructure and sanitation service chains (SSCs), especially in low-income and lower-middle-income countries (Lüthi et al., 2011). Urban sanitation in such countries is currently at a turning point. Although centralized wastewater treatment plants (WWTPs) are still seen as the ideal, they cannot be the only solution for urban areas. In 2020, the population served by on-site sanitation worldwide exceeded for the first time the one relying on sewer connections (WHO & UNICEF, 2021). It is evident that connecting all urban areas to centralized WWTPs will not be possible in the foreseeable future, nor is it desirable (Reymond et al., 2016). A provision of a mixture of sanitation systems is often common to a whole urban area, which are appropriate for different parts of the city and adaptable to different scales of implementation (Parkinson et al., 2014). Typically, sanitation in low- and middle-income countries are a combination of on-site sanitation (i.e., septic tanks) as pre-treatment and centralized WWTPs (Harada et al., 2015; Hyun et al., 2019; Medland et al., 2016). Thus, when evaluating and improving sanitation services, it is important to consider not only on-site sanitation or centralized WWTPs but rather the entire sanitation service chain. While improvement of the provision of adequate sanitation with safe water environments has been prioritized, greenhouse gas emissions (GHGs) produced within sanitation service chains are often overlooked (Lambiasi et al., 2024). Therefore, the quantification and mitigation of GHG emissions from a whole sanitation service chain remain a global challenge.

1.2 GHG emissions from sanitation service chains

Typically, a sanitation service chain in low- and middle-income countries consists of five components including: (i) user interface (e.g., toilets), (ii) containment and storage/treatment (e.g., septic tanks), (iii) conveyance or transport (e.g., sewers), (iv) (semi-) centralized treatment, and (v) end-use and/or disposal (Tilley et al., 2014). The technological options of sanitation determine where and how GHGs are emitted. For example, septic tanks can be a source of methane (CH₄) production due to their anaerobic nature, while centralized WWTPs,

which employ aerobic process, primarily emit carbon dioxide (CO₂) and nitrous oxide (N₂O). Due to urbanization and the increase of on-site sanitation worldwide, it is important that sanitations should be designed and improved with the aims to lower GHG emissions. Improper designs and lack of sufficient maintenance of sanitation service chains can lead to an increase of GHG emissions. For example, CH₄ emissions increased when septic tanks had longer emptying intervals (Huynh et al., 2021). Sewers with improper construction and inadequate maintenance could lead to a stagnation of wastewater, resulting in significant CH₄ production (Chaosakul et al., 2014). It is thus crucial to explore options for sanitation technologies with lower emissions, while simultaneously ensuring that users, particularly in low- and middle-income countries, are not entirely responsible for the potential financial burdens of lower-emissions sanitation systems.

1.3 Goals of this thesis

This thesis comprises of three main goals. The first goal of this thesis is to estimate CH₄ emission from septic tanks with long emptying intervals. To enable to achieve this goal, the thesis aims to analyze field data of CH₄ emissions and compare with the current available CH₄ emissions estimation approach, which is based on biochemical oxygen demand (BOD) removal efficiency. Consequently, the thesis attempts to answer if the BOD removal efficiency can be used to estimate the CH₄ emission and, if not, what alternative indicators can be used.

The second goal is to estimate GHG emissions from operations along a sanitation service chain, considering the complexity and multiplicity of SSCs to provide systemic GHG emissions estimation by integrating the results of the first goal and available GHG emissions estimation approaches.

The final goal of this thesis is to explore potential GHG emission mitigation for sanitation service chains and evaluate different mitigation strategies, particularly based on the operational conditions and existence of septic tanks. This attempts to understand the impact of septic tanks to the entire system's emissions.

To fulfil the above-mentioned goals, the thesis consists of 6 chapters as outline in the research framework in Figure 1.1.

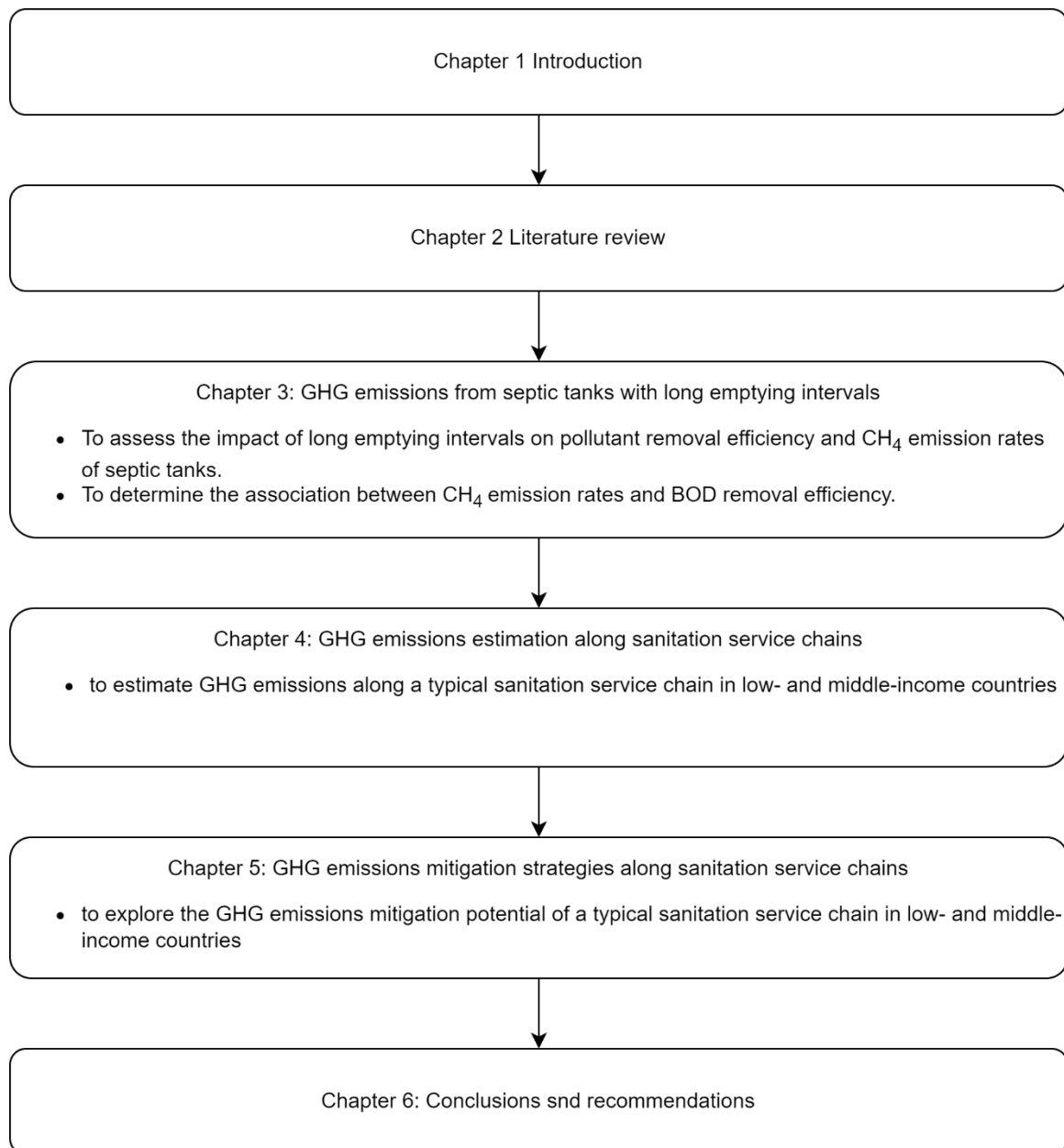


Figure 1.1 Research framework

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Chapter 2 Literature review

2.1 Introduction to GHG emissions from sanitation facilities

2.1.1 Overview of the significance of GHG emissions from sanitation facilities

Global emissions related to wastewater treatment are estimated to account for up to 1.5% of total GHG and 5% of non-CO₂ GHG emissions, and are expected to contribute 42% to all waste related GHG emissions by 2030, compared to 36% in 1990 (Bogner et al., 2008; US EPA, 2012). On-site treatment facilities (e.g., septic tanks, pit latrines) contribute significantly to global GHG emissions, estimated at 377 (22-1003) Mt CO₂e/year, comparable to emissions from WWTPs, highlighting their non-negligible impact (Cheng et al., 2022). For example, septic tanks with soil treatment contributed to 1.5% of global GHG emissions, with mainly as CO₂, CH₄, and N₂O (Knappe et al., 2022). Pit latrines, contribute to global CH₄ emissions, which emitted 5.2 to 3.8 Tg/yr. (1 Tg=1 million tons) of CH₄ between 2000 and 2015, impacting around 1% of global anthropogenic CH₄ emissions (Reid et al., 2014). Thus, the global impact of sanitation treatment facilities on GHG emissions can be varied by treatment options influenced by operational aspects and local conditions.

2.1.2 Importance of quantifying and mitigating GHG emissions from sanitation service chains

Research shows that on-site treatment facilities play a vital role in contributing substantially to CH₄ emissions, comparable to those from centralized WWTPs (McNicol et al., 2020). Significant contribution to climate change, with CH₄ being a potent GHG, emphasized the need for effective emission reduction strategies (Cheng et al., 2022). Septic tanks were identified as a potential source of CH₄ emissions (Diaz-Valbuena et al., 2011; Huynh et al., 2021). One possible way to reduce CH₄ emissions from septic tanks is through regular emptying of septic tanks (Huynh et al., 2021). Rehabilitated WWTP would lead to a 26% reduction in GHG emissions for the sanitation service chains where septic tanks are connected to WWTPs (González et al., 2019). However, these studies remain limited to the assessments of specific types of technologies and the analysis of the entire sanitation chain nor the sanitation policies for a region. Therefore, understanding GHG emissions estimation and mitigation from sanitation service chains is crucial for climate action, sustainable water management, and

economic growth, as they can significantly reduce emissions contributing to global warming and are essential for policy integration and improved environmental practices.

2.2 GHG emissions from components of sanitation service chains and their challenges

2.2.1 Septic tanks

Septic systems are a commonly chosen option of on-site wastewater treatment, and are used by over 1.5 billion people worldwide (WHO & UNICEF, 2021). These systems can contribute to GHG emissions, particularly CH₄ emissions (Diaz-Valbuena et al., 2011; Huynh et al., 2021). In 1999, the United States Environmental Protection Agency (USEPA) estimated the global methane (CH₄) emissions from septic systems as 3.0 Tg-CH₄/year, which accounted for 10.4% of the global CH₄ emissions from domestic wastewater (Doorn et al., 1999). However, these estimates are based on limited studies, primarily a single study conducted in north-central California that only considered CH₄ emissions (Truhlar et al., 2016).

Intergovernmental Panel on Climate Change (IPCC) introduced the method of estimating CH₄ emissions from septic systems. This emission assumes a direct relationship between the amount of biochemical oxygen demand (BOD) in domestic wastewater and CH₄ from septic systems involving three parameters: i) region- or country-specific per-capita BOD (g BOD/(cap·d)), ii) maximum CH₄ production capacity (0.6 g CH₄/g BOD), and iii) CH₄ correction factor or BOD removal efficiency of septic tanks (40–72%) as shown in eq. (2.1). It is currently utilized to estimate GHG emissions from the wastewater sector on a global scale. However, the uncertainties of those parameters were reported as follow: ±30% for CH₄ production capacity, ±30% for CH₄ correction factor, and ±30% for country-specific per-capita BOD (IPCC, 2006, 2019).

$$CH_4 emission = B_0 \cdot MCF \cdot BOD \quad (2.1)$$

where B_0 is maximum CH₄ producing capacity (0.25 kg CH₄/ kg COD or 0.6 kg CH₄/kg BOD); MCF is methane conversion factor, in case of septic tanks, a default MCF is 0.5; BOD is region- or country-specific per-capita BOD (kg BOD/(cap·d)).

The previous studies are summarized in Table 2.1. Diaz-Valbuena et al. (2011) reported that emission rates of CH₄, CO₂, and N₂O, as measured with a modified flux chamber approach in

eight septic tank systems, were determined to be 11, 33.3, and 0.005 g/(cap·d), respectively. Truhlar et al. (2016) demonstrated that total septic system carbon footprint was 0.27 tCO₂e/(cap·d), which comprised of emissions from vent, sand filter, and leach field. Leverenz et al. (2010) reported that the geometric mean of the total emission rates for CH₄, CO₂, and N₂O based on samples from the vent system were 10.7, 335, and 0.20 g/(cap·d), respectively. The information about GHG emissions from septic systems is currently limited, although a large section of the population is using septic systems globally.

Table 2.1 Summary of GHG emissions from septic systems

	Previous study	Methods	Influent	Country	Emission Factor (g/(cap·d))		
					CH ₄	CO ₂	N ₂ O
	Leverenz et al., 2010	Onsite measurement using floating chamber on fecal sludge surface	Black and greywater	USA	10.7	335	0.2
	Diaz-Valbuena et al., 2011	Onsite measurement from septic tanks	Black and greywater	USA	11	33.3	0.005
	Diaz-Valbuena et al., 2011	Onsite measurement from roof vent	Black and greywater	USA	10.7	335	0.2
	Truhlar et al., 2016	Onsite measurement from roof vent	Black and greywater	USA	11	160	0.12
	Truhlar et al., 2016	Onsite measurement from sand filter	Black and greywater	USA	0.0072	120	0.006
	Truhlar et al., 2016	Onsite measurement from leach field	Black and greywater	USA	-0.0038	130	0.022
∞	Huynh et al., 2021	Onsite measurement using floating chamber on fecal sludge surface	Blackwater	Hanoi	11.92	20.24	< 1 ppm

2.2.2 Sewers

GHG emissions from sewers are a major problem since they contribute to global warming and climate change. Several studies have attempted to quantify these emissions, revealing a complexity of the estimation, influenced by a variety of factors, including the sewer system's design and maintenance, the biological processes that occur within the sewers, and the materials used in sewer infrastructure. This emission is primarily due to CH₄ produced from the degradation of organic matter in wastewater. CH₄ from sewers are often produced by methanogenic archaea in sewer biofilms and sediments (Foley et al., 2009; Guisasola et al., 2008; Liu et al., 2015). Produced CH₄ from the sewer system, when it enters ventilated spaces such as gravity sewers, pumping stations, wastewater treatment plants, manholes, and rain gutters, is released to the atmosphere (Liu et al., 2015). For example, a comprehensive three-year investigation on CH₄ emissions conducted on sewer networks in Xian, China showed that the emission levels were at 7.96 Mt/day, comparable to emissions from the dairy, automotive, and steel sectors (Jin et al., 2015). Furthermore, most sewers in low- and middle-income countries are usually under improper construction and maintenance, resulting in considerable CH₄ production due to long hydraulic retention time. However, the data related to GHG emissions of sewers has been limited, and standardized calculation methods and further research to accurately quantify these emissions is critical for developing effective GHG reduction strategies.

Estimating GHG emissions from sewer systems is crucial for understanding their contribution to global warming and developing strategies for mitigation. Due to limited studies, GHG emissions from sewers tend to rely on the IPCC's approach, which is, similarly to septic systems, based on i) CH₄ producing capacity, ii) *MCF*, and iii) country-specific per-capita BOD or COD (eq. (2.2))

$$CH_4 emission = B_0 \cdot MCF \cdot BOD \quad (2.2)$$

where B_0 is maximum CH₄ producing capacity (0.25 kg CH₄/ kg COD or 0.6 kg CH₄/kg BOD); *MCF* is methane conversion factor, in case of poorly-maintained sewers, a default *MCF* is 0.5.

Several attempts have been focused on the estimation on GHG emissions in both on-site and laboratory scale. The previous research attempts are listed in Table 2.2.

Table 2.2 Summary of CH_4 emissions from sewers

References	Types of sewers	Type of CH_4 formation	Estimating equation
Foley et al. (2009)	Rising main	Sewer biofilm	$C_{CH_4} = 5.24 \times 10^{-5} \cdot \left[\frac{A}{V} \times HRT \right] + 0.0015$ C_{CH_4} = concentration of methane (kg/m ³) V = volume of pipe (m ³) A/V = surface area per volume (m ⁻¹) HRT = hour
Chaosakul et al. (2014)	Gravity sewer	Sewer biofilm	$C_{CH_4} = 6 \times 10^{-5} \times \left[\frac{A}{V} \times HRT \right] \times 1.05^{(T-20)} + 0.0015$ C_{CH_4} = concentration of methane (kg/m ³) V = volume of pipe (m ³) A/V = surface area per volume (m ⁻¹) HRT = hour T = temperature (°C)
Liu et al. (2015)	Gravity sewer	Sewer sediment	$C_{CH_4} = k \cdot S_f^{0.5}$ C_{CH_4} = methane production rate (gCH ₄ /(m ² -d)) $k = 0.224 \pm 0.002$ ((gCH ₄ /m) ^{0.5} /d) S_f = bulk fermentable COD (mg/L)
Sun et al. (2018)	Rising main	Sewer biofilm	$C_{CH_4} = a \cdot S_{SO_4} + b \cdot S_{sCOD} + c$ C_{CH_4} = methane production rate (gCOD/(m ² -d)) S_{SO_4} = sulphate concentration (mgS/L), (applicable range is 5-30 mg/L) S_{sCOD} = sCOD concentration (mgCOD/L) (applicable range is 100-500 mg/L) $a = -0.41 \pm 0.02$ $b = 0.0078 \pm 0.001$ $c = 1.62 \pm 0.46$

However, the accuracy of current methods for estimating methane emissions from sewers varies significantly, largely due to the complex nature of sewer systems, variability in emissions, and limitations in measurement techniques.

2.2.3 Vacuum trucks

The transportation of fecal sludge by vacuum trucks contributes to GHG emissions, a significant concern for global climate change. The emission factors from trucks transporting waste vary significantly based on vehicle type, fuel type, operational conditions, and trip distance particularly the latter being the most influential factor (Wei et al., 2022). Direct emissions from fecal sludge in the vacuum trucks are considered negligible due to short period during transportation. Indirect emissions from fuel consumption are however the main contributor. The size of vacuum trucks used for collecting waste varies significantly depending on their specific design and intended application, as evidenced by the diverse configurations and capacities. For vacuum trucks using for emptying fecal sludge, they are reported diesel trucks with capacity around 3.6 m³ (Nakamura et al., 2014). The emission factors of a diesel truck are summarized in Table 2.3.

Table 2.3 Summary of emissions factor of a diesel truck

Source	CO ₂	CH ₄	N ₂ O
SIMAP (2019)	2.684 kg/L	7.83E-06 kg/L	8.14E-06 kg/L
U.S. EPA (2014)	2.697 kg/L	3.17E-06 kg/km	2.98E-06 kg/km
Larsen et al. (2009)	2.629 kg/L	N/A	N/A

2.2.4 WWTPs

As mentioned earlier, in low- and middle-income countries, sanitation service chains are usually a combination of on-site treatment facilities and centralized WWTPs. WWTPs therefore receive effluent discharged from on-site treatment facilities (i.e., septic tanks) and/or storm water and industrial wastewater. WWTPs are identified as significant sources of GHG emissions, primarily due to the energy-intensive nature of the treatment processes and the biochemical reactions occurring within these systems. The GHG emissions from WWTPs include a combination of direct emissions from the treatment processes and indirect emissions associated with energy and consumable consumption (IPCC, 2019). Frequently, only CH₄ and/or N₂O are accounted for, excluding CO₂ emissions of biological treatment processes as

these are generally derived from biogenic organic matter in human excreta or food waste and should not be included in national total emissions (IPCC, 2019). Only CO₂ that are directly emitted from energy and consumable in WWTPs are included in GHG emissions inventory. Current GHG accounts often do not consider differences of treatment processes/technologies. The accounting of GHG emissions of WWTPs at the regional level mainly uses IPCC emission factors (IPCC, 2019), where the centralized biological treatment processes are only categorized into aerobic and anaerobic processes but neglect the differentiation of sub-categories of aerobic or anaerobic technologies (Du et al., 2018; Wang et al., 2022), leading to large uncertainties of GHG emission factors. To accurately account GHG emissions in WWTPs, detailed processes/technologies should be considered and analyzed.

The estimation of GHG emissions from entire WWTPs involves various tools and methodologies, each with its unique approach to addressing the complexities of GHG accounting in the water sector. For example, GPS-X software is a pivotal tool in the estimation and management of GHG emissions from entire WWTPs, facilitating the simulation and optimization of wastewater treatment processes. The GHG emissions are usually divided into three scopes. Scope 1 emissions (i.e., direct emissions from biological processes) are calculated by modelling a plant-wide simulation using carbon, nitrogen, and phosphorus removal, integrating anaerobic digestion processes (i.e., ASM2d (Henze et al., 2015) and UCTADM1(Sötemann et al., 2005)), a four steps N₂O production model (Hiatt & Grady, 2008) and N₂O production by autotrophic bacteria (Mampaey et al., 2013; Ni et al., 2012). Scope 2 and Scope 3 are considered as indirect emissions. Following IPCC approaches, Scope 2 emissions (i.e., emissions from electricity or energy) involve energy consumption models by applying regional electricity emissions, and Scope 3 emissions (i.e., emissions from consumables) are based on chemical consumption. Similarly, the population-equivalent method recommended by the IPCC has been employed to analyze GHG emission characteristics and assess mitigation potentials, offering a standardized framework for large-scale assessments (IPCC, 2019). Additionally, the studies of the quantification and the optimization of operational conditions to reduce N₂O emissions from domestic wastewater treatment facilities have been receiving attention. (Gruber et al., 2020; Kampschreur et al., 2009; Van Dijk et al., 2021).

2.2.5 FSTPs

FSTPs specifically handle fecal sludge or septage from onsite sanitation facilities such as septic tanks and pit latrines. FSTPs focus on the safe collection, transportation, treatment, and disposal or reuse of this sludge, employing various treatment technologies to convert it into usable products like manure or soil conditioners, and treated water for non-potable purposes (Samal et al., 2022). A comprehensive approach to FSTP design involves understanding the local and global scenarios of sanitation, quantification, and characterization of fecal sludge, and selecting appropriate treatment technologies. For example, in Hanoi, a FSTP is operated with a composting process for organic waste. Fecal sludge, brought by vacuum trucks, is discharged into settling tanks. The solid fraction is further disposed of at a landfill (Schoebitz et al., 2014), while the liquid fraction is used in the composting process or overflows into stabilization ponds. Additionally, the implementation of converting FS into resource-recoverable by-products, such as biochar, treated water, and thermal energy, through thermal technology, can be also the promising design to deal with fecal sludge sustainably (Rayavellore Suryakumar & Pavithra, 2020). Since FSTPs can be designed quite differently from WWTPs, to the best of the author's knowledge, GHG emissions from FSTPs have not yet been reported.

2.3 Research gaps

Despite increasing concerns regarding GHG emissions and sanitation sustainability, estimates of GHG emissions are still mostly focused on centralized treatment facilities (Johnson et al., 2022; Orner & Mihelcic, 2018). Relatively little research has been focused on the estimation of GHG from on-site treatment facilities, especially on primary data collection. IPCC approaches can serve as preliminary estimation but they still require intensive improvement by collecting more data on ground. Consequently, the inadequacy of field data hinders the accurate GHG emissions from on-site treatment facilities and therefore limited understanding of GHG emissions from such facilities. Furthermore, given the complexity of SSCs, GHG emissions related to SSCs were mostly reported in disaggregated manner, including GHG emissions from septic tanks (Diaz-Valbuena et al., 2011; Huynh et al., 2021), gravity sewers (Chaosakul et al., 2014; M. D. Short et al., 2014), and WWTPs (Cakir & Stenstrom, 2005; Doorn, 1997; Frijns, 2012; Law et al., 2012; Mamais et al., 2015b). However, the first attempt of GHG emissions estimation from whole system was conducted using Kampala, Uganda as a study area (Johnson et al., 2022). The results also emphasized that the lack of field data in most of low- and middle-

income countries pose the difficulties in conducting a similar analysis of GHG emissions estimation in other cities (Johnson et al., 2022). Moreover, technology used and how well treatment facilities are managed in other low- and middle-income countries are the important factors to determine GHG emissions. This key challenge to improving SSCs with lower emissions remains limited due to hurdles in the complexity around designing, implementing, and operating sanitation systems (Lambiasi et al., 2024). The challenges can be summarized into three major issues:

1. Inadequacy of applicable data for GHG emissions estimation from on-site treatment facilities,
2. GHG emissions from SSC were reported in separated components and required further analysis from a system view point.
3. Pressing need of GHG emissions mitigation strategies from SSCs to keep pace with the rising of urbanization and therefore an increasing use of on-site treatment facilities.

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Chapter 3 GHG emissions from septic tanks with long emptying intervals

3.1 Introduction

Since 2010, more people have reportedly been relying on septic systems than improved latrines (WHO & UNICEF, 2021). In Southeast Asia, septic systems are used by a majority of the population (i.e., 90% in Vietnam (Australian Aid & World Bank, 2013), 84% in the Philippines (Baltazar, Harada, Fujii, Tan, & Akib, 2021), and 79% in Indonesia (Widyarani et al., 2022)). While septic systems are preferable over open defecation, they can potentially emit substantial amounts of greenhouse gases (GHG), such as methane (CH_4) (Cheng et al., 2022; Diaz-Valbuena et al., 2011; Huynh et al., 2021; Shaw, Kennedy, & Dorea, 2021). Thus, assessing the GHG emissions from septic systems is crucial to achieving climate change mitigation (McNicol, Jeliarovski, François, Kramer, & Ryals, 2020; Ryals, McNicol, Porder, & Kramer, 2019; United Nations, 2022). The Intergovernmental Panel on Climate Change (IPCC) approach has been widely used to estimate CH_4 emission rates ($\text{g CH}_4/(\text{cap}\cdot\text{d})$) based on biochemical oxygen demand (BOD) (IPCC, 2019). The method is based on three parameters: i) region- or country-specific per-capita BOD ($\text{g BOD}/(\text{cap}\cdot\text{d})$), ii) maximum CH_4 production capacity ($0.6 \text{ g CH}_4/\text{g BOD}$), and iii) CH_4 correction factor or BOD removal efficiency of septic tanks (40–72%). Different from the IPCC, in Hanoi, BOD removal efficiencies of 10–50% have been reported (JICA, 2019). Applying the suggested BOD removal efficiency from the IPCC might lead to a considerable estimation error of CH_4 emissions from septic systems with long emptying intervals. Therefore, the goal of this article is to investigate if the suggested BOD removal efficiency can be used to estimate the CH_4 emission and, if not, what alternative indicators can be used.

A septic system is usually constructed in either of the following two ways: i) with two components, namely, a septic tank and a soil treatment unit (e.g., leach, infiltration, or drain fields); or ii) with only a septic tank without a soil treatment unit. The septic system of type ii) has to be connected to a sewerage for further treatment. However, in low- and middle

income countries, type ii) septic tanks are frequently found and they are not always connected to sewerage but discharged to open environments (Leverenz, Tchobanoglous, & Darby, 2010; Pussayanavin, Koottatep, Eamrat, & Polprasert, 2015). This study focused on the septic system of type ii) which from here onwards is called septic tanks. In low- and middle-income countries in Southeast Asia, septic tanks often receive only blackwater (i.e., blackwater septic tanks), while graywater is directly discharged to a combined sewer or a drain channel (IGES, 2015).

The basic function of a septic tank is to remove solids by separating settleable solids and scum of wastewater. A proportion of the settled digestible matter is stabilized in a septic tank; the untreated effluent is discharged, and a mix of stabilized and undigested solids accumulates at the bottom of the tank (Al Momani, 2015; Bounds, 1995). The solids retained in septic tanks must be emptied at a proper time to maintain the functionality of the septic tank (M. Brandes, 1978; Mahon, Knappe, & Gill, 2022a; Mehta, Mehta, & Yadav, 2019a). The recommended emptying interval is 1–5 years (HM Government, 2015; Koottatep, Surinkul, & Panuvatvanich, 2012; USEPA, 2002). In this chapter, the term emptying interval is identified as the time from the latest emptying or the time after construction if there was no emptying practice. In low- and middle-income countries, long emptying intervals appear to be common; for instance, the average emptying intervals of septic tanks in Southeast Asia are 8.1 years in Hanoi (Harada, Dong, & Matsui, 2008), 12.7 years in Mandalay (Naing, Harada, Fujii, & Hmwe, 2020) and 16 years in six cities in Indonesia (Mills, Blackett, & Tayler, 2014)), indicating that septic tanks are not operated under recommended conditions. Emptying intervals may play a significant role in septic tanks' BOD removal efficiency which is an important parameter for estimating CH₄ emissions in the IPCC's approach. However, the understanding of their complex relationships is still limited and hence merits further investigation to be able to quantify GHG emissions and develop effective mitigation strategies.

To address the goal of estimating CH₄ emissions, CH₄ emission rates of septic tanks with long emptying intervals were investigated. Hanoi was selected as a study area where 84% of households use septic tanks (K. Brandes, Schoebitz, Nguyen, & Strande, 2016), and the average emptying interval was reportedly 8.1 years (Harada et al., 2008), which is considered a long emptying interval. Data from 15 different septic tanks were collected in winter, including septage composition, influent and effluent characteristics, and CH₄ emissions. The same method was selected to collect data on the septage composition, effluent characteristics, and CH₄ emissions as a previous study in Hanoi in summer (Huynh et al., 2021). Two datasets into

a total of 23 different septic tanks were combined. In the previous study, the BOD removal was not measured, but in the present study, influent was collected and consequently BOD removal efficiency was calculated. This chapter further analyzed the data with the aims to:

- i) Assess the impact of long emptying intervals on pollutant removal efficiency and CH₄ emission rates of septic tanks, and
- ii) Determine the association between CH₄ emission rates and BOD removal efficiency.

In addition, this chapter provide a dataset of the operating conditions of septic tanks (e.g., emptying intervals and sludge accumulation rate) and the characteristics of septage, influent, effluent, and CH₄ emission rates. This dataset can serve for further studies on septic tanks and other onsite sanitation in Southeast Asia and countries with similar social and climatic settings.

3.1 Materials and methods

3.1.1 Study area

Hanoi, the capital and second-largest city in Vietnam, located in northern Vietnam, was selected as the study area. The city covers an area of 3,358.6 km² with a population of 8.25 million people (GSO: Hanoi, 2019). Hanoi has two main seasons: summer (May to August) and winter (November to March). In summer, the weather is hot and humid with a monthly average temperature of 26–33 °C, while in winter, it is comparably cold and relatively dry with a monthly average temperature of 14–19 °C (GSO: Hanoi, 2019; Huyen, Sekiguchi, Ly, & Nghiem, 2023). In Hanoi, 94% of septic tanks receive only blackwater (JICA, 2019). These septic tanks are constructed underground usually without installing an access hole for emptying (Huynh et al., 2021). The graywater is usually discharged directly into a drain channel or combined sewer without passing through a septic tank (Australian Aid & World Bank, 2013).

3.1.2 Overview of septic tank investigation

Data was collected from 15 septic tanks (T1–T15) that had plans for emptying, thereby allowing access the septic tanks with long emptying intervals. Since none of the investigated septic tanks had any access holes for emptying, an access hole was drilled and installed a cover on top of the first compartment for emptying purposes. The septage, gas, and influent samples

were collected through the access holes. The effluent samples were collected through the outlet of the septic tanks. The experimental setup is shown in Figure 3.1. In this study, only the first compartment of the septic tanks could be located because this compartment is typically built directly beneath the cistern flush toilets. The second and third compartments were arranged differently from site to site, hence difficult to locate.

All 15 septic tanks were sampled in December 2019–January 2020 (winter). In addition to the data collected from septic tanks in the present study, data from 10 septic tanks (ST1–ST10) investigated by Huynh et al. (2021) in June–July 2019 (summer) was integrated into the analysis of CH₄ emission rate in this study. Both the present study and Huynh et al. (2021) employed the same method of gas sample collection and analysis. This allows us to investigate the seasonal variations in CH₄ emission rates. It should be noted that T1 and T2 of the present study were the same septic tanks as ST1 and ST2 of Huynh et al. (2021) Therefore, in total, data from 23 septic tanks were used for the analysis of CH₄ emission rates, and the data from 15 septic tanks in this study were used for the analysis of influent and pollutant removal efficiency.

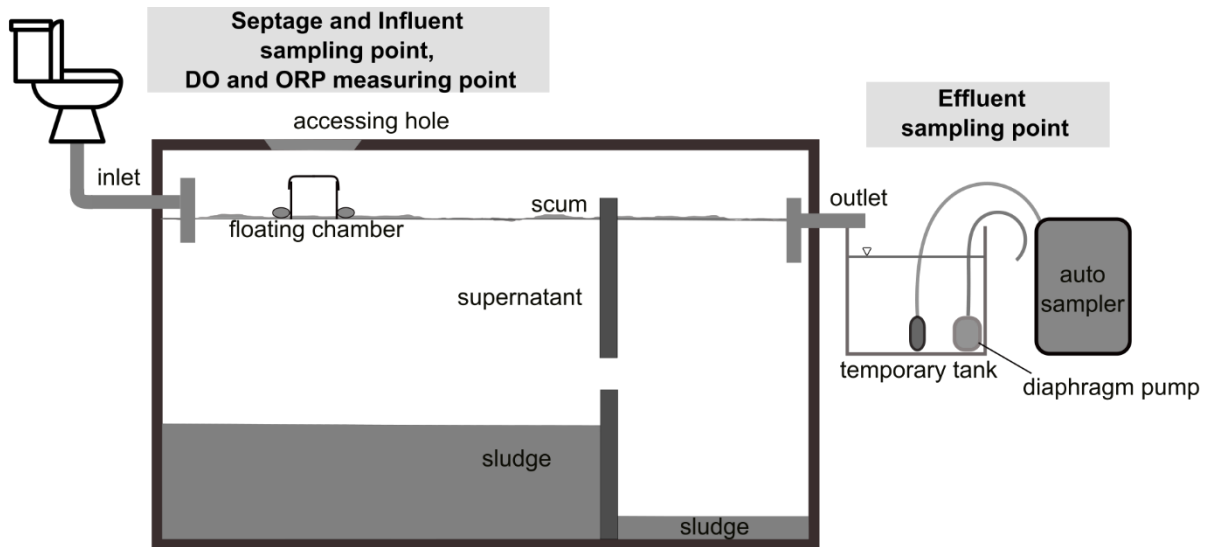


Figure 3.1 Experimental set-up for septage, influent, effluent, and gas collection

3.2 Data collection

3.2.1 General septic tank information

After obtaining consent to conduct the experiment from households' owners, we obtained information about the septic tank, including the septic tank emptying intervals, the number of toilet users, the number of septic tank compartments, and the size of the septic tanks (Table A1).

3.2.2 Sample collection

The details of the sampling schedule, including dates and frequency of sample collection for T1–T15, are shown in Table A2.

3.2.3 Off-gas measurement

Gas samples were collected in the first compartment using the floating-chamber method, which was the same one used in Huynh et al. (2021). The gas collection was always carried out between 9.30 and 11.30 a.m. The time was selected together with the toilet users because the toilet was not usable during the sampling and emptying time. Additionally, this timing aligns with the data collection schedule employed by Huynh et al. (2021). The design of the floating chamber is shown in Figure 3.2. A floating chamber was placed on the surface of the septage through an access hole. The gas generated inside the floating chamber was collected using 24-

mL syringes at $t = 0, 10, 20, 30$, and 40 minutes through the sampling tube connected to the chamber; this series of gas collections is referred to as one operation.

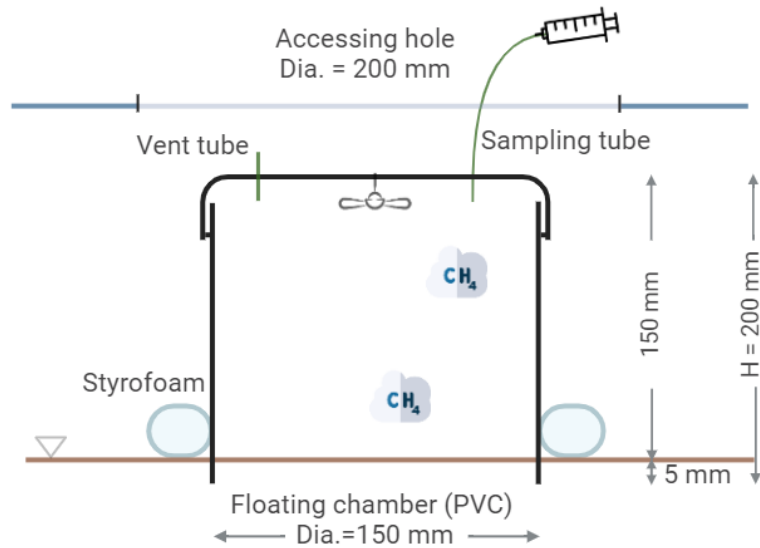


Figure 3.2 Floating chamber design

At septic tanks T1 and T2, where CH_4 emission rates in June–July 2019 (summer) were also measured by Huynh et al. (2021), the operation was replicated for five consecutive days to investigate seasonal variations by comparison of two datasets. The operation was carried out once for the other septic tanks (T3–T15).

3.2.4 Septage

At the time of gas collection, sensors of oxidation-reduction potential (ORP) (9300-10D, HORIBA), dissolved oxygen (DO) (HQ30D, HACH-LDO), and electrical conductivity (EC) with water temperature (U-24, HOBO) were inserted into septage at 0.25 m below water surface through the access holes, and these parameters were measured. After gas collection, the septage was sampled through the access holes using a sludge core sampler Figure 3.3(A). The device consisted of a cylindrical acrylic pipe connected to a check valve at its bottom and sampling valves every 30 cm along its height. After collecting the septage with the sludge core sampler, we allowed settleable solids to be separated from the supernatant for 30 minutes. The separation of sludge and liquid layers was visually observed, and sludge depth was measured as shown in Figure 3.3(B).

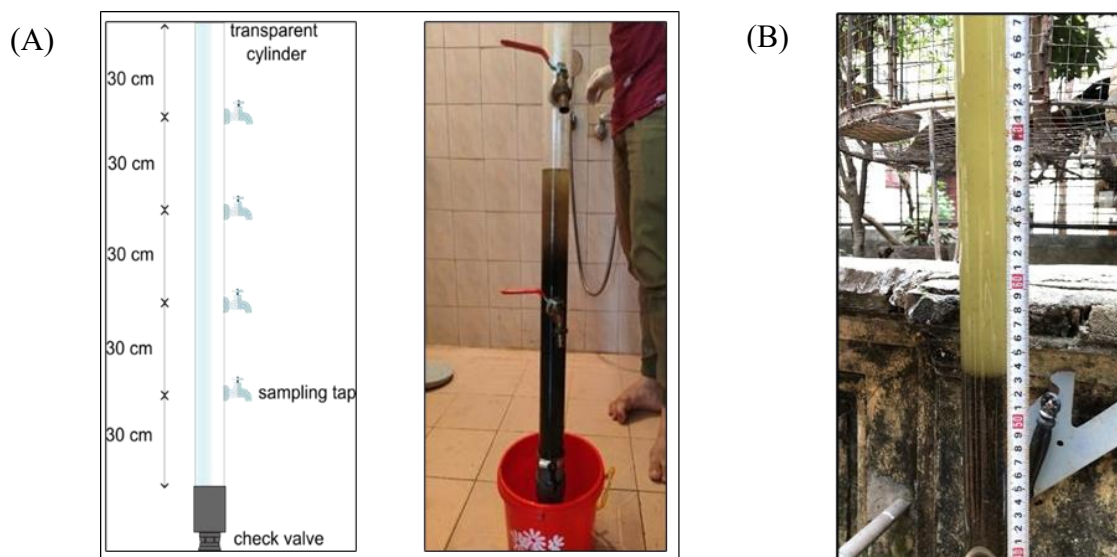


Figure 3.3 A sludge core sampler consisting of transparent tubes with a check valve at the bottom and sampling valves every 30 cm (A), Sludge and supernatant separation after 30 mins of collection (B)

3.2.5 Effluent

Effluent samples were collected at the outlet of septic tanks. A temporary tank (4.5 L) was installed to store the effluent from T1 and T2 before taking samples using an autosampler with cooling preservation by ice (3700, Teledyne ISCO). The autosampler was connected to the temporary tank to collect effluent. Effluent samples (500 mL) were collected at 2-hour intervals for seven consecutive days in December 2019. A diaphragm pump was set to empty the temporary tank immediately after each 2-hour collection. The composite samples of effluent were produced daily. An average of seven days was reported. For T3–T15, we used the grab sampling method for effluent because it was not possible to properly install the temporary tank and autosampler on the sites due to space limitations.

3.2.6 Influent

After all other measurements were taken, the septic tanks were completely emptied using a vacuum truck, washed with tap water, and emptied again through accessing holes. The clean, empty tank was used to store new wastewater, referred to as influent. We allowed the septic tank users to use the septic tanks for 24 hours. Shortly before collecting the samples, we mixed the accumulated wastewater in the septic tank by using a long stick, and then we collected 500

mL of the wastewater through the access hole using a bucket. For T1 and T2, we collected the influent once a day for three days. After each influent collection, both septic tanks were emptied and washed immediately to prepare for the subsequent sample collection. One grab sample of influent was collected from each of the remaining septic tanks (T3–T15).

3.3 Sample analysis

CH₄ was analyzed for all gas samples using gas chromatography (Shimadzu GC-2014) with a flame ionization detector. The detector temperature was 200 °C with a retention time of 5.25 min. Carbon dioxide (CO₂) was not included in this study because CO₂ emissions from the decomposition of wastewater are biogenic and not included in the total CO₂ estimation (Diaz-Valbuena et al., 2011; IPCC, 2019).

All septage, effluent, and influent samples were kept on ice immediately after collection and transported to a refrigerator (4 °C) in the laboratory. The septage samples were analyzed for chemical oxygen demand (COD), BOD, suspended solids (SS), and ammonium-nitrogen (NH₄-N). The effluent and influent samples were analyzed for COD, BOD, and SS. BOD and SS analyses were performed according to standard methods (APHA, 2005). The COD and NH₄-N were analyzed using the HACH method (DR6000, HACH). The septage, effluent, and influent samples were duplicated for every five samples and analyzed. The presented results are averages of two analyses.

The emission rate was calculated following the method by Diaz-Valbuena et al. (2011). In short, the CH₄ concentration of each sample during the operation was plotted against the collection time. After verifying the linearity of the increase in CH₄ concentration over time, the slope of the linear regression line ($y = mt + b$), m was obtained as the mass emission rate (g/(m³·d)). The CH₄ emission rates were converted to CH₄ emission rates per capita (g/(cap·d)) for the first compartment of the septic tanks, according to Eq. (3.1).

$$CH_4 \text{ emission rate} = \frac{m \times V_{FC} \times A_{comp}}{A_{FC} \times n} \quad (3.1)$$

where V_{FC} is the chamber volume = 0.00265 m³; A_{comp} is the area of the first compartment (m²); A_{FC} is the area covered by the floating chamber = 0.018 m²; and n is the number of septic tank

users (capita). Given our goal to provide an average CH₄ emission rate which can be used to estimate GHG emissions for septic tanks without measurements, it was important to perform an outlier test to assess the potential that a measurement leads to an overestimation of the average. Therefore, the interquartile range method was used before performing correlation analysis.(Whaley, 2005) One extremely high CH₄ emission rate was identified (see Figure A1).

The removal efficiency was calculated by comparing the pollutant concentration in the influent to the effluent (Eq. (3.2)). According to the sampling plan, the removal efficiency was defined as the removed proportion of influent pollutants at the moment when the effluent and influent samples were taken. This represents the removal efficiency at the particular emptying interval, and we used it to compare to other different septic tanks.

$$Removal\ efficiency\ (\%) = \frac{C_{inf} - C_{eff}}{C_{inf}} \times 100 \quad (3.2)$$

where C_{inf} is the influent concentration (g/m³), and C_{eff} is the effluent concentration (g/m³).

For a seasonal comparison of CH₄ emissions, the results of the present study (winter: December 2019–January 2020; $n = 15$) were compared with those reported by Huynh et al. (2021) (summer: June–July 2019; $n = 10$). The average ambient and liquid temperatures were 20.0 °C (17.0–24.0 °C) and 21.6 °C (19.1–24.2 °C) in winter, respectively, while they were 36.0 °C (35.0–38.0 °C) and 31.1 °C (30.1–31.7 °C) in summer.

3.4 Results and discussion

3.4.1 General septic tank conditions

The majority (83%) of the 23 septic tanks analyzed in this chapter had three compartments, and the others had two compartments. All the septic tanks were constructed in a rectangular shape with bricks or reinforced concrete underneath the toilet floors. The average proportion of the first compartment was 53% of the total volume. The surveyed septic tank served 4.4 persons on average and had an average volume of $2.3 \pm 1.5\text{ m}^3$ (average $\pm$ SD). Details of the septic

tank design are shown in Figure 3.4 and Table 3.1. The average emptying interval was 11.7 years, ranging from 3.9 years to 23.0 years. Although the average volume was lower than the minimum volume of the septic tank of at least 3.0 m³ of the national guidelines (Ministry of Construction (MOC), 1999), the emptying intervals, tank shape, and number of users were in line with previous studies in Hanoi (Harada et al., 2008; JICA, 2019; Pham et al., 2014).

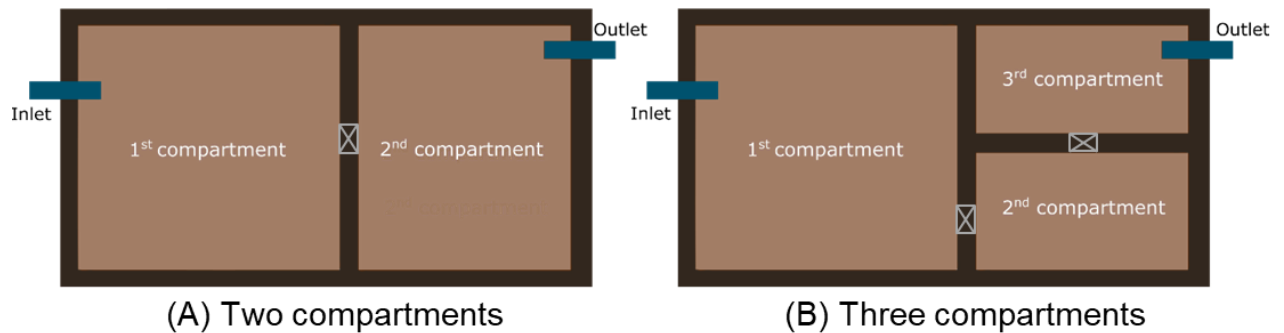


Figure 3.4 Plans of septic tank with two compartments (A), the plan of septic tank with three compartments (B)

The average emptying interval in Hanoi is comparably longer than the average emptying interval of septic tanks in Thailand of 1.90 years for different types of sanitation facilities (cesspools, cement septic tanks, and plastic septic tanks) (Koottatep et al., 2012). The significant difference in the emptying interval could be due to the difference in sludge accumulation rates and different designs of septic tanks. In other Southeast Asian countries, except for Thailand, the average emptying interval is also reported to exceed the recommended value of 1–5 years (HM Government, 2015; Koottatep et al., 2012; USEPA, 2002).

Table 3.1 General septic tanks conditions

Septic tank	Emptying interval (years)	User (person)	Sludge depth (m)	Sludge accumulation rate (L/(cap·d))	No. of compartment	Entire septic tank ¹		First compartment ²			First/Entire tank ratio
						W (m)	L (m)	W (m)	L (m)	D (m)	
T1	4.4	5	0.44	0.12	3	3	3	1.45	1.45	0.87	23%
T2	10.5	5	0.50	0.04	3	1.5	1.5	0.98	1.4	0.70	61%
T3	7	5	0.45	0.03	3	1.4	1.2	0.7	1.4	0.90	58%
T4	23	4	1.05	0.04	3	1.9	1.2	0.65	1.85	1.09	53%
T5	20	4	1.04	0.05	2	1.9	1.7	0.7	1.84	1.11	40%
T6	19	5	0.82	0.03	3	1.5	1.3	0.97	1.21	0.87	60%
T7	20	2	0.87	0.07	3	1.5	1.4	0.88	1.42	0.94	60%
T8	5	4	0.55	0.05	2	1.2	1.1	0.71	1.01	0.75	54%
T9	14	4	0.69	0.02	2	1.2	1	0.69	0.92	0.81	53%
T10	20	4	0.90	0.10	3	2.3	1.9	1.37	2.25	1.12	71%
T11	5	5	0.44	0.03	3	1.2	0.9	0.71	0.83	0.95	55%
T12	4	4	0.27	0.06	3	1.6	1.4	0.87	1.52	0.89	59%
T13	6	5	0.30	0.03	3	1.3	1.3	0.72	1.26	0.86	54%
T14	17	5	0.52	0.01	3	1.2	1	0.68	0.92	0.78	52%
T15	15	4	0.78	0.03	3	1.7	1.2	0.81	1.15	1.12	46%
ST1	3.9	5	0.39	0.11	3	2	1.5	1.45	1.45	0.87	70%
ST2	10	5	0.49	0.04	3	1.5	1.5	1.4	0.98	0.70	61%
ST3	14	4	0.66	0.04	3	2	1.5	1.45	0.95	0.72	46%
ST4	7	4	0.71	0.17	3	2.3	1.5	1.67	1.45	0.94	70%
ST5	18	3	0.70	0.05	3	1.5	1.5	1.49	1.01	1.09	67%
ST6	4	4	0.79	0.17	2	1.5	1.3	1.28	0.99	0.84	66%
ST7	9	3	0.80	0.15	3	1.7	1.5	1.51	1.2	1.18	71%
ST8	19	6	0.83	0.03	3	1.5	1.5	1.51	0.99	0.88	67%
ST9	14	5	0.50	0.04	3	2	1.5	1.51	1.49	1.00	75%
ST10	4	6	0.30	0.03	3	1.2	1.2	1.18	0.69	1.00	57%
Avg.	11.7	4.4	0.63	0.06	2.8	1.7	1.4	1.09	1.27	0.92	58%
SD	6.5	0.9	0.23	0.05	0.4	0.5	0.5	0.3	0.36	0.14	11%

¹ST1-ST10 are obtained from Huynh et al. (2021), ²The data was from the interview of houses' owners, ³The data was from direct measurement

3.4.2 Septage accumulation and composition against emptying intervals

Sludge depth and sludge accumulation rates

Sludge depth in the first compartment of the 23 septic tanks ranged from 0.27 to 1.05 m. Seven out of these septic tanks had sludge that filled the tank to more than 90% of the effective depth. A maximum depth of 1.05 m was observed in the septic tank with an emptying interval of 23.0 years; the sludge occupied 96% of the effective depth of the septic tank. Excessive accumulation of sludge resulted in malfunction of settling solids and potentially led to the short-

circuiting of raw blackwater. It is concluded that these tanks cannot fulfill the basic function of a septic tank. Sludge depth was linearly correlated with the emptying interval ($R = 0.769$, $p < 0.001$), as shown in Figure 3.5. More information on the sludge depth and septic tank dimensions is shown in Table 3.1.

The sludge accumulation rate in this study was 0.06 ± 0.05 L/(cap·d). It is comparable to 0.04 L/(cap·d) in a previous study in Hanoi (Pham et al., 2014), and 0.07 L/(cap·d) in six cities in Indonesia (Mills et al., 2014), while it was high in some other countries: 0.5 L/(cap·d) in Thailand (Koottatep et al., 2012), 0.1 L/(cap·d) in France (Maunoir, Philip, & Rambaud, 2007), and 0.1 L/(cap·d) in Canada (Lossing, Champagne, & McLellan, 2010). Potential factors for the difference in accumulation rate include the type of wastewater entering the septic tanks (blackwater or both black and graywater), solid and organic strength of the influent, diets, flushing water quantity, hydraulic retention time, and temperature (Al Momani, 2015; Elmitwalli, 2013; Gray, 1995).

Septage composition

Detailed septage composition data are provided in Table A3. Briefly, septage COD, BOD, and SS were $16,400 \pm 8,940$, $13,600 \pm 7,780$, and $7,800 \pm 1,860$ g/m³, respectively. The DO concentration was 0.18 ± 0.14 g/m³, and the ORP value was -369 ± 97 mV. As the DO and ORP were measured at 0.25 m below the water surface and the septage depth was 0.92 m on average, these results indicate that the septage were in anaerobic conditions. An ORP of less than -330 mV is reportedly suitable for the growth of methane-forming bacteria (Hungate, 1969). The favorable ORP for methanogenesis ranges from approximately -400 mV to -200 mV (Zehnder, A. J. B., 1978). The range of NH₄-N concentration was 172–750 g N/m³, which did not exceed the inhibitory level for anaerobic processes of 3,000 g N/m³ (Anjum, Grohmann, & Krakat, 2017). Thus, the septage DO, ORP, and NH₄-N values potentially cause anaerobic digestion and, therefore, CH₄ production.

As shown in Figure 3.5 (A)–(E), emptying intervals showed significant correlations with septage SS ($R = 0.917$, $p < 0.001$), COD ($R = 0.914$, $p < 0.001$), BOD ($R = 0.895$, $p < 0.001$), DO ($R = -0.542$, $p = 0.005$), and ORP ($R = -0.800$, $p < 0.001$). The results showed that the long emptying intervals led to the accumulation of solids and organic matter under anaerobic conditions (low DO and ORP values). Sludge depth had significant correlations with septage

SS ($R = 0.726, p < 0.001$), COD ($R = 0.789, p < 0.001$), BOD ($R = 0.775, p < 0.001$), DO ($R = -0.504, p = 0.01$), and ORP ($R = -0.583, p = 0.002$) (Figure 3.6). The correlations indicate that emptying interval and sludge depth could be used to predict the septage compositions and conditions inside septic tanks.

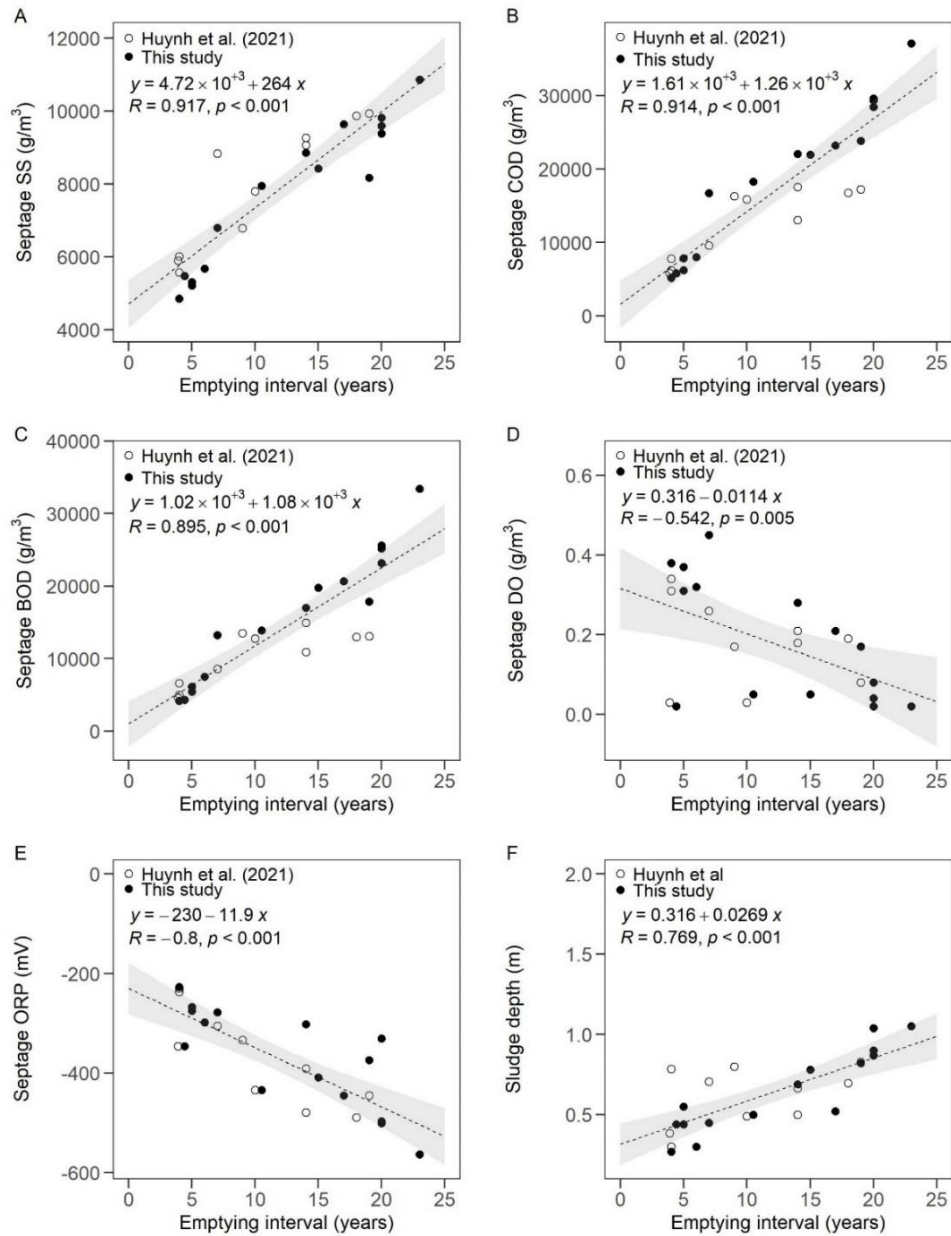


Figure 3.5 Correlations between emptying intervals and septage SS (A); septage COD (B); septage BOD (C); septage DO (D) and septage ORP (E), and sludge depth (F) for 25 septic tanks in Hanoi. The lines show the linear regression and the gray zones mark the 95% confidence intervals.

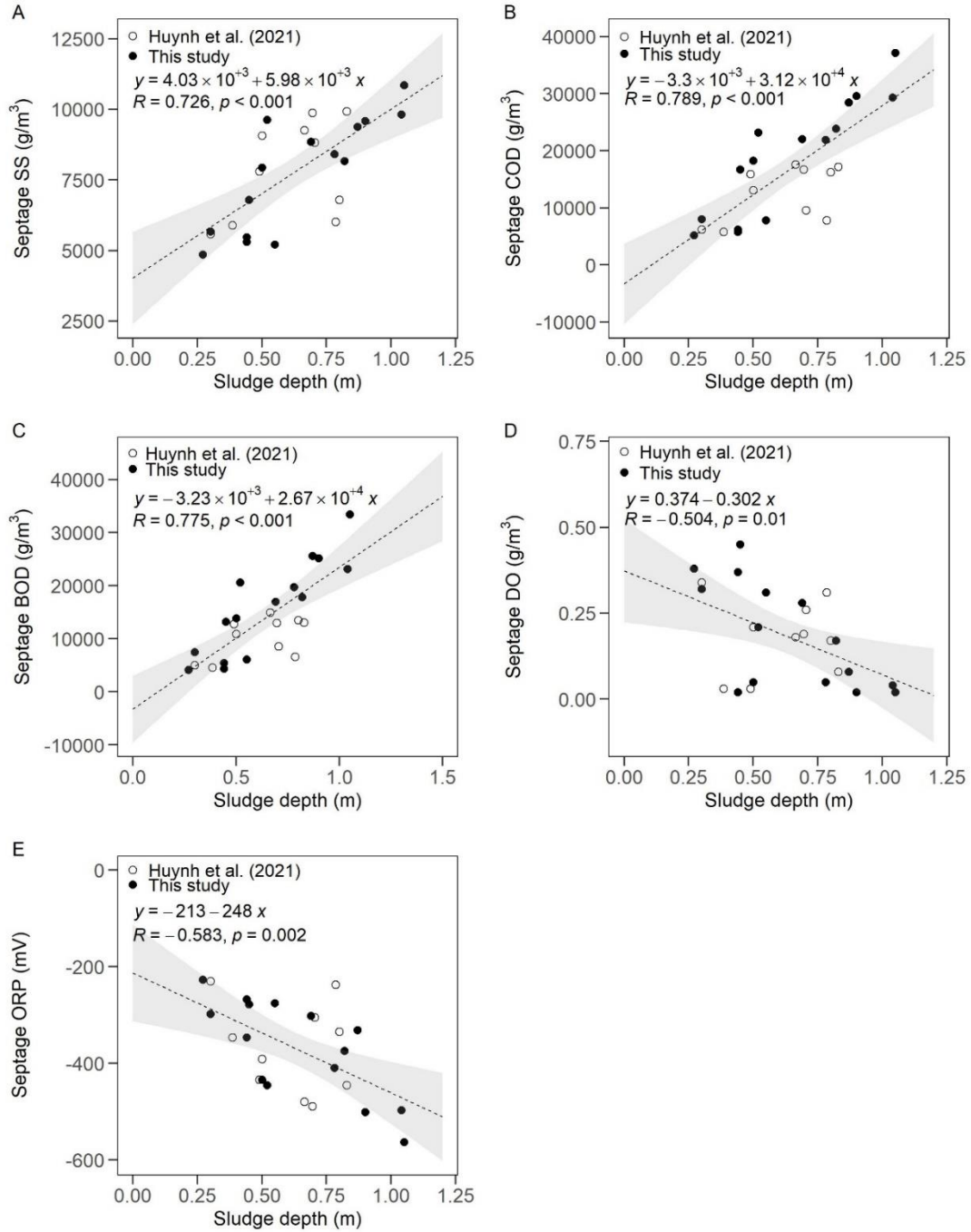


Figure 3.6 Correlations between sludge depth and septage SS (A); septage COD (B); septage BOD (C); septage DO (D) and septage ORP (E) for 25 septic tanks in Hanoi. The lines show the linear regression and the gray zones mark the 95% confidence intervals.

3.4.3 Pollutant removal efficiencies against emptying intervals

SS

The SS concentrations of septic tank influent and effluent were $1,110 \pm 321$ and 142 ± 67 g/m³, respectively Table A4. and the SS removal efficiency was $87.0 \pm 5.8\%$. The effluent SS concentration was within the previously reported range of 12–733 g/m³ in a study in Hanoi (JICA, 2019). All the septic tanks had an SS removal efficiency above the SS removal efficiency reported for well-functioning septic tanks (i.e., 50%) (Dasgupta & Agarwal, 2022; Dasgupta, Agarwal, & Mukherjee, 2021; Shi & Doulaye Kone, 2010). Possible explanations for the functionality of SS removal might be that 1) an extremely high SS concentration in the influent might allow the effective removal of a significant part of SS in septic tanks, and 2) the well-functioning second or third compartments of the tanks could help prevent solids from being carried over into the effluent (Mahon et al., 2022a). However, despite a high SS removal efficiency, it is not sufficient for septic tanks with long emptying intervals to discharge effluent with SS concentrations below the national regulation of 100 g/m³ (Ministry of Natural Resources and Environment (MONRE), 2008).

Additionally, there was very strong evidence for the relationships between the emptying interval and both effluent SS ($R = 0.948$, $p < 0.001$) and SS removal efficiency ($R = -0.822$, $p < 0.001$) as illustrated in Figure 3.7(A) and (B), respectively. The results indicate the deterioration of the SS removal efficiency due to the long emptying interval.

COD and BOD

The influent and effluent concentrations of COD were $1,240 \pm 244$ and 813 ± 234 g/m³, respectively, and those of BOD were 937 ± 197 and 587 ± 181 g/m³, respectively. Subsequently, the COD and BOD removal efficiencies were calculated as $34 \pm 20\%$ and $37 \pm 17\%$, respectively. COD and BOD concentrations of the effluent were within the ranges of a previous study in Vietnam: COD of 91–1,780 g/m³ and BOD of 60–920 g/m³ (JICA, 2019). The BOD removal efficiency of well-functioning septic tanks is reported as 30–50% (Dasgupta & Agarwal, 2022; Dasgupta et al., 2021). In the present study, 11 of 15 septic tanks (73%) had BOD removal efficiencies exceeding 30%. However, the effluent BOD concentrations from 15 septic tanks were considerably higher than the national effluent standard of 50 g/m³ (Ministry of Natural Resources and Environment (MONRE), 2008).

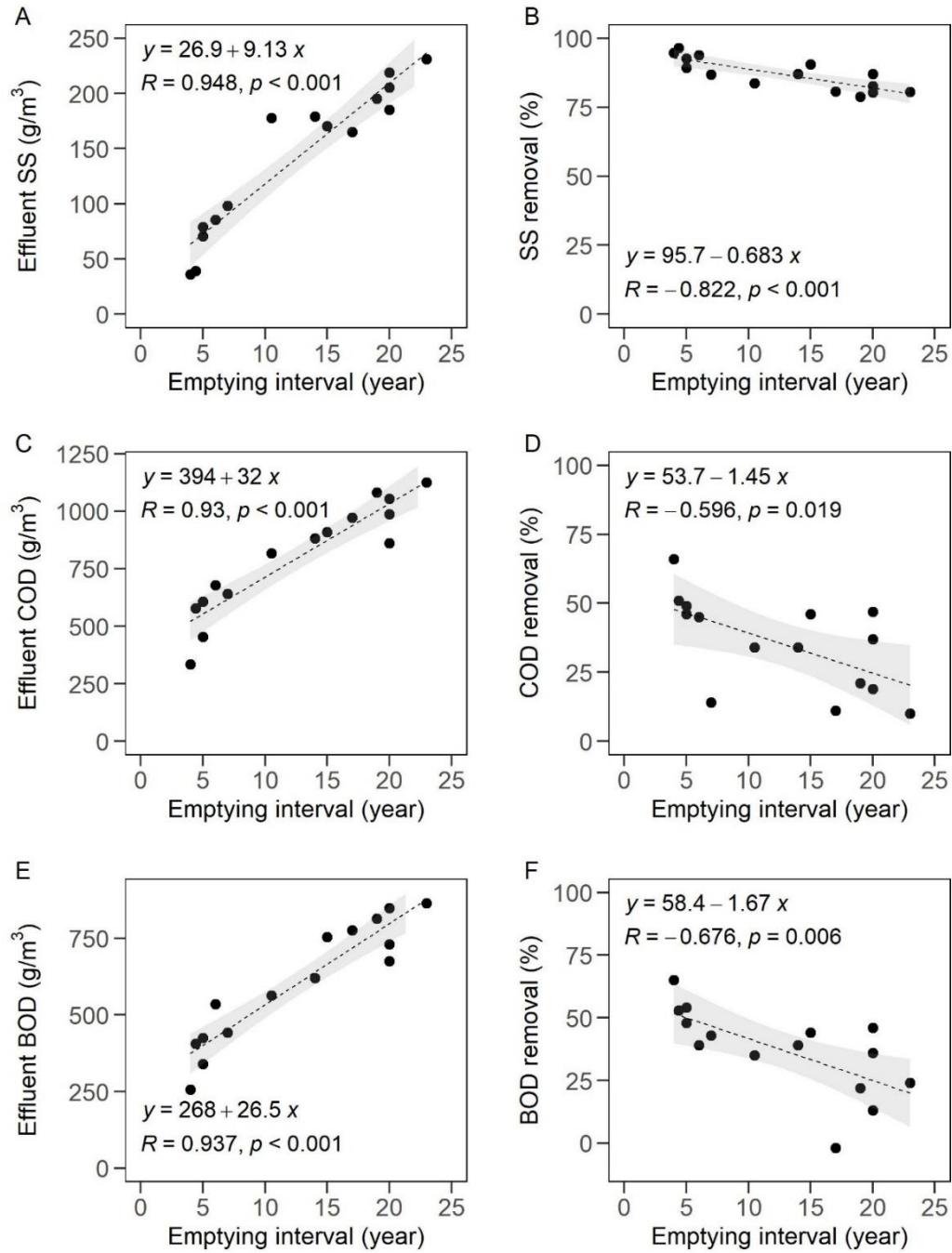


Figure 3.7 Correlations between emptying interval and effluent SS (A); SS removal (B); effluent COD (C); COD removal (D); effluent BOD (E); and BOD removal (F) for 15 different septic tanks in Hanoi. The lines show the linear regression, and the gray zones mark the 95% confidence intervals.

Similar to SS, there was very strong evidence for the relationships between the emptying and effluent COD ($R = 0.930$, $p < 0.001$), BOD ($R = 0.937$, $p < 0.001$), and the removal efficiencies of COD ($R = -0.596$, $p = 0.019$) and BOD ($R = -0.676$, $p = 0.006$), indicating that prolonged use of septic tanks without emptying also deteriorated organic removal efficiencies (Figure 3.7(C)–(F)).

3.4.4 CH₄ emission

Seasonal variation

The average CH₄ emission rates in winter and summer were 10.3 ± 7.6 g/(cap·d) (range = 2.2–26.8 g/(cap·d) and 11.9 ± 4.5 g/(cap·d) (Huynh et al., 2021) (range = 4.4–18.8 g/(cap·d)), respectively. These emission rates did not differ significantly despite an average liquid temperature difference of 9.4 °C between winter (average = 21.7 °C, range = 19.1–24.2 °C) and summer (average = 31.1 °C, range = 30.1–31.7 °C). The average CH₄ emission rate of septic tanks from both winter and summer data was 10.9 (range: 2.2–26.8) g/(cap·d). The data on CH₄ emission rates and liquid temperature is presented in Table A6. Although CH₄ production has been reportedly affected by temperature (Mao, Feng, Wang, & Ren, 2015), there was no evidence that CH₄ emission rates are dependent on liquid temperature among the 23 septic tanks (Figure 3.8). (Huynh et al., 2021) reported no statistically significant correlation between CH₄ emission rates and liquid temperature, and (Diaz-Valbuena et al., 2011) also observed no clear correlation between them, while the average liquid temperature differences of (Huynh et al., 2021) and (Diaz-Valbuena et al., 2011) were 1.1 °C and 15 °C, respectively.

The results of CH₄ emission rates and septage composition in the winter and summer of two individual septic tanks, T1 and T2, were further compared, which were the same septic tanks investigated in the two seasons (Figure A2). The CH₄ emission rates in winter and summer of T1 were 11.1 g/(cap·d) at 21.6 °C and 11.1 g/(cap·d) at 31.1 °C, and those of T2 were 15.5 g/(cap·d) at 22.1 °C, and 15.5 g/(cap·d) at 31.4 °C, respectively. The septage COD, BOD, SS, DO concentrations, and ORP were comparable between the two seasons (Table A7). CH₄ emission rates were comparable between summer and winter, although the liquid temperature differed by 9.4 °C. Hence, the impact of temperature might have been limited, possibly because the temperature was lower than the optimal temperature of anaerobic digestion of 35–37 °C (Wang et al., 2018). Additionally, the impact of temperature on CH₄ emission rates might be

masked by the impact of other influential factors, such as organic accumulation (BOD and COD) and anaerobic conditions (low DO and ORP values), which are discussed in the following section.

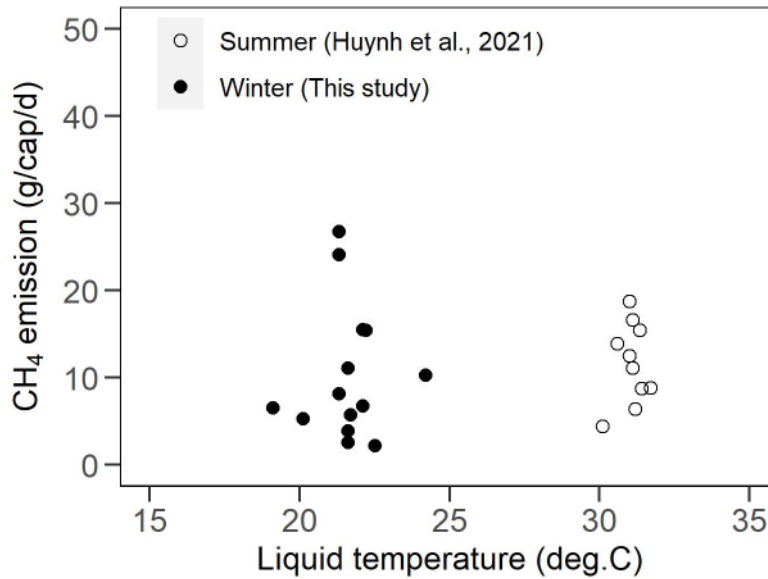


Figure 3.8 Variation of CH₄ emission rates between summer and winter

The CH₄ emission rates of the same septic tanks between winter and summer were in a similar range and seem to be only marginally affected by the liquid temperature difference of 9.4 °C. Hence, the data of the present study in winter was integrated with the data of the previous study in summer, following the same sampling and analytical methods in summer, and analyzed the correlation of CH₄ emission rates and other parameters of both summer and winter together. This was possible because we followed the same sampling and analytical procedures as in the previous study.

CH₄ emission rates against emptying intervals and removal efficiencies

The CH₄ concentrations of the gases sampled from the floating chamber of the 15 septic tanks at $t = 0, 10, 20, 30$, and 40 min are listed in Table A5. The septic tanks were confirmed to produce significant concentrations of CH₄ and the CH₄ concentrations in the floating chamber linearly increased ($R = 0.976\text{--}0.996$), reaching $3,430\text{--}22,600$ g/m³ at $t = 40$ min.

The CH₄ emission rates were strongly correlated with emptying intervals ($R = 0.614, p = 0.001$) and sludge depth ($R = 0.596, p = 0.002$), as shown in Figure 3.9(A) and (B). Furthermore, they were strongly correlated with the septage compositions including COD ($R = 0.641, p < 0.001$), BOD ($R = 0.654, p < 0.001$), DO ($R = -0.704, p < 0.001$), and ORP ($R = -0.597, p = 0.002$), as shown in Figure 3.9(C)–(F). These correlations could be explained as follows. Emptying intervals become longer, and the sludge depth increases accordingly. Figure 3.5 and Figure 3.6 indicate that long emptying intervals led to higher BOD and COD and lower DO and ORP in septage, meaning organic matter accumulation under anaerobic conditions. Accordingly, CH₄ emissions increase with increasing emptying intervals and sludge depth. A previous study also showed that higher BOD and COD concentrations and lower DO and ORP were key chemical conditions for the CH₄ emission from septic tanks, although the study did not confirm the significant correlation between the emission and the sludge depth (Huynh et al., 2021).

Considering the relationship between CH₄ emission and BOD removal efficiency, one septic tank (T14) had not been emptied for 17 years and had BOD removal efficiencies less than 0%, of which the CH₄ emission rate was 5.3 g/(cap·d). The negative BOD removal rate could be due to a short circuit in the septic tank, or the accumulated sludge may be carried over through the effluent. Both phenomena are caused by excessive sludge accumulation. Notably, the observation showed that even though the tank was not functional as a septic tank and, consequently, no longer removed BOD from the influent, CH₄ was still emitted from the tank. The CH₄ emission rates were plotted against the BOD and COD removal efficiencies, as shown in Figure 3.10. Although the correlations were not statistically confirmed, CH₄ emission rates were negatively correlated with BOD ($R = -0.219, p = 0.451$) and COD ($R = -0.270, p = 0.351$) removal efficiencies. These indicate that the CH₄ emission could not be estimated based on the positive correlation with BOD or COD removal efficiencies for the septic tanks with long emptying intervals.

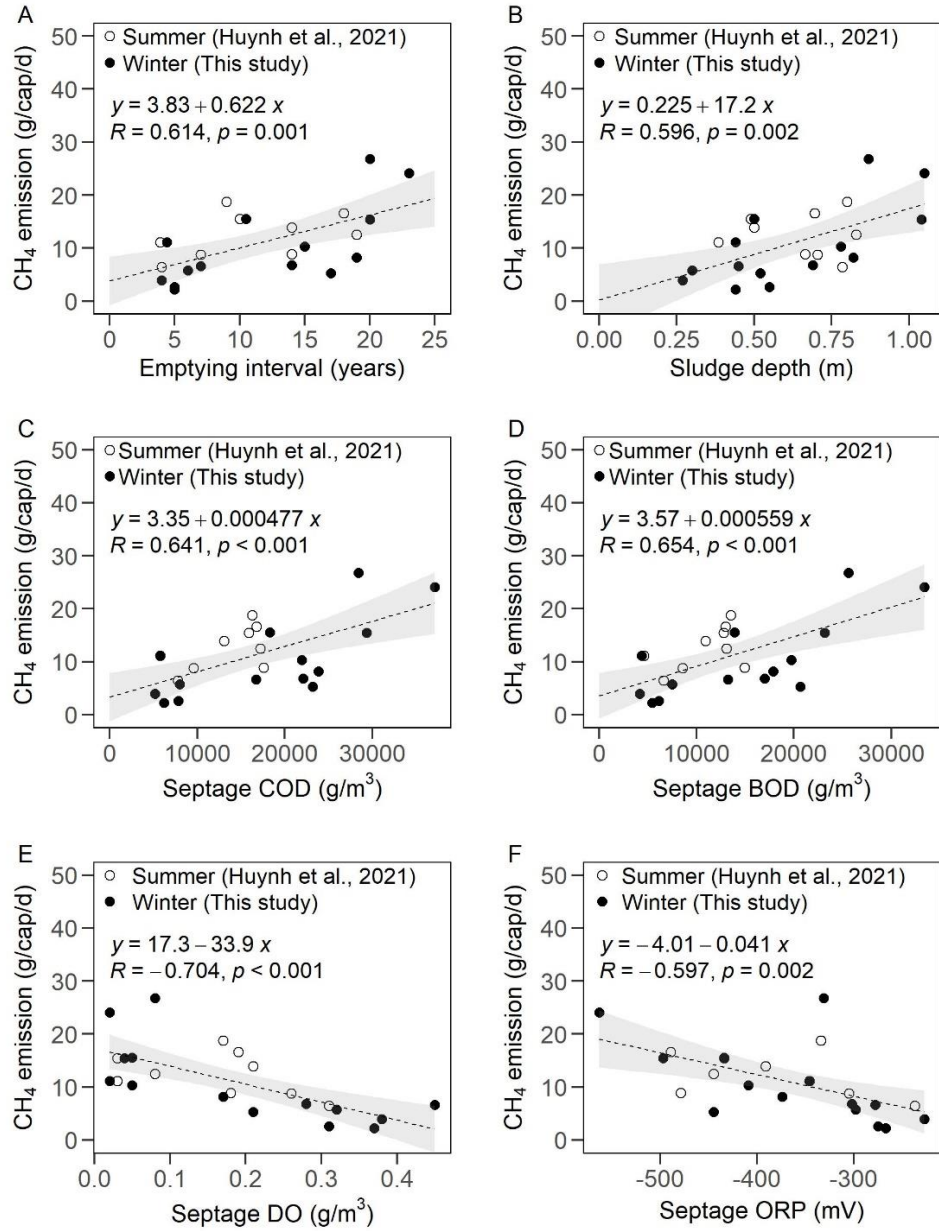


Figure 3.9 Correlations between CH_4 emission and emptying interval (A); sludge depth (B); septage COD (C); septage BOD (D); septage DO (E); and septage ORP (F) for 15 septic tanks in Hanoi in winter (the present study) and 10 septic tanks in summer (Huynh et al. 2021). The lines show the linear regression, and the gray zones mark the 95% confidence intervals.

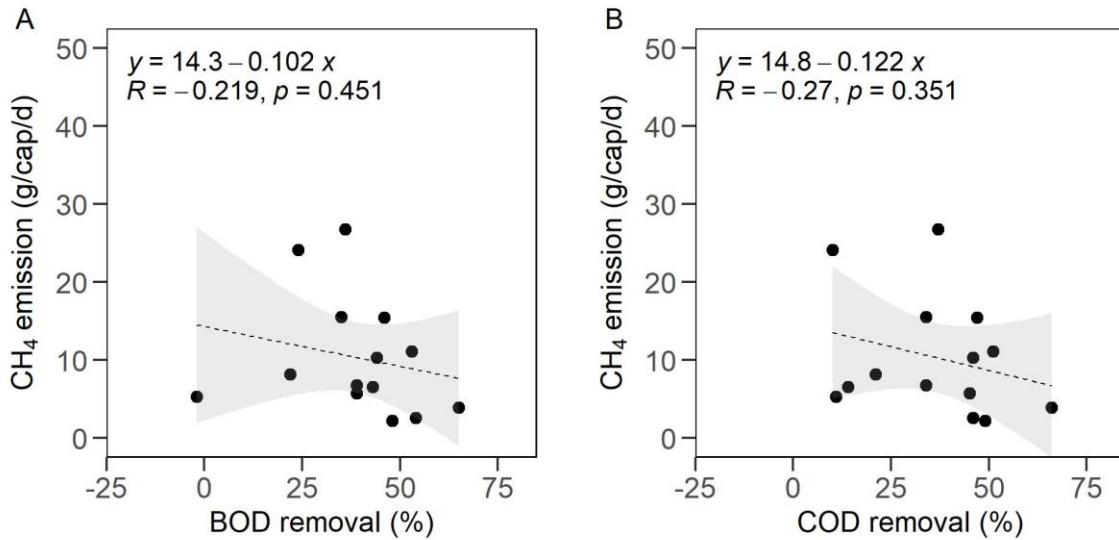


Figure 3.10 Correlations between CH₄ emission and BOD removal (A) and COD removal (B) for 15 septic tanks in Hanoi. The lines show the linear regression, and the gray zones mark the 95% confidence intervals.

3.4.5 Challenges and implications to the current CH₄ emission estimation methods

In 2010, the wastewater sector accounted for 8% of the global anthropogenic CH₄ emissions, following enteric fermentation (28%), agriculture (20%), oil and gas (18%), and landfills (10%) (Yusuf, Noor, Abba, Abu Hassan, & Din, 2012). From 1990 to 2005, global CH₄ emissions from wastewater were estimated to have increased by about 35% and are predicted to increase by 28% in 2030 (U.S. Environmental Protection Agency, 2012). The major contributors to emitting CH₄ in the wastewater sector are the low- and middle-income countries in Asia, and Africa regions (U.S. Environmental Protection Agency, 2012), where septic systems are prevalent. However, the quantification of CH₄ emissions and, thus, the implementation of mitigation strategies within this sector poses significant challenges.

In the case of septic tanks, the findings indicate that shortening the emptying interval could improve pollutant removal efficiencies, including COD, BOD, and SS, thereby preventing septic tanks that have been in use for a long time and have poor functionality from discharging highly polluted effluent into the environment. For septic tanks where the effluent quality cannot meet the environmental standard, effluents must be treated by further processes such as a soil treatment unit or collected and treated at the centralized wastewater treatment plants.

Furthermore, shortening the emptying interval could reduce CH₄ emission rates from septic tanks. For climate change mitigation and pollution control, it is therefore recommended to create incentives for shortening emptying intervals of the septic tank as an efficient measure to improve the treatment efficiency of septic tanks and, at the same time, reduce GHG emissions. In the interest of fostering demand for the emptying service and supporting GHG mitigation, appropriate intervals should be considered to balance the impact on climate change and the aquatic environment with the financial burdens caused by the emptying, transportation, treatment, and disposal of emptied sludge. Additionally, even if CH₄ emissions are mitigated from septic tanks, CH₄ and other GHG can potentially be emitted from other steps of the sanitation service chain, including emissions from sludge transportation, sludge treatment facilities, and disposal sites. As septic tanks are only a part of the sanitation service chain, GHG-mitigating FSM along the entire sanitation service chain is ultimately required. Moreover, a city-wide balance might be needed to investigate if previous storage in a septic tank could lead to additional GHG emissions when compared to direct treatment in a centralized wastewater treatment plant and if, in such a case, the septic tank would better be removed to sustainably mitigate GHG emissions from urban sanitation.

Regarding CH₄ emission estimation, the IPCC employs an approach where the CH₄ emission rate is estimated based on a positive correlation with BOD removal efficiencies; a default value of 50% (40–72%) of the influent BOD is assumed to be removed in septic tanks, and this fraction is then converted into CH₄ (IPCC, 2019). To highlight the differences, the emissions rates was estimated based on IPCC and compared with our results. For the IPCC approach, CH₄ emissions was calculated by utilizing the recommended per-capita BOD for Asia of 40 g/(cap·d) for domestic wastewater (IPCC, 2019). Given that the BOD of blackwater in low- and middle-income countries accounts for 55% of the total BOD in domestic wastewater (Mara, 2013), the per-capita BOD value for blackwater would be 22 g/(cap·d). Based on the IPCC approach, accounting for maximum and minimum BOD removal efficiencies within the suggested range (i.e., 40% and 72%), the estimated CH₄ emission rates are 5.3 g/(cap·d) and 9.5 g/(cap·d), respectively. In the present study, the average BOD removal efficiency was 37% (-2–65%), and the average CH₄ emission rate was 10.9 g/(cap·d) (2.2–26.8 g/(cap·d)). The difference between the results of our study and those of the IPCC suggests an estimation error when using BOD removal to estimate CH₄ emission rates (Table 3.2).

Table 3.2 CH₄ emissions rates from IPCC method and direct measurement

Method	BOD removal		Per-capita BOD (g/(cap·d))	Equation	CH ₄ emissions (g/(cap·d))
	efficiency or Methane correction factor (MCF)	B ₀ (g CH ₄ /g BOD)			
IPCC	40% (min.)	0.6	22	$CH_4 emission =$	5.3
	50% (default)	0.6	22	$B_0 \cdot MCF \cdot BOD$	6.6
	72% (max.)	0.6	22		9.5
This study	Estimation based on direct CH ₄ off-gas measurement from the first compartment of 23 blackwater septic tanks in Hanoi with long emptying intervals				10.9 ± 6.46

It should be noted that in this study, 53% of 15 septic tanks could not meet the lower range of the BOD removal efficiency (40%) suggested by the IPCC, and the CH₄ emissions were only assessed in the first compartment, which accounts for 53% of the entire tank's volume. Furthermore, the negative correlation between CH₄ emission rates and BOD removal efficiencies demonstrated that the CH₄ emission cannot be estimated by BOD removal efficiencies in the case of septic tanks with long emptying intervals. For better quantification, other influential parameters should be considered for the CH₄ emission estimation. Based on the findings, emptying intervals could be a potential factor in estimating CH₄ emissions due to their strong and significant correlation with CH₄ emission rates and the fact that they can be obtained without conducting on-site measurements. Sludge depth could serve as a measured parameter that is obtainable with much less effort than direct CH₄ measurements. The CH₄ emission factor per capita obtained in the present study could also be useful data for the estimation of the city-wide emission, reflecting the reality of long emptying interval septic tanks in low- and middle-income countries. As CH₄ emission rates were strongly correlated with the emptying intervals, and emptying is a crucial component of FSM, the conditions of FSM would affect the emission from septic tanks in the city. Accordingly, the GHG emission estimation should include the factor of the FSM. Hence, the distribution of emptying intervals and/or sludge depth in the city would be a key factor to reflect the effect of FSM on the city-wide estimation.

In conclusion, this study examined how emptying intervals affect septic tank removal efficiency and CH₄. The main findings are as follows.

1. Longer emptying intervals significantly reduced the pollutant removal efficiencies while they increased the CH₄ emission rate from the septic tanks.
2. The negative correlation between BOD removal efficiency and CH₄ emission rates signals that the CH₄ emission estimation based on BOD removal efficiency might not reflect a realistic emission for long emptying interval septic tanks. For better quantification, it is suggested that using alternative factors for CH₄ emission, including emptying intervals, sludge depth, and CH₄ emission factors per capita reflecting long emptying intervals is more appropriate.

The following limitations of this study should be noted. The present study investigated only the first compartment of the septic tanks. Further studies are required to investigate potential CH₄ emissions from other compartments. An appropriate emptying strategy should be explored to balance the financial cost and environmental impacts, including water pollution and climate change. Nevertheless, the findings of the present study and the data set of septic tanks with long emptying intervals are crucial for mitigating GHG emissions from septic tanks and exploring strategic septic tank usage/removal and FSM in low- and middle-income countries.

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Chapter 4 GHG emissions estimation along sanitation service chains

4.1 Introduction

GHG emissions related to SSCs were mostly reported in a separated component. Septic tanks with long emptying intervals tend to emit more CH₄ than the ones with shorter emptying intervals as discussed in Chapter 3. Gravity sewers with poor maintenance can result in the stagnation of wastewater, serving as a source of CH₄ emissions (Chaosakul et al., 2014; IPCC, 2006), and during a period of high flow, it can also be a source N₂O emissions (M. D. Short et al., 2014). WWTPs and FSTPs are identified as potential sources of CH₄, and N₂O emissions during biological treatment processes (i.e., direct emissions), and a source of indirect emissions of carbon dioxide (CO₂) for the energy and chemicals production (Cakir & Stenstrom, 2005; Doorn, 1997; Frijns, 2012; Law et al., 2012; Mamais et al., 2015b). However, the first attempt of GHG emissions estimation from a whole system was conducted using Kampala, Uganda as a study area. The results showed that the lack of field data in most of low- and middle-income countries pose the difficulties in conducting a similar analysis of GHG emissions estimation in other cities (Johnson et al., 2022). Additionally, technology used and how well treatment facilities are managed in other low- and middle-income countries are the important factors that can vary GHG emissions estimation and further mitigation attempts. As a result, there is a pressing need for more observational data collection and analysis regarding GHG emissions estimation with different settings of SSCs. In addition, it is essential to quantify from a system perspective along SSCs.

The goal of this chapter is to estimate GHG emissions from process and operation along a sanitation service chain. Embedded emissions in construction material and other emissions related to infrastructure were not included in this study. Therefore, we quantified the current amount of GHG emissions for a typical example from low- and middle-income countries, the Truc Bach drainage area in Hanoi, where on-site treatment facilities (i.e., septic tanks) are used with centralized WWTPs.

4.2 Materials and methods

4.2.1 Study area

The criteria for selecting a study area were as follows: i) the area contains all components of SSCs, ii) the SSC is a representative of SSCs in low- and middle-income countries, in terms of management and infrastructure conditions, and iii) the area has data that is accessible, including septic tanks' GHG emissions, wastewater characteristics (i.e., black and graywater, fecal sludge, influent of WWTP), and WWTP configuration. The closest to fulfill all these criteria was the Truc Bach drainage area in urban Hanoi, Vietnam (Figure 4.1). The area fulfils most necessary criteria. However, the following data are lacking: effluent data of FSTP, infiltration and exfiltration in sewers, and locations of fecal sludge disposal sites in case of direct disposal.



Figure 4.1 Truc Bach drainage area obtained from Hanoi drainage company

The Truc Bach drainage area covers 0.55 km² with a population of 15,700 people (Brandes et al., 2016). In Hanoi, 88% of households rely on septic tanks (Brandes et al., 2016) with average emptying intervals of 10.2 years (Pham, 2014). Typically, in Hanoi, septic tanks receive only blackwater (Huynh et al., 2021). Effluent of septic tanks is discharged to sewers. Graywater, on the other hand, is usually directly discharged to combined gravity sewers or open drains (World Bank Group, 2013). The Truc Bach WWTP has a capacity to treat wastewater of 2,500 m³/d. The fecal sludge in the septic tanks is emptied by vacuum trucks and transported to and

treated at Cau Dien FSTP (i.e., Hanoi URENCO 4), which is the only FSTP in the entire Hanoi area (JICA, 2019). The Cau Dien FSTP has a capacity of 10–30 m³/d and the majority of sludge treated in the FSTP is from public toilets (Brandes et al., 2016).

4.2.2 Data analysis

System boundary and input data

The designed system boundary for GHG emissions along the SSC in this study area is illustrated in Figure 4.2. The boundary includes the emissions from five components: septic tanks, vacuum trucks, sewers, WWTP, and FSTP. Emissions from end-use and disposal in either safe or unsafe management are excluded in this study.

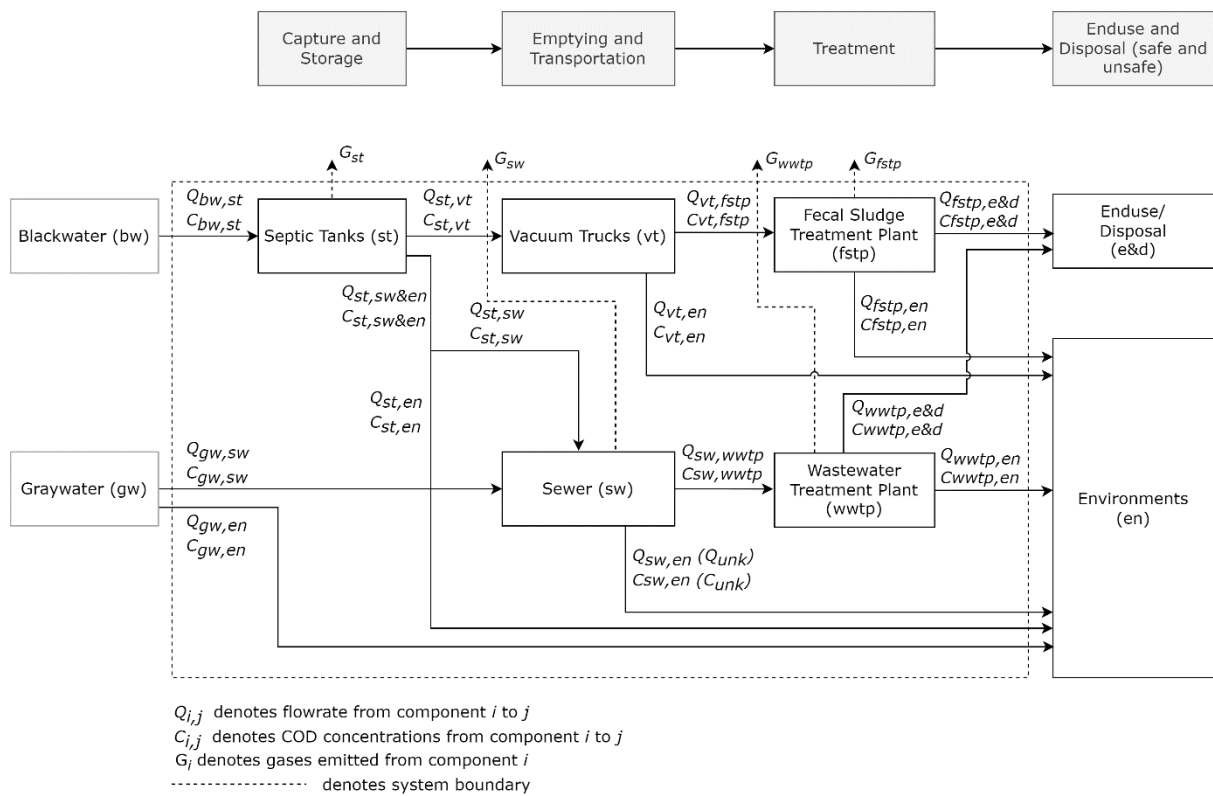


Figure 4.2 System boundary for mass balance of flow rates (Q), COD concentrations (C) and gases (G) of the sanitation service chain

Wastewater flow rates (Q) and COD loadings (L) were calculated for each component using the mass balance approach (eq. (4.1) and (4.2)). The description and equations of all parameters for the estimation of Q and L are listed in Table 4.1. The measured and reported

parameters for the estimation of Q and L were input (Table 4.2) into the system boundary, and used mass balance to calculate the missing data.

$$\sum Q_{in,i} - \sum Q_{out,i} = 0 \quad (4.1)$$

$$\sum L_{in,i} - \sum L_{out,i} = 0 \quad (4.2)$$

where Q is wastewater flow rate (m^3/d); L is COD loading ($\text{g COD}/\text{d}$), which is obtained by multiplying Q (m^3/d) by COD concentration (C) (g/m^3).

However, when performing mass balance around sewers, the data on net flow rate of wastewater discharged from sewers to environments were lacking. This lacking flow rate was referred to as unknown flow rate (Q_{unk}) and unknown concentration (C_{unk}), representing the flow and concentration of wastewater that is not transferred to the WWTP (Figure 4.3). Hence, COD loading of Q_{unk} (L_{unk}) is the remained COD loading after subtracting the COD loading of wastewater from sewers transferred to WWTP ($L_{sw,wwtp}$). Additionally, it was assumed that some portion of COD loading is converted into CH_4 through biological processes in sewers (Δ_{sw}), following the guidelines of the IPCC. The converted portion is represented by a default methane correction factor (MCF) of 0.5 (IPCC, 2019). Hereafter, the Sankey diagrams (Bogart, 2024) were used to separately present percentages of Q and L along the SSC to provide an overview of the current state of the wastewater streams.

Derivation of concentration of unknown wastewater

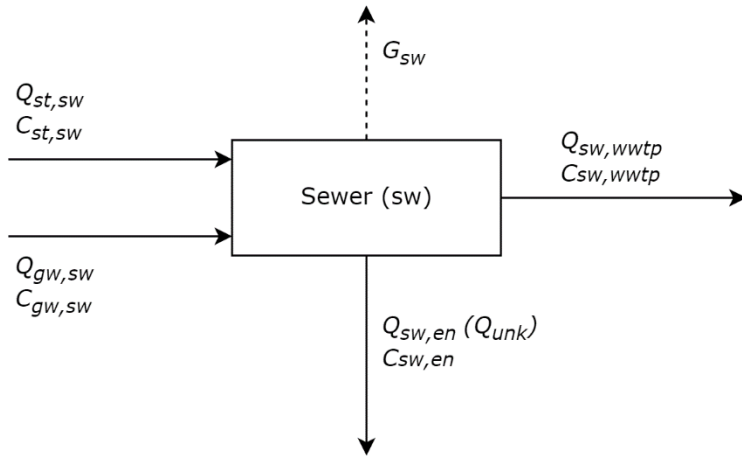


Figure 4.3 Mass balance around sewers

$$\sum Q_{sw-in} - \sum Q_{sw-out} = 0 \quad (4.3)$$

$$Q_{st,sw} + Q_{gw,sw} - Q_{sw,wwtp} - Q_{unk} = 0 \quad (4.4)$$

$$Q_{unk} = Q_{st,sw} + Q_{gw,sw} - Q_{sw,wwtp} \quad (4.5)$$

Where Q_{unk} is flow rate of unknown wastewater not transferred to WWTP (m^3/d); $Q_{st,sw}$ is flow rate of effluent from septic tanks to sewers (m^3/d); $Q_{gw,sw}$ is flow rate of graywater discharged to sewers (m^3/d); and $Q_{sw,wwtp}$ is flow rate of wastewater from sewers transferred to WWTP (m^3/d).

Gas production (G_{sw}) was calculated from COD that is removed in sewers (Δ_{sw}). Δ_{sw} was calculated by using COD loading entering sewers (L_{sw-in}) and a removal fraction or MCF suggested from IPCC for the CH_4 conversion as shown in eq. (4.6).

$$\Delta_{sw} = \sum L_{sw-in} \times MCF_{sw} \quad (4.6)$$

$$\sum L_{sw-in} - \sum L_{sw-out} - \Delta_{sw} = 0 \quad (4.7)$$

$$L_{unk} = Q_{st,sw} \times C_{st,sw} + Q_{gw,sw} \times C_{gw,sw} - Q_{sw,wwtp} \times C_{sw,wwtp} - \Delta_{sw} \quad (4.8)$$

$$C_{unk} = \frac{L_{unk}}{Q_{unk}} \quad (4.9)$$

Where Δ_{sw} is COD loading that is removed in sewers (g COD/d); L_{sw-in} is COD loading entering sewers (g COD/d); MCF is methane collection factor (fraction) of sewers; L_{unk} is unknown COD loading discharged from sewers to environments (g COD/d); L_{sw-out} is COD loading leaving sewers (g COD/d); and C_{unk} is COD concentration of unknown wastewater not transferred to WWTP (g COD/d).

Table 4.1 Description for Q and COD flow balances along the sanitation service chain

Component	Symbol	Description	Equation	Unit
Septic tanks (ST)	$Q_{st,vt}$	Flow rate of fecal sludge emptied from septic tanks to vacuum trucks	$Q_{st,vt} = N_{st,emp} \times S_r$	m ³ /d
	$Q_{st,sw\&en}$	Flow rate of effluent from septic tanks to sewers and environments	$Q_{st,sw\&en} = Q_{bw} - Q_{st,vt}$	m ³ /d
	$Q_{st,sw}$	Flow rate of effluent from septic tanks to sewers	$Q_{st,sw} = Q_{st,sw\&en} \times P_{st,sw}$	m ³ /d
	$Q_{st,en}$	Flow rate of effluent from septic tanks to environments	$Q_{st,en} = Q_{st,sw\&en} - Q_{st,sw}$	m ³ /d
	$C_{st,vt}$	COD of fecal sludge emptied from septic tanks to vacuum trucks	$C_{st,vt} = C_{st,fs}$	g/m ³
	$C_{st,sw}$	COD of effluent from septic tanks to sewers	$C_{st,sw} = C_{st-eff}$	g/m ³
	$C_{st,en}$	COD of effluent from septic tanks to environments	$C_{st,en} = C_{st-eff}$	g/m ³
Vacuum trucks (VT)	$Q_{vt,fstp}$	Flow rate of fecal sludge emptied by vacuum trucks and transported to FSTP	$Q_{vt,fstp} = Q_{st,vt} \times P_{vt,fstp}$	m ³ /d
	$Q_{vt,en}$	Flow rate of fecal sludge emptied by vacuum trucks and discharged to environments	$Q_{vt,en} = Q_{st,vt} - Q_{vt,fstp}$	m ³ /d
	$C_{vt,fstp}$	COD conc. of fecal sludge emptied by vacuum trucks and transported to FSTP	$C_{vt,fstp} = C_{st,vt}$	g/m ³
	$C_{vt,en}$	COD conc. of fecal sludge emptied by vacuum trucks and discharged to environments	$C_{vt,en} = C_{st,vt}$	g/m ³
Fecal sludge treatment plant (FSTP)	$Q_{fstp,e\&d}$	Flow rate of treated fecal sludge from FSTP to end-use and disposal	$Q_{fstp,e\&d} = Q_{vt,fstp} \times P_{fstp,e\&d}$	m ³ /d
	$Q_{fstp,en}$	Flow rate of treated fecal sludge from FSTP to environments	$Q_{fstp,en} = Q_{vt,fstp} - Q_{fstp,e\&d}$	m ³ /d
	$C_{fstp,e\&d}$	COD conc. of wastewater from FSTP to end-use and disposal	$C_{fstp,e\&d} = C_{vt,fstp} \times R_{fstp}$	g/m ³
Sewer (SW)	$Q_{gw,sw}$	Flow rate of graywater discharged to sewers	$Q_{gw,sw} = Q_{gw} \times N_{pop} \times 10^{-3} \times P_{gw,sw}$	m ³ /d
	$Q_{gw,en}$	Flow rate of graywater discharged to environments	$Q_{gw,en} = Q_{gw} \times N_{pop} \times 10^{-3} \times (1 - P_{gw,sw})$	m ³ /d
	$Q_{sw,wwtp}$	Flow rate of wastewater from sewers transferred to WWTP	$Q_{sw,wwtp} = (Q_{st,sw} + Q_{gw,sw}) \times P_{sw,wwtp}$	m ³ /d
	Q_{unk}	Flow rate of unknown wastewater not transferred to WWTP	$Q_{unk} = Q_{st,sw} + Q_{gw,sw} - Q_{sw,wwtp}$	m ³ /d
	$C_{gw,sw}$	COD conc. of graywater discharged into sewers	$C_{gw,sw} = C_{gw}$	g/m ³
	$C_{sw,wwtp}$	COD conc. of wastewater discharged from sewers to WWTP	$C_{sw,wwtp} = C_{wwtp-inf}$	g/m ³
	C_{unk}^*	COD conc. of unknown wastewater not transferred to WWTP	$C_{unk} = L_{unk}/Q_{unk} \times 1000$	g/m ³
Wastewater treatment plant (WWTP)	$Q_{wwtp-e\&d}$	Flow rate of sludge from WWTP to end-use and disposal	estimated by GPS-X	m ³ /d
	$Q_{wwtp-en}$	Flow rate of treated wastewater from WWTP to environments	estimated by GPS-X	m ³ /d
	$C_{wwtp-e\&d}$	COD conc. of sludge from WWTP to end-use and disposal	estimated by GPS-X	g/m ³
	$C_{wwtp-en}$	COD conc. of treated wastewater from WWTP to environments	estimated by GPS-X	g/m ³

Table 4.2 Input parameters for wastewater flow rate, COD loadings, and GHG emissions estimation

Symbol	Description	Value	Unit	Sources
B_0	Maximum CH ₄ producing capacity	0.25	kg CH ₄ /kg COD	IPCC (2019)
C_{bw}	COD conc. of blackwater	1245	g/m ³	Huynh et al. (2021) and this study
C_{st-eff}	COD conc. of effluent of septic tanks	813	g/m ³	Huynh et al. (2021) and this study
C_{gw}	COD conc. of graywater	533	g/m ³	Huynh (2020) ($n=3$)
$C_{wwtp-inf}$	COD conc. of influent of WWTP	244.5	g/m ³	Watanabe (2018)
C_{st-fs}	COD conc. of fecal sludge in septic tanks	16397	g/m ³	Huynh et al. (2021) and this study
D	Distance from the drainage area to FSTP (round trip)	26	km/trip	OpenStreetMap 2023
$EF_{CH_4,vt}$	Emission factor of methane (diesel)	0.00000 317	kg CH ₄ /km	U.S. EPA (2014)
$EF_{CH_4,sw}$	Emission factor of methane from sewers	1.63	g N ₂ O/(cap·year)	Michael D. Short et al. (2014)
$EF_{CO_2,vt}$	Emission factor of carbon dioxide (diesel)	2.697	kg CO ₂ /L	U.S. EPA (2014)
$EF_{N_2O,vt}$	Emission factor of nitrous oxide (diesel)	0.00000 298	kg N ₂ O/km	U.S. EPA (2014)
FC_{vt}	Fuel consumption of a diesel vacuum truck	5.5	km/L	Nakamura et al. (2013)
GWP_{CH_4}	Global warming potential of methane	28	-	IPCC (2023)
GWP_{N_2O}	Global warming potential of nitrous oxide	273	-	IPCC (2023)
MCF_{fstp}	Methane correction factor at FSTP	0.2	-	IPCC (2019)
MCF_{sw}	Methane correction factor at sewers	0.5	-	IPCC (2019)
N_{pop}	Population	15700	person	Brandes et al. (2016)
$N_{st-area}$	Number of septic tanks in the study area	3140	septic tank	$N_{pop} / N_{user/st}$
N_{st-emp}	Number of septic tanks to be emptied (rounded-up number)	1	septic tank/d	$N_{st-area} / (T_{st} \times 365)$
$N_{user/st}$	Number of users per septic tank	5	Person/tank	Pham (2014) ($n=46$)
$P_{fstp,e\&d}$	Proportion of treated fecal sludge to end-use and disposal	1.00	-	Brandes et al. (2016)
$P_{gw,sw}$	Proportion of graywater discharged into sewers	0.74	-	Watanabe (2018)
$P_{st,sw}$	Proportion of septic tanks connected to sewers	0.53	-	Watanabe (2018)
$P_{sw,wwtp}$	Proportion of wastewater collected by sewers and transferred to WWTP	0.26	-	Watanabe (2018)
$P_{t,st}$	Proportion of toilets connected to septic tanks	1.00	-	Watanabe (2018)
$P_{vt,fstp}$	Proportion of fecal sludge emptied by vacuum trucks and transported to FSTP	0.04	-	World Bank Group (2013)
Q_{bw}	Flow rate of blackwater per capita	25.3	L/(person·d)	Huynh (2020) ($n=15$)

Table 4.2 Input parameters for wastewater flow rate, COD loadings, and GHG emissions estimation (cont.)

Symbol	Description	Value	Unit	Sources
R_{fstp}	Fraction of COD removal of stabilization ponds	0.53		Saqqar and Pescod (1995)
V_{fs-emp}	Volume of fecal sludge emptied per time	3.4	m ³ /septic tank	Pham (2014) ($n=46$)
T_{st}	Average emptying interval of septic tanks	10.2	year	Pham (2014) ($n=46$)
V_{vt}	Vacuum truck capacity	3.6	m ³	Nakamura et al. (2013)

Model validation

After estimating GHG emissions of all components, the model was validated by using mass balance for each individual component. The mass balances were based on total organic carbon (TOC). COD to TOC ratio of septic tanks' influent concentration was applied to convert COD into $TOC_{st,vt}$, $TOC_{wwtp,en}$, and $TOC_{wwtp,e\&d}$. For septic tanks, mass balance was performed under two assumptions: i) when 2nd and 3rd compartment of the septic tanks emitted GHGs at the same rate to the 1st compartment (i.e., maximum) and ii) when GHGs was emitted only from the 1st compartment (i.e., minimum).

GHG emissions estimation

GHG emissions were estimated separately for CH₄, N₂O, and CO₂. Direct CO₂ emissions from the decomposition of organic compounds were excluded in the estimation since they are considered entirely biogenic and would eventually cycle back to the atmosphere (Cheng et al., 2022; IPCC, 2006). In this study, the GHG emissions were categorized into three scopes following the IPCC guidelines, including scope 1 (i.e., process or direct emissions), scope 2 (i.e., emissions from energy consumption), and scope 3 (i.e., emissions from consumables) (IPCC, 2006).

GHG emissions from septic tanks

The equation proposed in Chapter 3 was used for CH₄ emissions of septic tanks with long sludge emptying intervals (eq.(4.10). Due to limitations in accessing the 2nd and 3rd compartments, the emission factor is only for the 1st compartment of the septic tanks. Consequently, it was assumed that other compartments of septic tanks have the same rate of CH₄ production as the 1st compartment. The emissions for the 2nd and 3rd compartments were then extrapolated with directionally proportional to their respective surface areas as shown in

eq. (4.11). The summation of emission factors from three compartments represents the CH₄ emission factor of the septic tanks (EF_{CH_4-st}) as shown in eq. (4.12). N₂O produced from septic tanks was reportedly less than 1.0 ppm and hence considered negligible (Huynh et al., 2021). The EF_{CH_4-st} was then used to calculate for CH₄ emission from septic tanks (E_{st}) (eq. (4.13)). Therefore, GHG emissions from septic tanks include only CH₄ emission.

$$EF_{CH_4-st1} = 3.83 + 0.622T_{st} \quad (4.10)$$

$$EF_{CH_4-st2\&3} = EF_{CH_4-st1} \times \frac{S_{st2\&3}}{S_{st1}} \quad (4.11)$$

$$EF_{CH_4-st} = EF_{CH_4-st1} + EF_{CH_4-st2\&3} \quad (4.12)$$

$$E_{st} = EF_{CH_4-st} \times N_{pop} \times GWP_{CH_4} \times 365 \times 10^{-6} \quad (4.13)$$

where EF_{CH_4-st1} is CH₄ emission factor of the 1st compartment of septic tanks (g CH₄/(cap·d)); T_{st} is emptying intervals of septic tanks (year); $EF_{CH_4-st2\&3}$ is CH₄ emission factor of the 2nd and 3rd compartment of septic tanks (g CH₄/(cap·d)); $S_{st2\&3}$ is a fractional surface area of the 2nd and 3rd compartments to the total surface area (0.47); S_{st1} is a fractional surface area of the 1st compartments to the total surface area (0.53); EF_{CH_4-st} is CH₄ emission factor of septic tanks (g CH₄/(cap·d)); E_{st} is GHG emissions from septic tanks (tonCO₂e/year); N_{pop} is population (persons); GWP_{CH_4} is global warming potential of CH₄ (28); 365 is the number of days in a year; and 10⁻⁶ is a conversion factor from gram to ton.

GHG emissions from sewers

The estimation of CH₄ emission from sewers with conditions of stagnant wastewater under warm climates was followed the guideline of IPCC (IPCC, 2019). The estimation involves COD loadings upon entry into the sewers obtained from the mass balance diagram (see Appendix B), methane correction factor (MCF), and IPCC's maximum CH₄ producing capacity (B_0). MCF is referred to the fraction of COD that is used for CH₄ production. B_0 is referred to the CH₄ production per COD (g CH₄/g COD). In this chapter, the default MCF of 0.5 and B_0

of 0.25 g CH₄/g COD were applied for the CH₄ estimation as shown in eq. (4.14). However, the minimum (0.4) and maximum (0.8) of MCF were used for uncertainty investigation.

N₂O emissions were estimated by using an emission factor derived from N₂O emission measurement for gravity sewers by Short et al., 2014 as shown in eq. (4.15).

$$E_{CH_4-sw} = COD_{sw-in} \times B_0 \times MCF_{sw} \times GWP_{CH_4} \times 365 \times 10^{-3} \quad (4.14)$$

where E_{CH_4-sw} is CH₄ emission from sewers (tonCO₂e/year); COD_{sw-in} is COD loadings upon entry into the sewers (kg COD/d); B_0 is IPCC's maximum CH₄ producing capacity (kg CH₄/kg COD); MCF_{sw} is CH₄ correction factor at sewers, indicating a fraction of COD converted into CH₄ in sewers (unitless); GWP_{CH_4} is global warming potential of CH₄; 365 is the number of days in a year; and 10^{-3} is a conversion factor from kilogram to ton.

$$E_{N_2O-sw} = EF_{N_2O-sw} \times N_{pop} \times GWP_{N_2O} \times 10^{-6} \quad (4.15)$$

where E_{N_2O-sw} is N₂O emission of sewers (tonCO₂e/year); EF_{N_2O-sw} is N₂O emission factor for gravity sewers (g N₂O/(cap·year)); GWP_{N_2O} is global warming potential of N₂O; and 10^{-6} is a conversion factor from gram to ton.

GHG emissions from vacuum trucks

The GHG emissions from vacuum trucks were calculated based on the emissions from fuel consumption of diesel vacuum trucks to transport fecal sludge from the center of the Truc Bach drainage area to the FSTP in a round trip or an equivalent distance if directly discharged into the local environment. This estimation involves the fuel consumption of the trucks, emission factors of CO₂, CH₄, and N₂O, and the total number of trips required to empty all septic tanks for a given emptying interval, following eqs. (4.16)–(4.19).

$$N_{trip/d} = \frac{N_{st-area}}{N_{st/trip} \times T_{st}} \quad (4.16)$$

where $N_{trip/d}$ is number of emptied trips per day (trip/d); $N_{st-area}$ is number of septic tanks in a study area (tank); $N_{st/trip}$ is number of septic tanks to be emptied per trip (septic tank/trip); and T_{st} is average emptying interval of septic tanks (year).

$$E_{CO2-vt} = \frac{D}{FC_{vt}} \times EF_{CO2,vt} \times N_{trip/d} \times 365 \times 10^{-3} \quad (4.17)$$

where E_{CO2-vt} is CO₂ emission from vacuum trucks (tonCO₂e/year); D is a round-trip distance from the drainage area to a FSTP (km); FC_{vt} is fuel consumption of a diesel vacuum truck (km/L); and $N_{trip/d}$ is number of emptied trips per day (trip/d).

$$E_{CH4-vt} = D \times EF_{CH4,vt} \times N_{trip/d} \times GWP_{CH4} \times 365 \times 10^{-3} \quad (4.18)$$

where E_{CH4-vt} is CH₄ emission from vacuum trucks (tonCO₂e/year); $EF_{CH4,vt}$ is emission factor of CH₄ from a diesel vacuum truck (kg CH₄/km); and $N_{trip/d}$ is number of emptied trips per day (trip/d); GWP_{CH4} is global warming potential of CH₄; 365 is the number of days in a year; and 10^{-3} is a conversion factor from kilogram to ton.

$$E_{N2O-vt} = D \times EF_{N2O,vt} \times N_{trip/d} \times GWP_{N2O} \times 365 \times 10^{-3} \quad (4.19)$$

where E_{N2O-vt} is N₂O emission from vacuum trucks (tonCO₂e/year); $EF_{N2O,vt}$ is emission factor of N₂O from a diesel vacuum truck (kg N₂O/km); and $N_{trip/d}$ is number of emptied trips per day (trip/d); GWP_{N2O} is global warming potential of N₂O; 365 is the number of days in a year; and 10^{-3} is a conversion factor from kilogram to ton.

GHG emissions from WWTP

Wastewater treatment processes

The Truc Bach WWTP utilizes an anaerobic–anoxic–oxic (A2O) process, which removes COD, nitrogen, and phosphorus from the wastewater. The details of Truc Bach WWTP's process diagram are shown in Figure 4.4. The design capacity of the WWTP is 2,500 m³/d (Brandes et al., 2016; JICA, 2019). The influent characteristics of Truc Bach WWTP are shown

in Table 4.3. The effluent of the WWTP is discharged to the Truc Bach lake, while the produced sludge is disposed of at a landfill site.

Table 4.3 Influent characteristics of Truc Bach WWTP

Influent	Value (median)
SS (g/m^3)	49
BOD (g/m^3)	58
COD (g/m^3)	244.5
TN (g N/m^3)	44.5
NH ₄ -N (g N/m^3)	N.A.
NO ₃ -N (g N/m^3)	N.A.
TP (g P/m^3)	2.18
PO ₄ -P (g/m^3)	N.A.
Temperature ($^{\circ}\text{C}$)	28

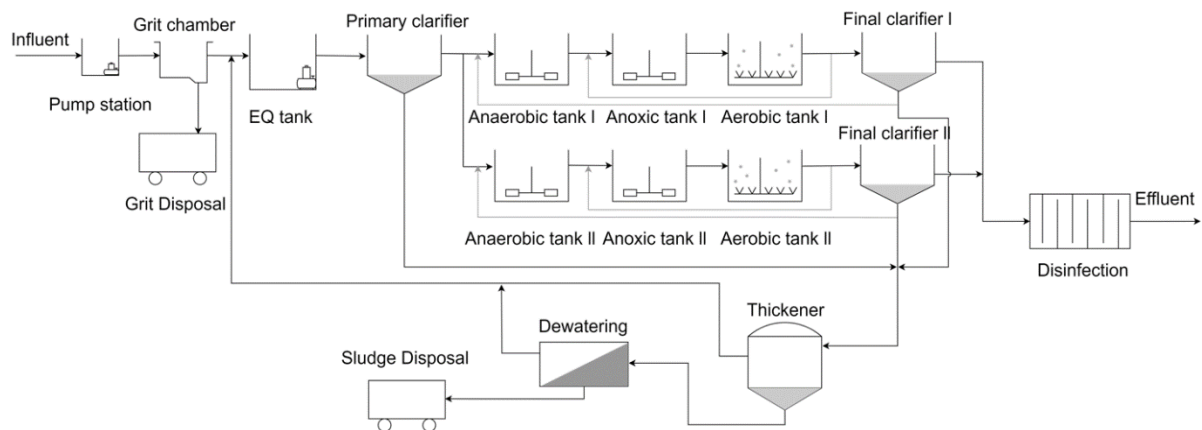


Figure 4.4 Truc Bach WWTP process diagram

Model simulation

The simulation employed *Mantis3lib* carbon footprint estimation model to assess GHG emissions from the WWTP. The WWTP was simulated under steady states with constant inflow using the GPS-X 8.5 software developed by HATCH (HATCH, 2022). The model input data includes flow rate ($Q_{sw,wwtp}$) obtained from the mass balance, influent characteristic measured from Watanabe (2018), and WWTP's configuration and equipment Table B1. Scope 1 emissions were obtained by modelling a plant-wide simulation using carbon, nitrogen, and

phosphorus removal, integrating anaerobic digestion processes (i.e., ASM2d (Henze et al., 2015) and UCTADM1(Söttemann et al., 2005)), a four steps N₂O production model (Hiatt & Grady, 2008) and N₂O production by autotrophic bacteria (Mampaey et al., 2013; Ni et al., 2012). Scope 2 emissions involve energy consumption models by applying regional electricity emissions, and Scope 3 emissions were estimated based on chemical consumption (eq. (4.20) and (4.21)). Other operational parameters for simulation in all scenario were maintained as shown in Table 4.4.

$$E_{scope2} = E_{wwtp} \times EF_{elec} \quad (4.20)$$

where E_{scope2} is GHG emissions from scope 2 (tonCO₂e/year); E_{wwtp} is electricity consumption in the WWTP (MWh/year); EF_{elec} is grid emission factor of Vietnam (0.7221 tonCO₂e/MWh (IGES, 2024)).

$$E_{scope3} = M_i \times F_i \times 10^{-3} \quad (4.21)$$

where E_{scope3} is GHG emissions from scope 2 (tonCO₂e/year); M_i is chemical consumption in WWTP (kg/year); and F_i is emission factors of chemicals (kg CO₂e/kg).

Table 4.4 Operational parameters in GPS-X model

Parameter	Value
DO in aeration tanks (g/m ³)	2
Internal recycle ratio (%)	200
Temperature (°C)	28
C:N ratio	5.5

GHG emissions from FSTP

The FSTP, namely, Cau Dien, is operated with a composting process for organic waste. Fecal sludge, brought by vacuum trucks, is discharged into the settling tanks. The solid fraction is further disposed of at the Nam Son landfill (Schoebitz et al., 2014), while the liquid fraction is used in the composting process or overflows into stabilization ponds without discharging into

the local environment. Therefore, all fecal sludge transported to and managed at the FSTP was categorized as safe end-use and disposal. The process diagram is shown in Figure 4.4.

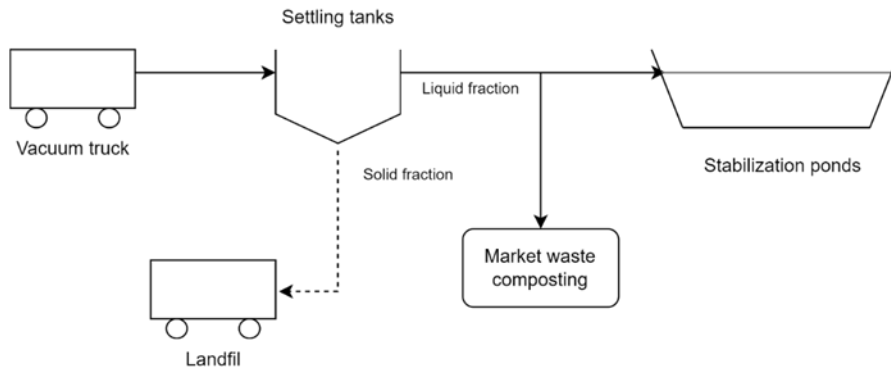


Figure 4.5 Cau Dien FSTP process diagram

Due to the lack of observational data of the FSTP, the GHG estimation was based on the IPCC's approach of anaerobic shallow and facultative lagoons, where mainly CH₄ is emitted while N₂O is neglected (IPCC, 2019) as shown in eq. (4.22).

$$E_{fstp} = COD_{vt,fstp} \times MCF_{fstp} \times GWP_{CH_4} \times 365 \times 10^{-3} \quad (4.22)$$

where E_{fstp} is emissions from FSTP (tonCO₂e/year); MCF_{fstp} is default CH₄ correction factor of anaerobic shallow lagoons; GWP_{CH_4} is global warming potential of CH₄; 365 is the number of days in a year; and 10⁻³ is a conversion factor from kilogram to ton.

4.3 Results and discussion

4.3.1 Wastewater flow diagram along the sanitation service chain in Hanoi, Vietnam

A wastewater flow diagram representing the distribution of households' wastewater (black and graywater) along the SSC is shown in Figure 4.6. Blackwater constituted 17% and graywater represented the remaining 83% of the entire generated wastewater. Only 18% of the wastewater was treated properly at WWTPs, leaving 82% to be discharged into the local environment. The percentage of wastewater treated appropriately in a WWTP seems feasible as it is in the similar range to other low- and middle-income countries in Asia such as Hue, Vietnam (23%) (Watanabe, 2018), Thailand (24–27%) (Boontanon & Buathong, 2013; WHO, 2021), India

(27%) (WHO, 2021), Bangladesh (16%) (WHO, 2021) and Iran (22%) (WHO, 2021). Of the whole wastewater generated in Hanoi, 52% was estimated to end up untreated in the local environment. This occurrence may be due to factors such as the effects of exfiltration (Watanabe, 2018), as well as the construction of sewers that are just constructed to drain the wastewater and not to transport it to the WWTP. Due to lack of data of exfiltration and sewer connection, we refer to this proportion as unknown flow rate (Q_{unk}). Additionally, considering septic tanks in Hanoi with average emptying intervals of 10.2 years, only 0.1% of the total generated fecal sludge was collected and transported by vacuum trucks. The collected fecal sludge of only 4% was transported to the FSTP.

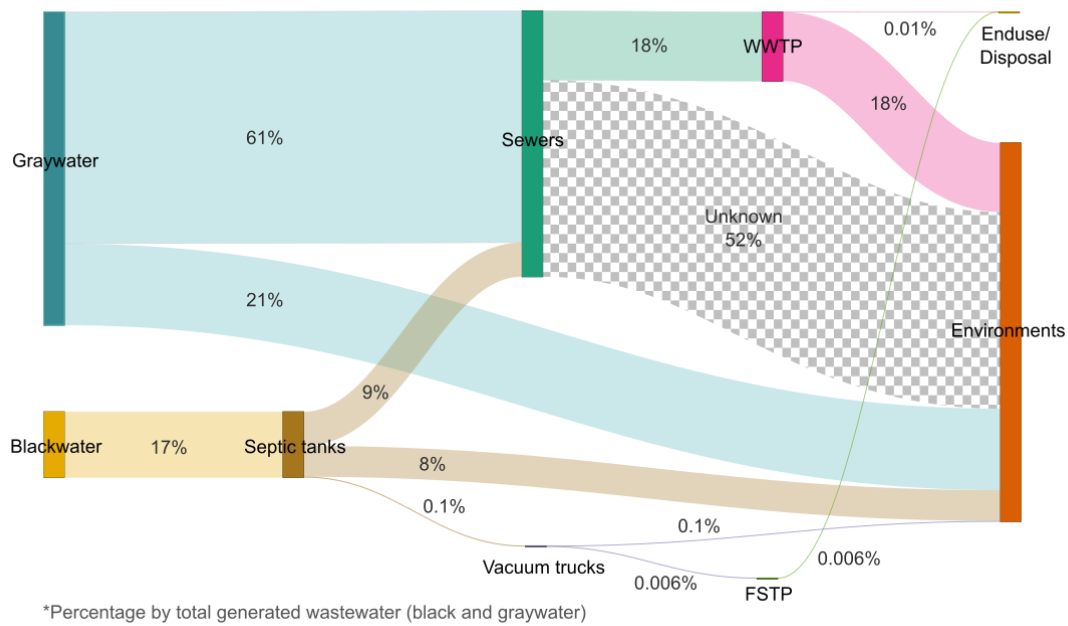


Figure 4.6 Wastewater flow diagram of Hanoi, Vietnam

COD flowing through each component along the SSC, expressed as a percentage of the total COD loadings generated from black and graywater is presented in Figure 4.7. The main COD proportion was from graywater, which accounted for 67%, while blackwater comprised of 33% of whole generated COD in the drainage area. The COD percentage of only 7% was transported to the WWTP. The low percentage of treated wastewater could be due to the following factors: i) low percentage of wastewater flow transported to the WWTP (Watanabe, 2018), ii) low COD concentrations of wastewater after passing through the sewers affected by infiltration and high degradation of COD in sewers (IPCC, 2019; Watanabe, 2018). Additionally, COD discharged

from the sewers to environments as an unknown COD accounted for 24% of the total COD, while a significant 50% of COD reaching the sewers was assumed to be removed in sewers, and was a carbon source for CH₄ emissions. As a result, a substantial portion of the total COD of 93.5% remained in sewers, septic tanks, and environments, resulting in potential sources of GHG emissions and water pollution.

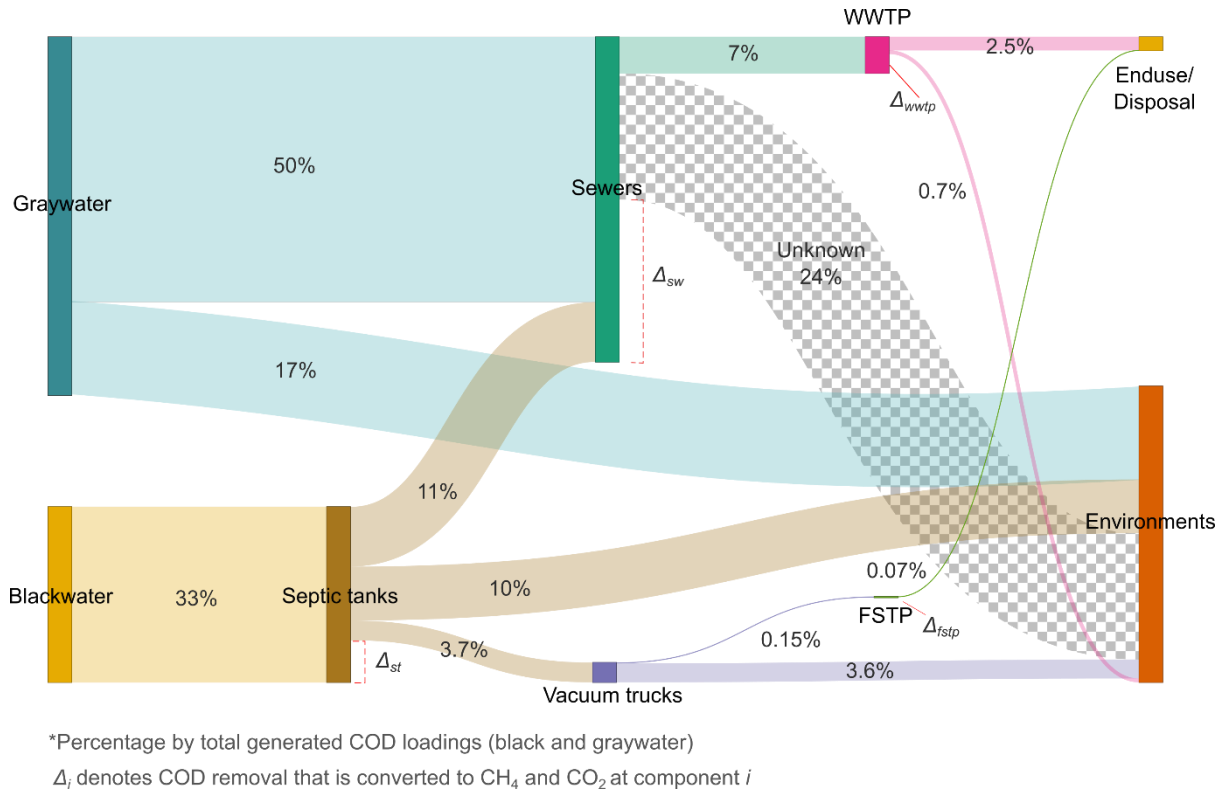


Figure 4.7 COD flow diagram of Hanoi, Vietnam

4.3.2 Model validation

At maximum GHG emissions rate, TOC remained in the septic tanks (Δ_{stock}) was -515 kg C/d (Figure 4.8) while it was -327 kg C/d at the minimum emission rates (Figure 4.9). These Δ_{stock} represent accumulated TOC in the septic tanks with the average emptying interval of 10.2 years. Furthermore, the Δ_{stock} was compared with the available TOC of fecal sludge of the septic tanks in the Truc Bach area. The stocked TOC was 231,432 kg C, which was enough to serve for Δ_{stock} . Although the TOC was sufficient, the available TOC would be completely converted at 449 days for the maximum case and 703 days for the minimum case. The mass balances of the septic tanks would only remain valid up to 449 and 703 days. Moreover, it should be noted that the mass balance represents septic tanks with long emptying intervals. Mass balance for

septic tanks with lower emptying intervals (< 3.9 years) may result in lower GHG emissions and higher Δ_{stock} . Therefore, the absolute values shown in the mass balance of septic tanks should be treated with cautions.

Mass balance for sewers is shown in Figure 4.10. Due to lack of data, COD of 356 kg/d calculated from the mass balance was used to adjusted the COD balance by referring it as C_{unk} , representing the COD of wastewater that is not converted into GHG and not transferred to the WWTP due to leakage or lack of sewer connection to the WWTP.

Mass balance for WWTP was carried out by using CH_4 and CO_2 from Scope 1 emissions (Figure 4.11). TOC converted into CH_4 and CO_2 (Δ_{wwtp}) was obtained from the simulation of GPS-X of 17.8 kg C/d. The Δ_{wwtp} was validated by comparing with TOC value obtained from mass balance of 17.4 kg C/d, or a difference of 2%. The difference demonstrated an acceptable error.

For FSTP, since the treatment plant employs stabilization ponds and all the wastewater was assumed to be used in the composting process, COD remained in the FSTP (Δ_{stock}) was obtained at -0.43 kg C/d (Figure 4.12). Similar to the septic tanks, the results shows that some portions of COD remained in the ponds. Because data of accumulated sludge under the ponds is unavailable, the Δ_{stock} was not compared with the field data. However, the proportion of fecal sludge emptied by vacuum trucks and transported to FSTP was only 4%. As a result, any errors in the mass balance are expected to be likely small.

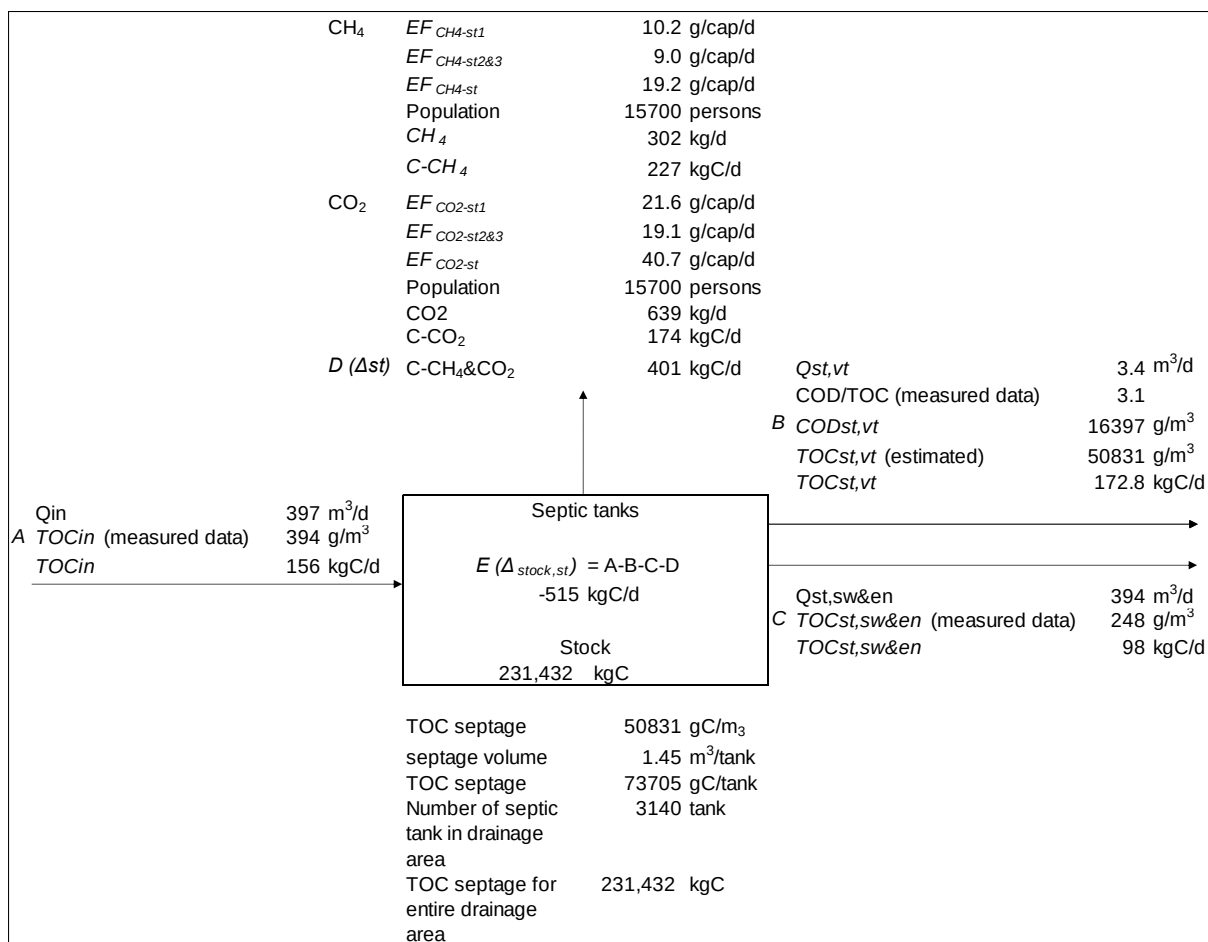


Figure 4.8 Mass balance of septic tanks at maximum rate of GHG emissions (baseline's assumption)

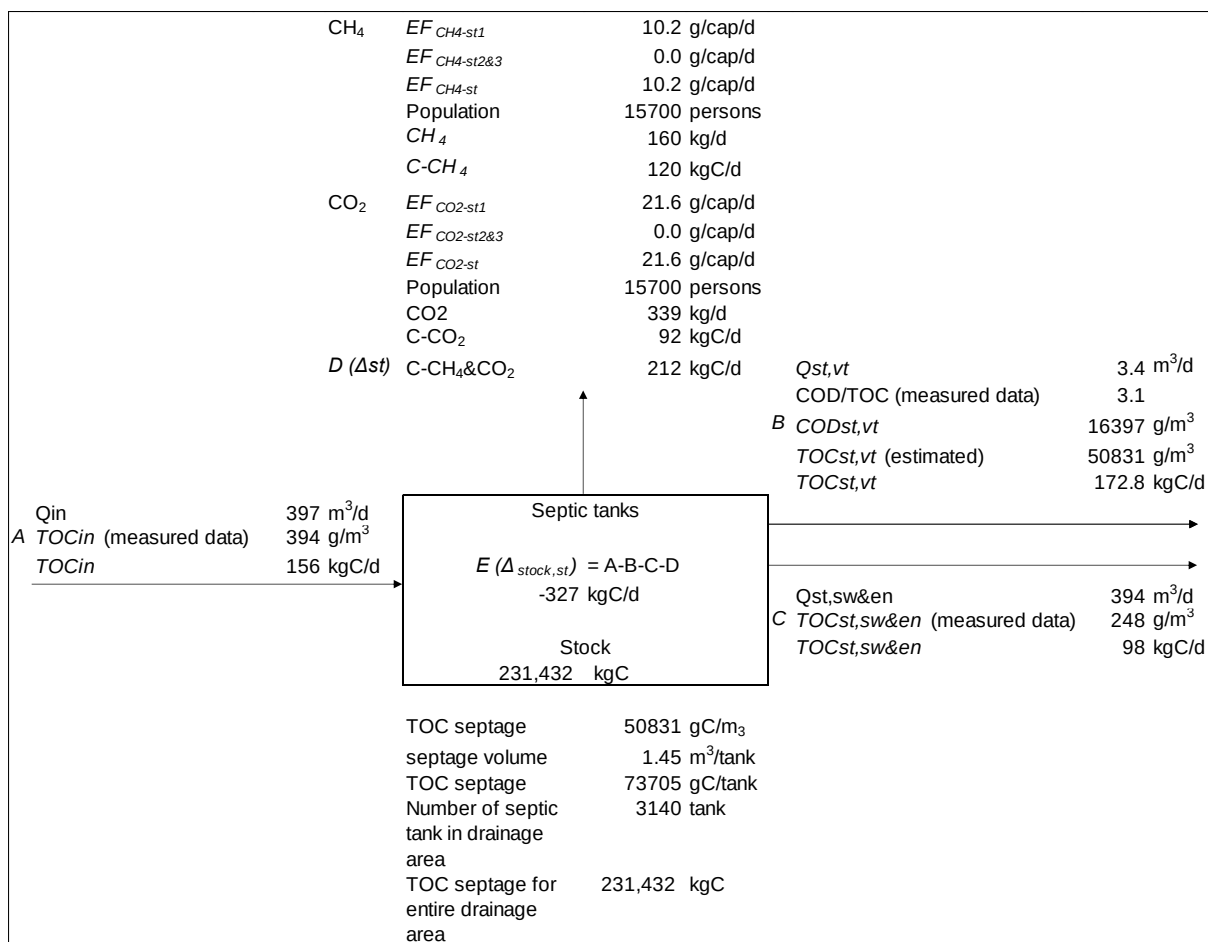


Figure 4.9 Mass balance of septic tanks at minimum rate of GHG emissions

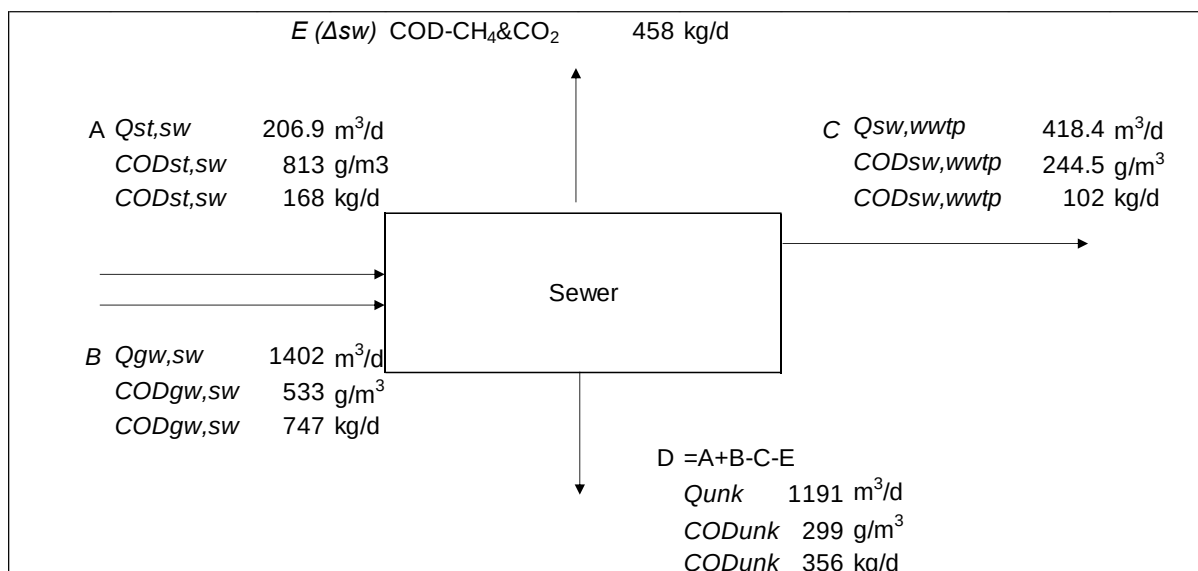


Figure 4.10 Mass balance of sewers

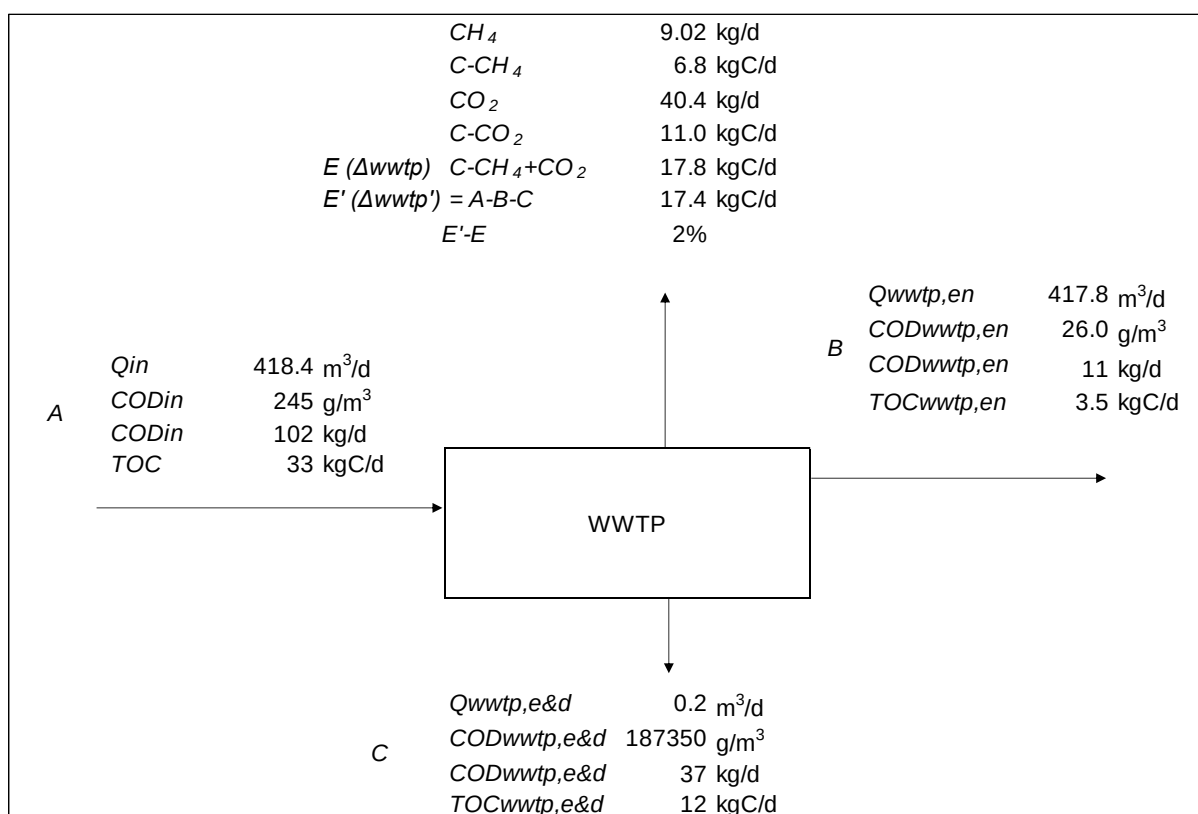


Figure 4.11 Mass balance of WWTP

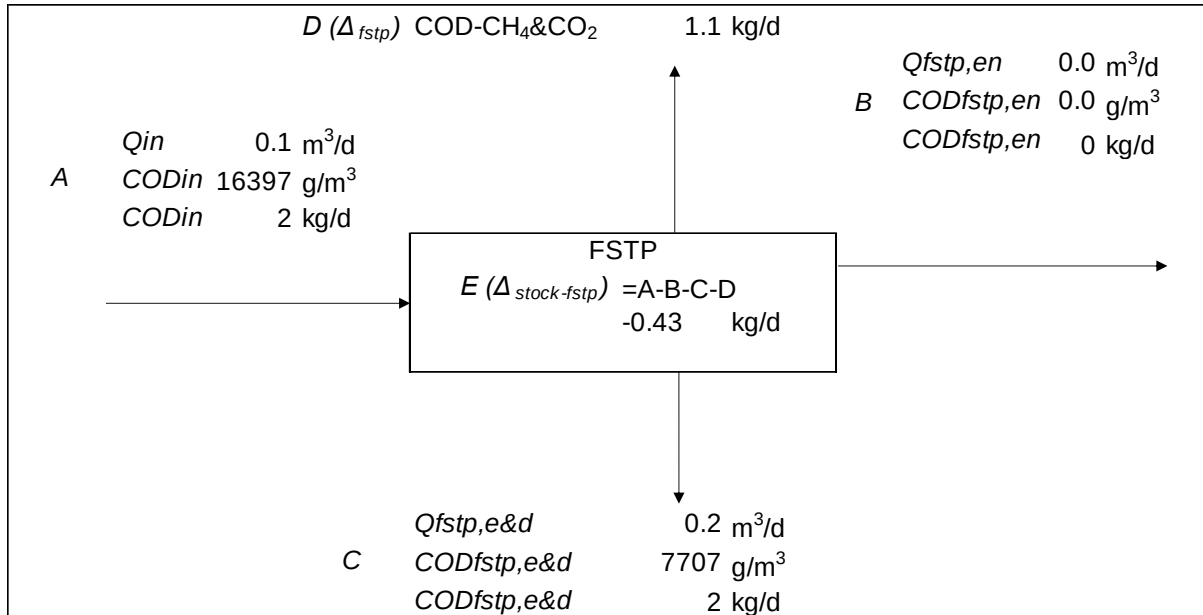


Figure 4.12 Mass balance of FSTP

4.3.3 GHG emissions estimation of sanitation service chains

Throughout the SSC, the primary contributors of GHG emissions were septic tanks (3,080 tonCO₂e/year, accounting for 60%), sewers (1,177 tonCO₂e/year, accounting for 23%), and WWTP (885 tonCO₂e/year, accounting for 17%) while the emissions from vacuum trucks and FSTP were 3.93 (0.08%) and 1.14 (0.02%) tonCO₂e/year, relatively small compared to other components, as illustrated in Figure 4.13.

When categorized by gas (Figure 4.14), it was identified that CH₄ was primarily released from septic tanks (3,080 tonCO₂e/year or 60%), sewers (1,177 tonCO₂e/year or 23%), and WWTP (100 tonCO₂e/year or 1.9%). CO₂ was predominantly emitted from WWTP (599 tonCO₂e/year or 12%), while additionally portion was emitted from vacuum trucks (3.9 tonCO₂e/year or 0.08%). Notably, WWTP was the only major source of N₂O emissions (187 tonCO₂e/year or 4%).

In addition, GHG emissions was analyzed based on the scope of emissions (Figure 4.15). The results shows that Scope 1 emission were mainly from septic tanks (3,080 tonCO₂e/year or 60%), sewers (1,177 tonCO₂e/year or 23%), and WWTP (272 tonCO₂e/year or 5%) while Scope 2 emissions was primarily released from WWTP (613 tonCO₂e/year or 12%). Scope 3 emission were relatively small (0.08%), compared to Scope 1 and 2.

In brief, the current GHG emissions of the SSC was 5,147 tonCO₂e/year, which consists of 3,080 tonCO₂e/year from the septic tanks (60%), 1,177 tonCO₂e/year from the sewers (23%), 885 tonCO₂e/year from the WWTP (17%), 3.9 tonCO₂e/year from the vacuum trucks (0.08%), and 1.1 tonCO₂e/year from the FSTP (0.02%), respectively. CH₄ was predominant, contributing a significant portion (84%), following by CO₂ (12%) and N₂O (4%). Scope 1 emissions or direct emissions were the majority share at 88%, while scope 2 and scope 2 emission represented a minor fraction of 12% and 0.08%, respectively. The further details are shown in Table 4.5 and Figure 4.16.

Compared to centralized WWTPs, Wu et al., 2022 reported that Scope 1 emissions accounted for 23-83% of the total GHG emissions, depending upon WWTP's configuration (Wu et al., 2022). De Haas and Andrews (2022) identified that Scope 1 emissions were 20–40% of the total emissions. In this study, the main sources of the Scope 1 emissions were from septic tanks and sewers with CH₄ as the primary GHG. CH₄ emissions accounted for 84% of total emissions due to the anaerobic nature of septic tanks and poorly-maintained gravity sewers. The emissions from scope 2 and 3 were comparatively smaller (12%). This is because, as mentioned earlier, only 18% of total generated wastewater was treated by aerobic centralized WWTP, where indirect GHG emissions are typically produced.

The GHG emissions per capita of this study was 328 kgCO₂e/(cap·year). Compared to the GHG emissions from centralized WWTP, the GHG emissions of this study was drastically higher than the emissions from centralized WWTPs in previous studies: China (37–58 kgCO₂e/(cap·year)) (Tian et al., 2022), and Greece (61 kgCO₂e/(cap·year)) (Mamais et al., 2015a) even though 54.6% of COD was excluded. The GHG emissions would be expected to be higher when COD proportion that was ended up untreated into the environments are included. We identified that the large difference of GHG emissions was also stemmed from the septic tanks and sewers where anaerobic processes occur (Diaz-Valbuena et al., 2011; IPCC, 2019). The influential factor behind high proportions of GHG emissions from septic tanks is long emptying intervals of septic tanks. The septic tanks that have long emptying intervals could significantly emit GHG emissions caused by high accumulation of organic matter under anaerobic conditions (Huynh et al., 2021). Similar to septic tanks, gravity sewers that are inadequately maintained or poorly designed can also be a potential source of CH₄ production due to stagnation of wastewater (Chaosakul et al., 2014; IPCC, 2019; Koottatep et al., 2014). Therefore, potential mitigation should focus on reducing GHG emissions from septic tanks and

sewers because of their substantial contribution. Also, improving sewers conditions will take unknown GHG emissions from the environments into the holistic estimation and mitigation.

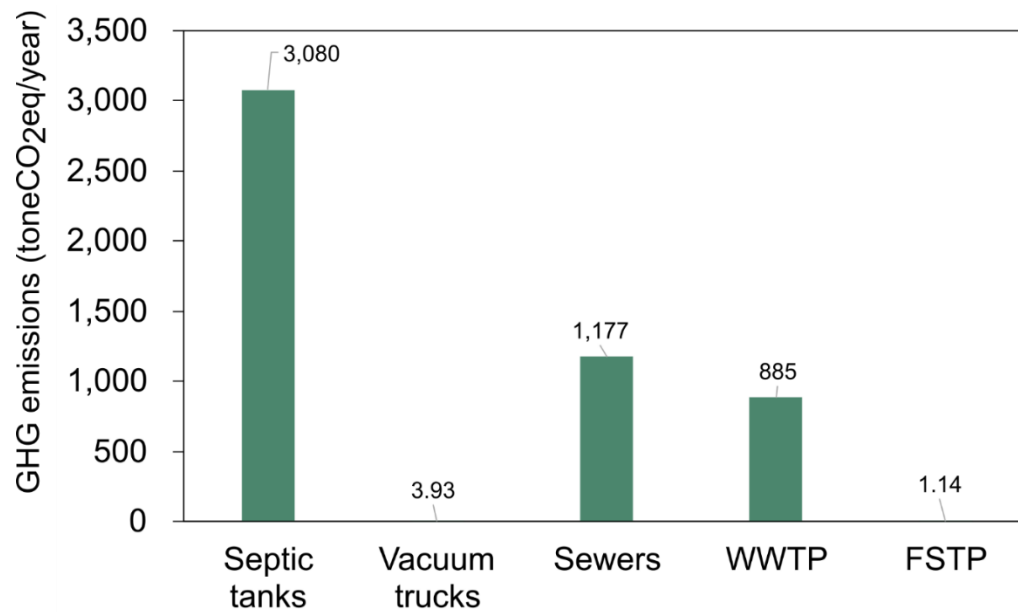


Figure 4.13 GHG emissions along sanitation service chains, categorized by component

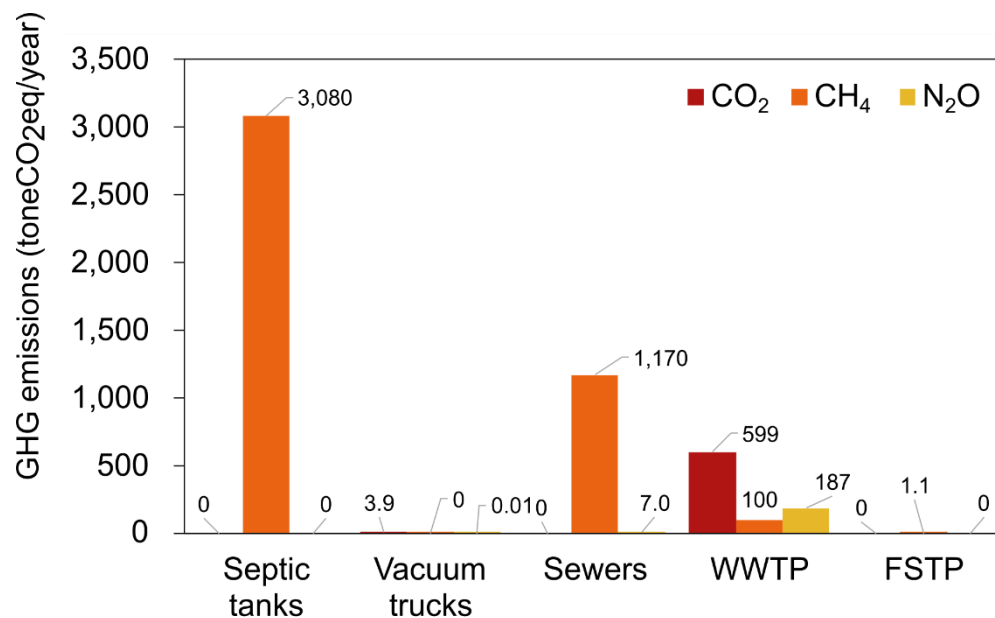


Figure 4.14 GHG emissions along sanitation service chains, categorized by gas

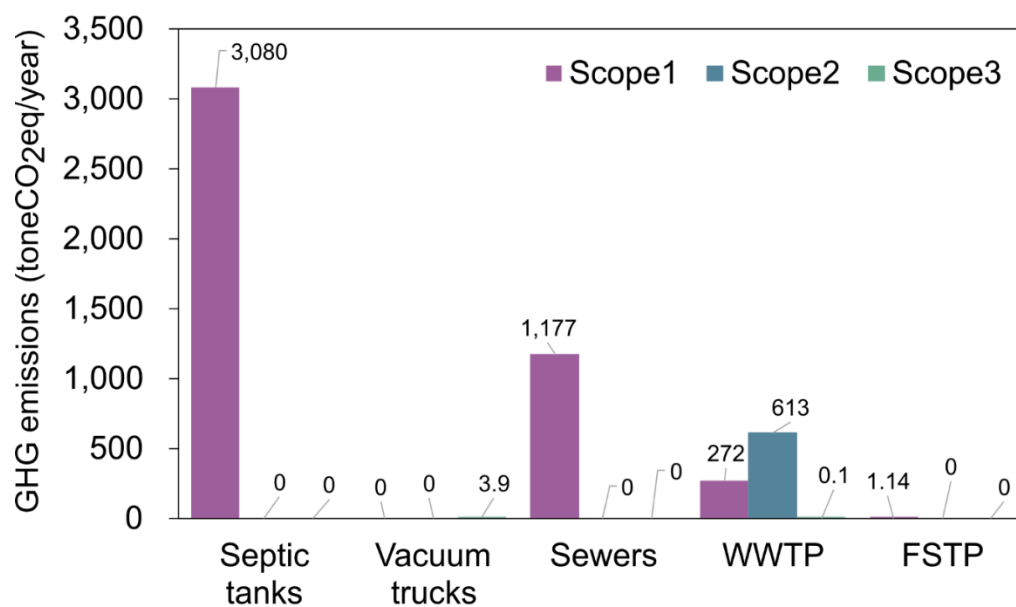


Figure 4.15 GHG emissions along sanitation service chains, categorized by scope

Table 4.5 GHG emissions of the sanitation service chain

Sanitation service	GHG emissions (tonCO ₂ e/year)						
	Total	CO ₂	CH ₄	N ₂ O	Scope 1	Scope 2	Scope 3
Septic tanks	3,080	0	3,080	0	3,080	0	0
Vacuum truck	3.93	3.92	0	0.01	0	0	3.93
Sewer	1,177	0	1,170	6.99	1,177	0	0
WWTP	885	599	100	187	272	613	0.14
FSTP	1.14	0	1.14	0.00	1.14	0	0
Total GHG emissions	5,147	603	4,351	194	4,530	613	4.07
Percentage	100%	12%	84%	4%	88 %	12%	0.08%

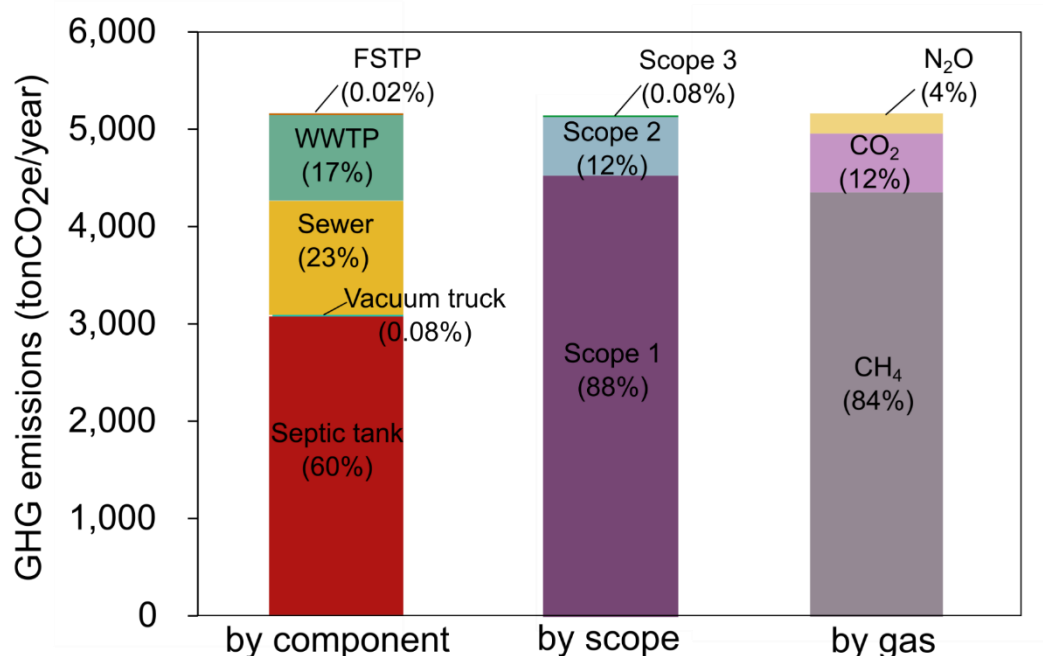


Figure 4.16 Baseline GHG emissions of the sanitation service chain, categorized by component, scope, and gas

4.3.4 Model limitations and uncertainties

Septic tanks

Due to limitations in accessing the 2nd and 3rd compartments of the septic tanks, the only available emission factors are from the 1st compartment. An assumption was made that, for septic tanks with long emptying intervals, the CH₄ production rate of other compartments remained consistent with that of the 1st compartment. However, this assumption can introduce additional uncertainty, particularly when applied to septic tanks with very short emptying intervals where microbial activity may not be fully developed or where significant variation in the amount of fecal sludge in 2nd and 3rd compartments exist.

Sewers

Since we lack of observational data for GHG emissions from sewers, it should be discussed that the emission estimation can be varied by *MCF* suggested by IPCC. By applying default, minimum, and maximum values of *MCF*, the GHG emissions from sewers were 1,177, 943, and 1,879 tonCO₂e/year, respectively. As a result, total GHG emissions were 5,147, 4,913, and

5,849 tonCO₂e/year. The results showed that the using *MCF* affected the total GHG emissions -5–14% (Table 4.6). The IPCC reported that their suggested *MCF* has an uncertainty range of $\pm 30\%$, which depends on retention time and temperature, and on other factors including the presence of a facultative layer and potentially components that are hazardous to anaerobic bacteria (IPCC, 2019). Therefore, the reported absolute numbers should be treated with cautions.

Table 4.6 Variation of GHG emissions from suggested MCF of sewers from IPCC

Sanitation components	<i>MCF_{sw}</i>		
	default (0.5)	min (0.4)	max (0.8)
Septic tanks	3,080	3,080	3,080
Vacuum truck	3.93	3.93	3.93
Sewer	1,177	943	1,879
WWTP	885	885	885
FSTP	1.14	1.14	1.14
Total GHG emissions	5,147	4,913	5,849
	0%	-5%	14%

WWTP

Noted that the simulation was conducted under steady inflow with constant parameters at steady state of operational conditions such as maintaining a DO level at 2 mg/L and internal recycle of 200%. The primary objective of the model was to estimate GHG emissions from the WWTP while focusing on achieving final effluent concentrations (e.g., BOD, COD, SS) compliant with the Vietnam's national standards (e.g., COD < 120 mg/L). It is important to highlight that implementing operational optimization of the WWTP could lead to a reduction in emissions. Additionally, that the simulation did not account diurnal fluctuation of wastewater characteristics, flow rate, and technological options, which can influence GHG emissions from WWTP.

FSTP

Due to the lack of observational data of the FSTP, the GHG estimation was based on the IPCC's approach. The uncertainty can be varied by *MCF* and technological selection.

In conclusion, we estimated the current GHG emissions along a typical SSC in low- and middle-income countries where septic tanks and sewers are in poor conditions. The primary contributors to GHG emissions along the SSCs were direct emission from septic tanks and sewers. CH₄ is significantly produced from anaerobic conditions of septic tanks and sewers, especially when they were inadequately maintained and designed. Thus, the potential mitigation should focus on the CH₄ emissions reduction from septic tanks and sewers.

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Chapter 5 GHG emissions mitigation strategies along sanitation service chains

5.1 Introduction

GHG emissions mitigation has been proposed for each component of the SSC. For example, shortening emptying intervals of septic tanks could contribute to the reduction of their CH₄ emissions (Chapter 3). Simultaneously, shortening emptying intervals could also lead to lower septic tanks' effluent concentrations (Mahon et al., 2022; Mehta et al., 2019), potentially reducing GHG emissions at WWTPs. Clean sewers that are operated with fast flowing conditions would be expected to produce CH₄ emissions at negligible level (IPCC, 2019). Thus, potential ways to mitigate GHG emissions can be achieved by improving the current state of SSCs through adequate management and maintenance, optimizing operational conditions or restructuring them. However, it is essential to recognize that shortening emptying intervals of septic tanks would increase GHG emissions from vacuum trucks. Accordingly, GHG emissions reduction from septic tanks is promising only if GHG emissions from vacuum trucks are taken into consideration. This consideration demonstrates that changing one part of an SSC can affect the quantity and quality of wastewater for downstream parts, and therefore a change in GHG emissions. Hence, it is crucial to quantify GHG emissions from a system perspective for effective mitigation along SSCs.

The goal of this study is to explore the GHG emissions mitigation potential of SSCs by quantifying the current amount of GHG emissions for the Truc Bach drainage area in Hanoi, and investigated three mitigation strategies as follows:

- i) Baseline: Current state,
- ii) Scenario A: Increased frequency of septic tanks' emptying,
- iii) Scenario B: No septic tanks without improved sewer conditions,
- iv) Scenario C: No septic tanks with improved sewer conditions.

It should be noted that this study investigated the GHG emissions from operation of an SSC. Emissions from construction work necessary to remove or bypass septic tanks, building

additional infrastructures, improving sewer conditions and other emissions related to infrastructure upgrades are therefore not included.

5.2 Materials and methods

5.2.1 Study area

This chapter is a comparison chapter where different mitigation scenarios were investigated and GHG emissions were compared to the baseline's emissions. Therefore, the study area was the same to the study area selected in Chapter 4. The full details are provided in section 4.2.1 in Chapter 4.

5.3 Data analysis

5.3.1 Scenario development

After the GHG emissions estimation of the current state of the SSC (hereafter referred to as baseline) in Chapter 4, d GHG emissions of each component of the SSC were re-estimated to explore how GHG emissions change for three different mitigation scenarios. The three mitigation scenarios are named as follows:

- 1) Scenario A: increased frequency of septic tank emptying,
- 2) Scenario B: No septic tanks *without* improved sewer conditions,
- 3) Scenario C: No septic tanks *with* improved sewer conditions.

In scenario A, GHG emissions of the SSC by shortening septic tanks' emptying intervals were estimated. In scenario B, the estimation of GHG emissions after septic tanks were removed from the SSC or wastewater bypassed the septic tanks were performed. Lastly, in scenario C, another system boundary was created where the WWTP treats all generated wastewater in the drainage area.

Scenario A: Increased frequency of septic tanks' emptying

The average emptying interval was changed from 10.2 years to 1 year (i.e., emptying once per year) to assess how GHG emissions are allocated to other components and how much emissions

can be reduced. As a result, the following variables were recalculated: EF_{st} , COD of fecal sludge (C_{st-fs}), and COD of effluent of septic tanks (C_{st-eff}) following eqs (5.1)–(5.3) provided in Chapter 3. Lastly, the mass balance was updated.

$$EF_{CH_4-st1} = 3.83 + 0.622T_{st} \quad (5.1)$$

$$COD_{st-fs} = 1600 + 1260T_{st} \quad (5.2)$$

$$COD_{st,eff} = 394 + 32T_{st} \quad (5.3)$$

where EF_{CH_4-st1} is CH₄ emission factor of the 1st compartment of septic tanks (g CH₄/(cap·d)); T_{st} is emptying intervals of septic tanks (year); COD_{stfs} is COD concentration of fecal sludge in septic tanks (g/m³); and $COD_{st,eff}$ is COD concentration. of effluent of septic tanks (g/m³).

Scenario B: No septic tanks without improved sewer conditions

The hypothesis was made that overall GHG emissions might be significantly reduced by either removing or completely bypassing the septic tanks. Another scenario without septic tanks was developed. Therefore, CH₄ emissions from septic tanks, and associated emissions, such as those from vacuum trucks and FSTP were eliminated. In this scenario, COD of wastewater transferred to the WWTP ($C_{sw-wwtp}$) and COD of wastewater discharged from sewers to the environment (C_{sw-en}) were re-estimated based on the ratio of $C_{sw-wwtp}$ and C_{sw-en} to COD entering sewers. These ratios were assumed to be the same as in the baseline.

Scenario C: No septic tanks with improved sewer conditions

As an extreme case scenario for the GHG emission estimation from the operation, a fully centralized SSC was developed with sewer coverage of 100% and sewer pipes have no leakage. To estimate the influent characteristics of wastewater reaching the WWTP, that the flow in sewers is assumed to be fast and sewers are clean. Furthermore, the change in wastewater characteristics within the sewers is negligible. Hence, CH₄ and N₂O emissions from sewers in this scenario were considered negligible according to IPCC (2019). It should be noted that for a comprehensive comparison, the GHG emissions for infrastructure changes would also need to be estimated.

5.3.2 GHG emission estimation

GHG emissions estimation were based on the same approach used in the baseline calculation as described in Chapter 4. The variables were modified to fit each scenario as described in Table 5.1. In the following detailed scenario description, any variables not mentioned were not subjected to change and thus remained the same as the baseline's values described in Table 4.2. GHG emissions were estimated separately for CH₄, N₂O, and CO₂. Moreover, the GHG emissions were categorized into three scopes following the IPCC guidelines, including scope 1 (i.e., process or direct emissions), scope 2 (i.e., emissions from energy consumption), and scope 3 (i.e., emissions from consumables) (IPCC, 2006).

Table 5.1 Variable application in all mitigation scenarios

Symbol	Description	Baseline	Scenario A	Scenario B	Scenario C
T_{st}	Average emptying interval of septic tanks	10.2	1.00	-	-
$P_{bw,sw}$	Proportion of blackwater discharged into sewers	0	0	1.00	1.00
$P_{t,st}$	Proportion of toilets connected to septic tanks	1.00	1.00	0	0
$P_{st,sw}$	Proportion of septic tanks connected to sewers	0.53	0.53	0	0
$P_{gw,sw}$	Proportion of graywater discharged into sewers	0.74	0.74	0.74	1.00
$P_{sw,wwtp}$	Proportion of wastewater collected by sewers and transferred to WWTP	0.26	0.26	0.26	1.00
$P_{vt,fstp}$	Proportion of fecal sludge emptied by vacuum trucks and transported to FSTP	0.04	0.04	0	0

5.4 Results and discussion

The results of GHG emissions of three different mitigation scenarios are presented by comparing with each scenario with the baseline results. The results were categorized by GHG, scopes of emissions. Furthermore, the summary of GHG emissions of each scenario with the percentage changes from the baseline were described in Table 5.4.

5.4.1 Scenario A: Increased frequency of septic tanks' emptying

This scenario focused on CH₄ emission reduction from the septic tanks by shortening the emptying interval from 10.2 years in the baseline to 1 year (i.e., emptying septic tanks once per year).

By exploring each component of the SSC, estimated COD of fecal sludge of septic tanks with 1-year emptying interval was 2,860 g/m³, while comparing to the baseline's data of 16,397 g/m³. The decreased concentrations of COD in fecal sludge resulted from lower accumulation of COD loadings in the septic tanks and lower COD concentration in effluent.

With the change of the emptying interval, septic tanks emitted 1,348 tonCO₂e/year in form of CH₄, equivalent to a 56% reduction compared to the baseline. Sewers and WWTP emitted CH₄ of 1,067 and 142 tonCO₂e/year, respectively, representing reduction of 9% and 48% compared to the baseline's value. It should be noted that all these emissions were the direct emissions from biological processes (scope 1).

As for indirect emissions, CO₂ was dominantly emitted from the WWTP, totaling 599 tonCO₂e/year. These emissions were not largely mitigated because of energy consumption used in the treatment plant, which was comparable to the baseline. This similarity in energy usage was from the flow rate reaching the WWTP did not change when the sewer connection was not improved. While energy consumption for aerobic process was lower, most of the energy used in the plant was attributed to pumps designed to serve the full capacity of the treatment plant. This can be an issue of energy consumption when the volume of wastewater reaching to the plant falls below its designed full capacity. The emissions from vacuum trucks were found to be relatively small in comparison to other components despite that the emptying frequency was increased by almost ten times.

The details information of the changes of GHG emissions are described in Table 5.4 and Figure 5.1.

In summary, GHG emissions from the septic tanks decreased by 56% from the baseline's value. GHG emissions from the vacuum trucks increased by 920% due to more emptying trips than the baseline (Table 5.4). However, this emission accounted for only 1.2% of the total GHG emissions of the SSC. GHG emissions from the sewers reduced by 9%. This decrease can be

explained by the lower COD of septic tanks' effluent discharged into sewers. However, GHG emissions at sewers could not significantly reduced by shortening the emptying intervals due to two reasons: i) only 53% of septic tanks were connected to sewers (Watanabe, 2018), and ii) the majority of COD (87%) entering sewers was originated from graywater, which is not passed the septic tanks. For the WWTP, GHG emissions were reduced by 15%. This reduction was also influenced by the decrease in COD in septic tanks' effluent entering sewers and then being transported to the WWTP with lower concentrations compared to the baseline. Additionally, the GHG emissions from the FSTP was decreased by 83% due to significantly lower COD of fecal sludge transported to the FSTP despite of more frequency of emptying. This contribution from the FSTP was only 0.2% of the total emissions. Overall, GHG emissions from the SSC was 3,217 tonCO₂e/yr.

Accordingly, we could minimize 37% of emissions from the baseline by only implementing emptying practice to once per year. Even though GHG emissions from emptying and transportation increased, they were still relatively small compared to emissions from other components. Therefore, shortening the emptying intervals of septic tanks could serve as a GHG mitigation initiative, considering that this implementation does not require a substantial transformation of the existing built environment while it could significantly reduce GHG emissions. However, GHG emissions from septic tanks alone were still predominant. Further, GHG emissions from the SSC when septic tanks are removed are presented in section 5.4.2.

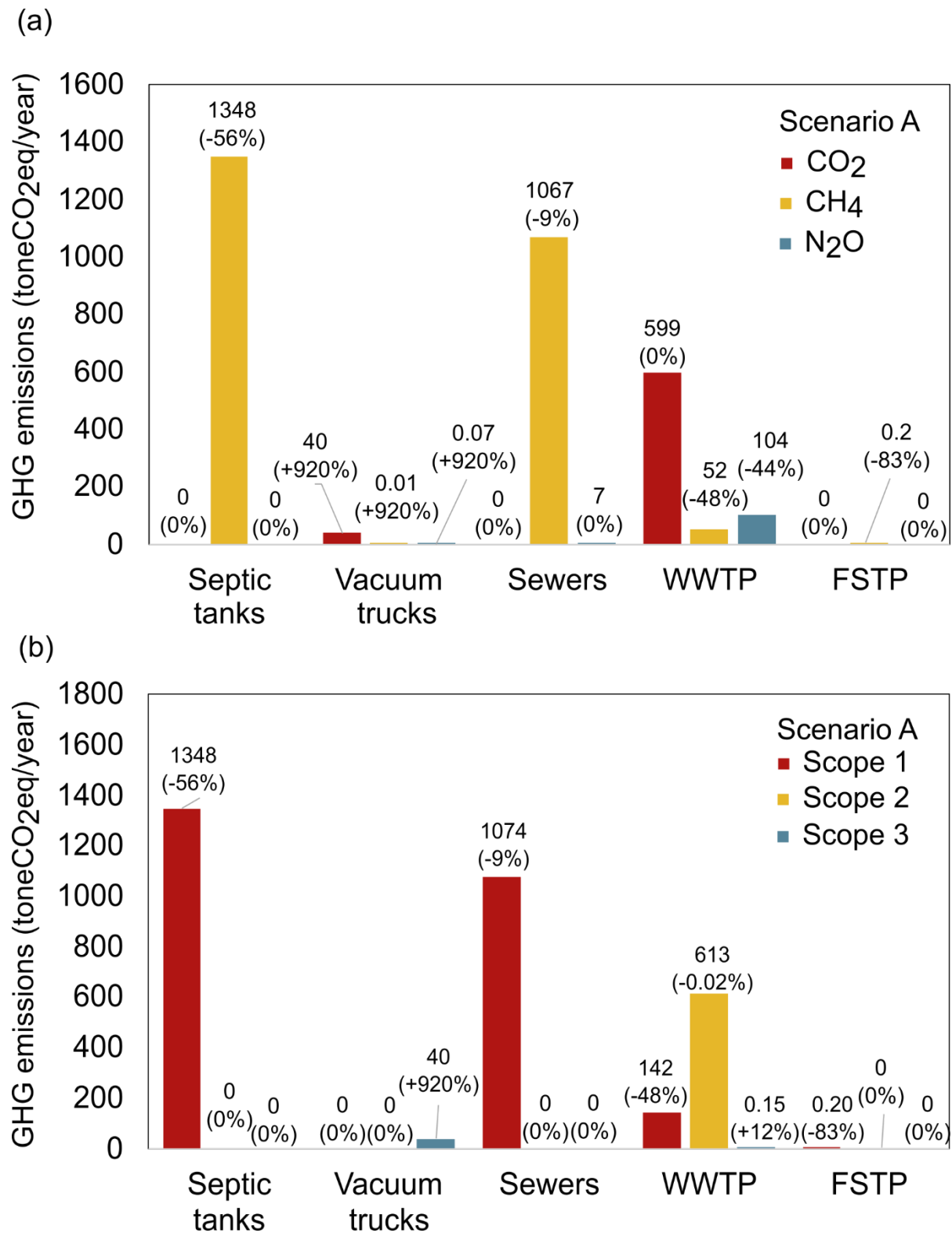


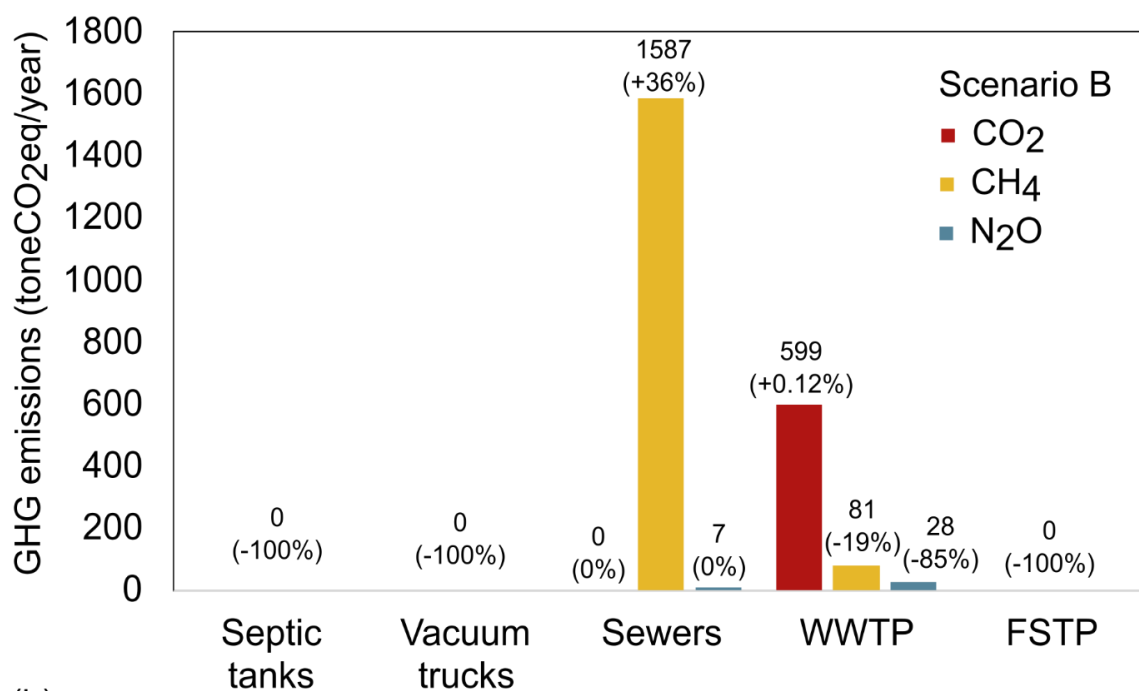
Figure 5.1 Changes of GHG emissions along the sanitation service chain of the mitigation scenario A, categorized by gas (a) and scope (b). The percentage describes the change of GHG emissions compared to the baseline scenario (+increase and -decrease).

5.4.2 Scenario B: No septic tanks without improved sewer conditions

In this scenario, septic tanks are either removed or by-passed, and hence all blackwater was directly discharged into sewers. Accordingly, GHG emissions emitted from the septic tanks and its associated components, including vacuum trucks, and FSTP, were eliminated (Figure 5.2). The main contributors in this scenario were CH₄ emission from sewers, which increased to 1,587 tonCO₂e/year, marking a 36% higher than the baseline, followed by CO₂ emission from WWTP with 599 tonCO₂e/year. Like Scenario A, the shift in CO₂ emission from the WWTP was not drastically notable because the energy consumption at the treatment plant remained comparable to the baseline due to unimproved sewer connections. Regarding these emissions, CH₄ emissions from sewers were mainly direct emissions (Scope 1) while CO₂ emission from WWTP was from energy used in the plant (Scope 2).

Overall, GHG emissions from sewers were increased by 35% compared to the baseline (Table 5.4). The higher COD loadings from directly discharge resulted in the increased emissions. Significant amount of CH₄ was still produced within the sewers without the improvement of sewer conditions. In addition, GHG emissions from the WWTP were decreased by 20%. The decrease of GHG emissions from the WWTP might be due to higher hydraulic retention time (HRT) in aeration tanks, since the simulation was modeled under the other same operational conditions and configuration to the baseline. Higher HRT significantly decreases the accumulation of nitrite and N₂O production during nitrification in aeration tanks (Kampschreur et al., 2009; Yu et al., 2021). It should be mentioned that operational conditions of WWTPs is the important keys in further mitigating GHG emissions (Campos et al., 2016; Kemmou & Amanatidou, 2023). In summary, overall GHG emissions were estimated to be reduced by 58% by removing septic tanks or by-passing them, and discharging the wastewater directly to the sewers. Potential mitigation can be further achieved by improving sewer conditions to avoid anaerobic conditions. In addition, improving sewer connection would help to collect and treat wastewater properly, and to minimize the GHG that is potentially emitted from discharging untreated wastewater into open environments.

(a)



(b)

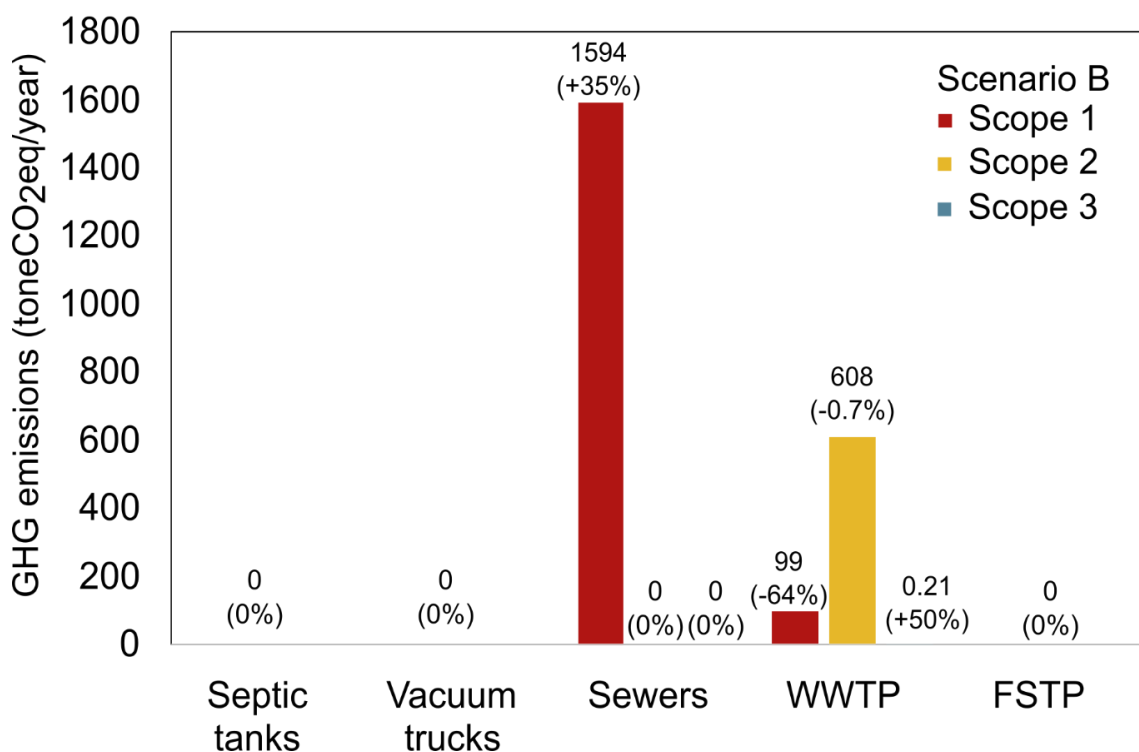


Figure 5.2 Changes of GHG emissions along the sanitation service chain of the mitigation scenario B, categorized by gas (a) and scope (b). The percentage describes the change of GHG emissions compared to the baseline scenario (+increase and -decrease).

5.4.3 Scenario C: No septic tanks with improved sewer conditions

This scenario outlines a design of the current SSC that is close to the existing centralized approach, wherein all generated wastewater from households is treated at WWTPs. As a result of improved sewer conditions, GHG emissions from sewers were eliminated. The only source of GHG emissions was the WWTP, mainly emitting N₂O and CO₂. N₂O was emitted of 1,020 tonCO₂e/year equivalent to an increase of 447% from the baseline's result. CO₂ was emitted of 953 tonCO₂e/year, which was 59%, higher than the baseline while CH₄ was emitted at 0.3 tonCO₂e/year, which was 99.7% lower than the baseline (Figure 5.3). As a result, scope 1 emissions were increased by 267% while scope 2 emissions were increased by 59%.

Considered the net emissions, the primary contributor to emissions is the WWTP, which emitted a total of 1,974 tonCO₂e/year, equivalent to 62% reduction. (Table 5.4). Notably, 52% of these emissions were N₂O emissions from scope 1, while the remaining 48% resulted from CO₂ emissions from scope 2. In comparison to the WWTP in baseline results, the emissions from the WWTP in this scenario was increased by 123% after all generated of wastewater was included in the scope of GHG emissions as shown in Table 5.4. Although all generated wastewater was properly treated, the produced GHG emissions were significantly lower than the emissions from the baseline. The majority of GHG emissions reduction was largely attributed to the removal of septic tanks and the improvement of sewer conditions, where they produce significant amount of CH₄. However, the implementation of septic tanks removal and sewer improvement presents considerable challenges in practice, and thus require substantial efforts across multiple sectors.

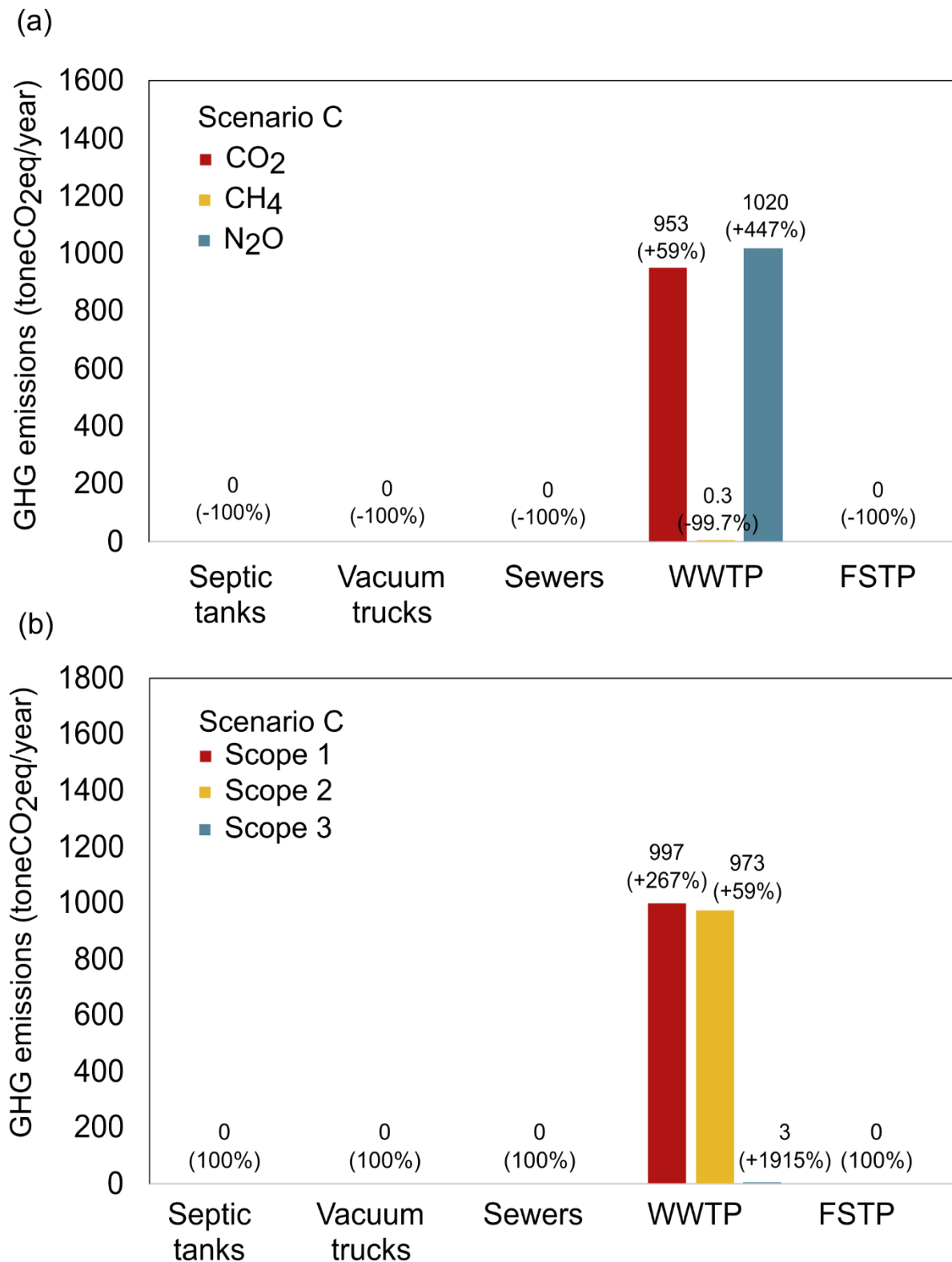


Figure 5.3 Changes of GHG emissions along the sanitation service chain of the mitigation scenario C, categorized by gas (a) and scope (b). The percentage describes the change of GHG emissions compared to the baseline scenario (+increase and -decrease).

Table 5.2 GHG emissions comparison between baseline and three mitigation scenarios based on greenhouse gas

Sanitation service	GHG emissions (tonCO ₂ e/year)											
	Baseline			Scenario A			Scenario B			Scenario C		
	CO ₂	CH ₄	N ₂ O	ΔCO ₂ (%)	ΔCH ₄ (%)	ΔN ₂ O (%)	ΔCO ₂ (%)	ΔCH ₄ (%)	ΔN ₂ O (%)	ΔCO ₂ (%)	ΔCH ₄ (%)	ΔN ₂ O (%)
Septic tanks	0	3,080	0	0%	-56%	0%	0%	-100%	0%	0%	-100%	0%
Vacuum truck	3.9	0.001	0.007	920%	920%	920%	-100%	-100%	-100%	-100%	-100%	-100%
Sewer	0	1,170	7.0	0%	-9%	0%	0%	36%	0%	0%	-100%	-100%
WWTP	599	100	187	0%	-48%	-44%	0%	-19%	-85%	59%	-99.7%	447%
FSTP	0	1.1	0	0%	-83%	0%	0%	-100%	0%	0%	-100%	0%
Total GHG emissions	603	4,351	194	6.0%	-43%	-42%	-0.5%	-62%	-82%	58%	-100%	427%

Table 5.3 GHG emissions comparison between baseline and three mitigation scenarios based on scope of emissions

Sanitation service	GHG emissions (tonCO ₂ e/year)											
	Baseline			Scenario A			Scenario B			Scenario C		
	Scope 1	Scope 2	Scope 3	ΔScope1 (%)	ΔScope2 (%)	ΔScope3 (%)	ΔScope1 (%)	ΔScope2 (%)	ΔScope3 (%)	ΔScope1 (%)	ΔScope2 (%)	ΔScope3 (%)
Septic tanks	3,080	0	0	-56%	0%	0%	-100%	0%	0%	-100%	0%	0%
Vacuum truck	0	0	4	0%	0%	920%	0%	0%	-100%	0%	0%	-100%
Sewer	1,177	0	0.0	-9%	0%	0%	35%	0%	0%	-100%	0%	0%
WWTP	272	613	0	-48%	-0.02%	12%	-64%	-0.7%	50%	267%	59%	1915%
FSTP	1	0.0	0	-83%	0%	0%	-100%	0%	0%	-100%	0%	0%
Total GHG emissions	4,530	613	4	-43%	-0.02%	889%	-63%	-0.7%	-95%	-78%	59%	-32%

Table 5.4 Summary of the comparison of the overall GHG emissions between baseline and three mitigation scenarios

Sanitation service chains	GHG emissions (tonCO ₂ e/year)			
	Baseline	Scenario A	Scenario B	Scenario C
Septic tanks	3,080	1,348 (-56%)	0 (-100%)	0 (-100%)
Vacuum trucks	3.9	40 (+920%)	0 (-100%)	0 (-100%)
Sewers	1,177	1,074 (-9%)	1,594 (+35%)	0 (-100%)
WWTP	885	755 (-15%)	708 (-20%)	1,974 (+123%)
FSTP	1.1	0.2 (-83%)	0 (-100%)	0 (-100%)
Total GHG emissions	5,147	3,217 (-37%)	2,301 (-55%)	1,974 (-62%)
COD removal of the SSC (kg/d)	631	780	680	892

In conclusion, GHG emissions were estimated along an SSC under three potential GHG mitigation scenarios for comparative analysis. The main findings are as follows.

1. Shortening septic tanks' emptying intervals could be an initiative to effectively reduce overall GHG emissions because the implementation does not require a substantial transformation of existing built environment.
2. Removing septic tanks and treating wastewater at centralized WWTPs could be the most effective mitigation to reduce GHG emissions.

It should be noted that the GHG emissions presented in this study were emissions from operations of the SSC, and it does not include GHG emissions from construction work necessary to remove or by-pass the septic tanks, building additional infrastructure. The further studies should focus on the inclusion of emissions from those implementations. Additionally, an appropriate implementation strategy should include balance of financial burdens and GHG emissions for better mitigation judgment.

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Chapter 6 Conclusions and recommendations

6.1 Conclusions

The main findings of each chapter are summarized as follows:

Chapter 3 GHG emissions from septic tanks with long emptying intervals

To tackle the challenge of estimating CH₄ emissions from septic tanks, the CH₄ emission rates were investigated for septic tanks with long emptying intervals, which is a common issue in low- and middle-income countries, especially in Southeast Asia. Data from 15 different septic tanks were collected and combined with the data in summer of 10 septic tanks from a previous study with the same study area. One outcome of this chapter is a unique dataset of the operating conditions of septic tanks (e.g., emptying intervals and sludge accumulation rate) and the characteristics of septage, influent, effluent, and CH₄ emission rates. This dataset provides crucial on ground information to support a better GHG estimation approach in low- and middle-income countries.

The main results of the investigation of CH₄ emission rates from septic tanks with long emptying intervals were as follows:

1. Longer emptying intervals significantly reduced the pollutant removal efficiencies while they increased the CH₄ emission rate from the septic tanks.
2. The negative correlation between BOD removal efficiency and CH₄ emission rates signals that the CH₄ emission estimation based on BOD removal efficiency might not reflect a realistic emission for long emptying interval septic tanks. For better quantification, alternative factors for CH₄ emission are emptying intervals, sludge depth, and CH₄ emission factors per capita reflecting long emptying intervals.

This study also identified the importance of GHG emissions from septic tanks to global GHG estimates and suggested potential reduction of septic tanks. However, it raised a further question of how much do GHG emissions from septic tanks contribute when GHG emissions are quantified from a perspective of a whole sanitation service chain.

Chapter 4 GHG emissions estimation along sanitation service chains

Previously, GHG emissions from septic tanks were introduced, which is from the only one component of SSCs. The next goal was to expand the scope to include GHG emissions from septic tanks and all downstream components, including sewers, vacuum trucks, WWTP and FSTP. Estimation approach developed in previous chapter was used to estimate GHG emissions from septic tanks. Currently available approaches from literatures were used to estimate GHG emissions from sewers, vacuum trucks, a WWTPs, and FSTP. The total GHG emissions were estimated and categorized. One outcome of this chapter is that an overview of wastewater management was unveiled through wastewater flow and COD diagrams. This allowed us to understanding the current conditions of wastewater management in low- and middle-income countries, which is pivotal for estimating GHG emissions for the entire system. The key findings are:

1. The primary contributors to GHG emissions along the SSCs were septic tanks and sewers due to significant CH₄ production from anaerobic conditions, especially when they were maintained and designed inadequately.
2. Different mitigation scenarios need to be investigated for GHG emissions to determine the most potential mitigation strategy.

In brief, this chapter provides the GHG emissions from a system view point, identifying potential components that were the most responsible for GHG emissions and pointed out where the mitigation should be focused. However, it raised a further question: if GHG emissions are mitigated at septic tanks and sewers, what might be the resultant shifts in emissions downstream? Therefore, the investigation of GHG emissions mitigation would be required, particularly in exploring different possible scenarios around septic tanks and sewers.

Chapter 5 GHG emissions mitigation strategies along sanitation service chains

In this chapter, the goal of analyzing different possible mitigation scenarios of the SSC was addressed. The results from Chapter 4 were used as the baseline results to compare with the GHG emissions from three potential mitigation scenarios: i) Scenario A: Increased frequency of septic tanks' emptying, ii) Scenario B: No septic tanks without improved sewer conditions,

and iii) Scenario C: No septic tanks with improved sewer conditions. The main results from the comparative analysis are the followings:

1. Shortening septic tanks' emptying intervals could be an initiative to effectively reduce overall GHG emissions because the implementation does not require a substantial transformation of existing built environment.
2. Removing septic tanks and treating wastewater at centralized WWTPs could be the most effective mitigation to reduce GHG emissions.

In summary, this thesis underscores the necessity of new alternative approaches aimed at accurately estimating and proposing potential alternatives for the estimation of CH₄ emissions from septic tanks with long emptying intervals, thereby improving global GHG estimates. Furthermore, the results highlight that the GHG emissions from septic tanks are dominant in total GHG emissions from the whole SSC. Consequently, it is important to include GHG emissions from septic tanks into global GHG estimates of domestic wastewater sector, giving that WWTPs are usually targeted in such assessment.

The thesis further demonstrates that the most effective mitigation strategy is to remove septic tanks and improve sewer conditions. However, the transformation of the entire SSC can be very challenging in practice. Therefore, strengthening emptying septic tanks with shorter frequency is suggested as it could be an effective initiative for GHG emissions mitigation of the SSC in low- and middle-income countries.

6.2 Recommendations

To improve the understanding and refinement of GHG emissions quantification methods, these suggestions for future research should be considered:

Potential CH₄ emissions from other compartments of septic tanks

In this study, we only the first compartment of the septic tanks could be located because this compartment is typically built directly beneath the cistern flush toilets. The second and third compartments were arranged differently from site to site, hence difficult to locate. This is challenging but necessary for better understanding of GHG emissions from multi-compartmented septic tanks.

Investigation of appropriate emptying strategy to balance financial cost and environmental impacts

As it is suggested to empty septic tanks with more frequency, finding the optimal balance between financial costs and environmental impacts, such as water pollution and climate change, remains crucial. Moreover, policy makers and stakeholders should be taken into consideration as they play a pivotal role in discussing strategies to enhance emptying practices and maintain this balance.

Field data of GHG emissions from sewers to improve the current estimation methods

The field data collection of GHG emissions from sewers are urgently essential, particularly poorly-maintained sewers due to several reasons: accuracy of estimation, policy development, infrastructure investment, climate mitigation etc.

Inclusion of GHG emissions from materials, construction, and infrastructure upgrades

Future research should integrate life cycle analysis to include the GHG emissions embedded in materials, construction, transportation to develop effective decision making of suggesting GHG emission mitigation strategies.

Inclusion of GHG emissions from untreated discharge

Future study should include the GHG emissions from untreated wastewater discharged into the environments into the system boundary. A substantial number of COD discharged through untreated wastewater could potentially be a source of GHG emissions elsewhere, and therefore warrants further consideration in both estimation and mitigation models.

Appendix-A

Table A1 Septic tank information from households

No.	Information
1	Emptying interval (year)
2	Number of toilet users (person)
3	Number of septic tank compartments
4	Entire tank dimension

Table A2 Sampling schedule for effluent, influent, septage and gas collection

Septic tank	Samples	December 2019																														January 2020								
		6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9				
T1	eff (•), inf (x) gas (□) sludge (∅)	•	•	•	•	•	•	•				x	x	x																										
T2	eff (•), inf (x) gas (□) sludge (∅)											•	•	•	•	•	•	•	x	x	x																			
T3	eff (•), inf (x) gas (□) sludge (∅)																	•	x																					
T4	eff (•), inf (x) gas (□) sludge (∅)																					•	x																	
T5	eff (•), inf (x) gas (□) sludge (∅)																								•	x														
T6	eff (•), inf (x) gas (□) sludge (∅)																								•	x														
T7	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T8	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T9	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T10	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T11	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T12	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T13	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T14	eff (•), inf (x) gas (□) sludge (∅)																										•	x												
T15	eff (•), inf (x) gas (□) sludge (∅)																																			•	x			

Table A3 Septage compositions

Septic tank ¹	Parameter					
	DO (g/m ³)	ORP (-mV) ²	COD (g/m ³)	BOD (g/m ³)	SS (g/m ³)	NH ₄ -N (g-N/m ³)
T1	0.02	-346	5800	4350	5472	242
T2	0.05	-434	18280	13893	7944	290
T3	0.45	-278	16740	13225	6800	353
T4	0.02	-563	37135	33422	10860	230
T5	0.04	-497	29340	23179	9822	700
T6	0.17	-374	23840	17880	8166	315
T7	0.08	-331	28441	25597	9382	620
T8	0.31	-275	7830	6123	5216	570
T9	0.28	-302	22080	17002	8854	500
T10	0.02	-501	29592	25153	9594	360
T11	0.37	-267	6245	5434	5307	225
T12	0.38	-227	5190	4152	4855	235
T13	0.32	-298	8024	7490	5682	425
T14	0.21	-445	23200	20648	9637	750
T15	0.05	-409	21945	19751	8422	615
ST1	0.03	-346	5800	4606.5	5895	258
ST2	0.03	-434	15892	12781.5	7805	278
ST3	0.18	-479	17576	14964	9264	478
ST4	0.26	-305	9584	8571	8830	584
ST5	0.19	-489	16758	13001	9870	533
ST6	0.31	-237	7820	6621	6020	175
ST7	0.17	-334	16286	13529	6788	532
ST8	0.08	-445	17220	13076	9934	451
ST9	0.21	-391	13068	10924	9067	440
ST10	0.34	-230	6250	5013	5573	172
Average	0.18	-369	16397	13615	7802	413
SD	0.14	96	8941	7782	1861	170

¹ST1-ST10 are obtained from Huynh et al. (2021)

¹ORP_{SHE} (mV) = ORP + 206 - 0.7(t - 25), where t is the temperature (°C)

Table A4 Influent and effluent compositions and septic tank efficiency

Septic tank	Influent(g/m ³)*					Effluent(g/m ³)*					Removal rate**			
	COD	BOD	SS	NH ₄ -N	pH	COD	BOD	SS	NH ₄ -N	pH	COD	BOD	SS	NH ₄ -N
T1	1,222	930	1,099	283	7.57	602	440	40	268	7.5	51%	53%	96%	5%
T2	1,236	872	1,087	295	7.81	817	563	178	299	7.8	34%	35%	84%	-1%
T3	971	777	750	564	7.71	831	442	98	297	8	14%	43%	87%	47%
T4	1,024	768	1,188	286	8.4	1,126	582	231	263	7.4	10%	24%	81%	8%
T5	1,631	1,256	1,113	268	7.76	862	676	182	319	7.7	47%	46%	84%	-19%
T6	1,368	1,040	924	233	7.74	1,082	814	195	247	8	21%	22%	79%	-6%
T7	1,574	1,149	1,588	631	7.56	987	731	206	249	7.7	37%	36%	87%	61%
T8	1,128	914	1,077	312	8.21	607	425	79	284	7.3	46%	54%	93%	9%
T9	1,327	1,022	1,387	270	7.81	882	621	179	325	7.9	34%	39%	87%	-20%
T10	1,299	974	1,071	266	7.94	1,055	849	185	343	7.5	19%	13%	83%	-29%
T11	887	648	662	435	8.75	454	340	71	292	7.4	49%	48%	89%	33%
T12	991	733	690	269	8.55	335	257	36	275	7.4	66%	65%	95%	-2%
T13	1,229	873	1,375	336	7.62	678	535	86	303	7.7	45%	39%	94%	10%
T14	1,093	765	857	503	7.87	973	777	165	320	7.7	11%	-2%	81%	36%
T15	1,693	1,337	1,785	431	8.45	909	754	170	290	7.8	46%	44%	90%	33%
Average	1245	937	1110	359	8.0	813	587	140	292	7.7	34%	37%	87%	11%
SD	245	197	321	124	0.4	234	181	64	28	0.2	20%	17%	6%	26%

* The units for all parameters are presented in mg/L except pH

** Average of removal rates were calculated based on both positive and negative data

Table A5 CH₄ concentrations in floating chamber at different time

Septic tank	CH ₄ concentration (g/m ³)				
	t=0	t=10	t=20	t=30	t=40
T1*	8	2,209	4,140	5984	7,375
T2*	9	4,963	8,337	13,366	15,665
T3	5	2,074	5,544	7,313	9,083
T4	6	7,645	12,881	18,629	22,571
T5	7	3,016	7,632	10,227	13,243
T6	7	3,094	6,481	7,648	9,955
T7	2	3,563	7,524	9,885	11,846
T8	3	1,354	2,507	3,255	4,199
T9	5	2,583	6,059	9,563	11,514
T10	5	5,438	8,261	15,239	16,317
T11	4	2,394	2,785	4,575	5,566
T12	4	1,531	2,088	3,045	3,433
T13	10	2,462	3,514	5,566	9,618
T14	6	3,357	6,713	9,966	11,420
T15	5	3,213	5,061	9,390	12,517
Average	6	3,260	5,968	8,910	10,955
SD	2	1,648	2,831	4,374	4,966

Table A6 CH₄ emission rates, liquid, and ambient temperatures

Septic tank ¹	CH ₄ emission (g/(cap·d))	liquid temperature (°C)	Ambient temperature (°C)
T1	11.12	21.6	19
T2	15.52	22.1	19
T3	6.61	19.1	20
T4	24.12	21.3	21
T5	15.46	22.2	23
T6	8.21	21.3	24
T7	26.81	21.3	21
T8	2.64	21.6	17
T9	6.79	22.1	18
T10	46.38	23.6	18
T11	2.23	22.5	22
T12	3.95	21.6	21
T13	5.78	21.7	18
T14	5.29	20.1	19
T15	10.29	24.2	24
ST1	11.11	31.1	37
ST2	15.48	31.4	35
ST3	8.87	31.7	36
ST4	8.76	31.4	38
ST5	16.62	31.1	38
ST6	6.43	31.2	35
ST7	18.79	31.0	35
ST8	12.51	31.0	35
ST9	13.93	30.6	36
ST10	4.42	30.1	38

¹ST1-ST10 are obtained from Huynh et al. (2021)

Table A7 Septage composition between summer and winter

Parameter	T1		T2	
	Summer*	Winter**	Summer*	Winter**
COD (g/m ³)	5,800	5,800	15,892	18,280
BOD (g/m ³)	4,607	4,350	12,782	13,893
SS (g/m ³)	5,895	5,472	7,805	7,944
DO (g/m ³)	0.03	0.02	0.03	0.05
ORP (-mV)	-346	-346	-434	-434

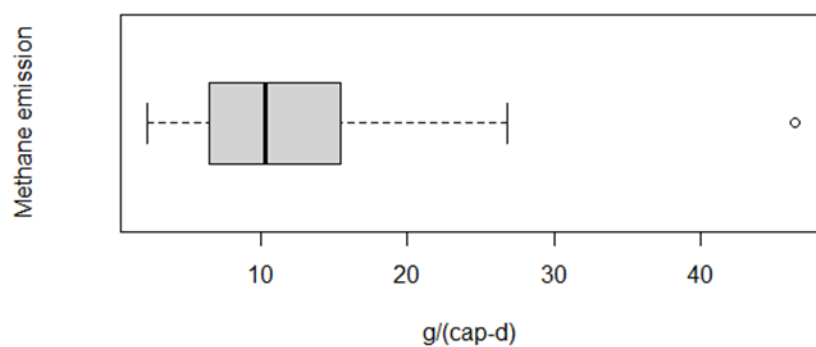


Figure A1 Box plot of CH_4 emission rates

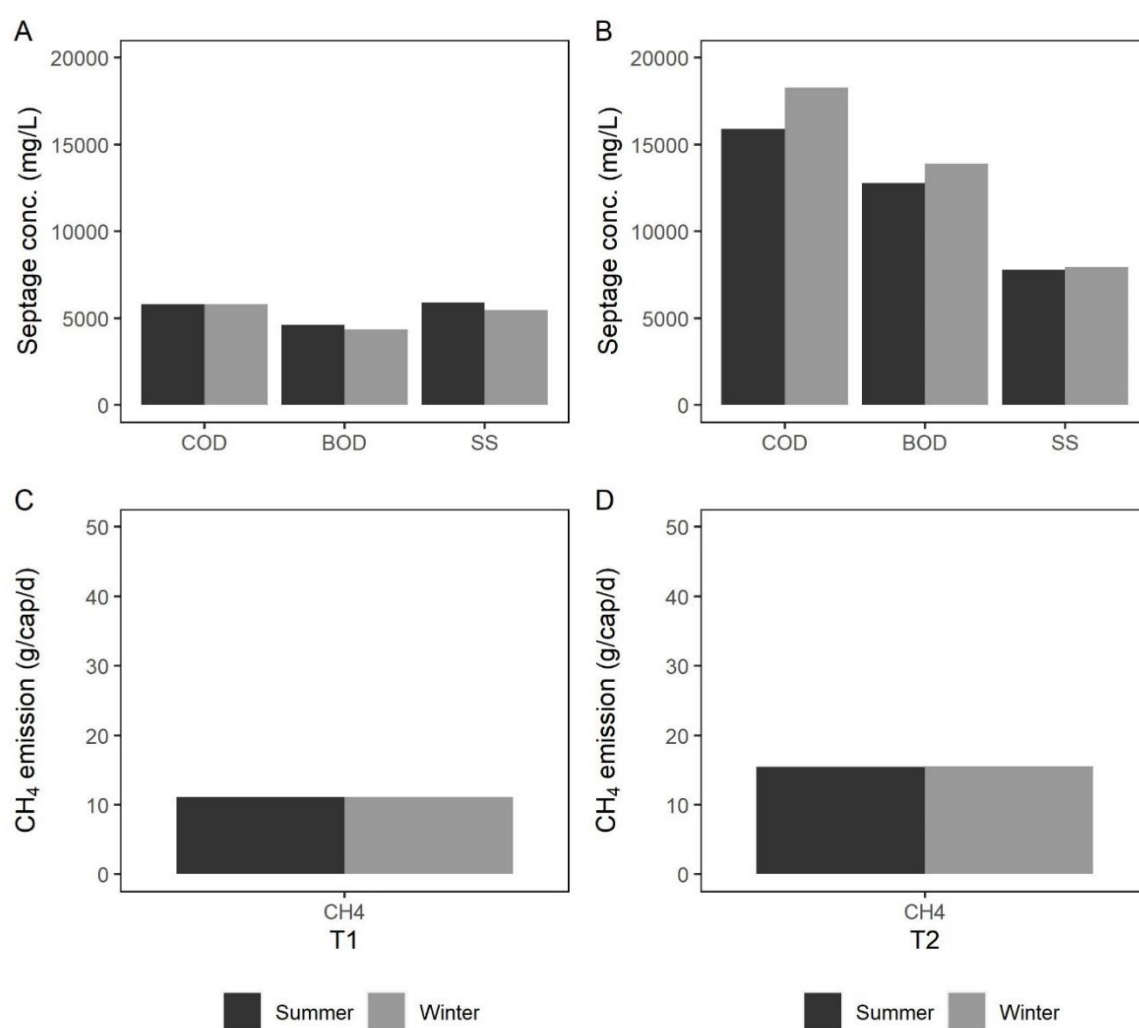


Figure A2 Septage compositions and CH_4 emission rate from summer and winter of septic tank T1 (A, C) and T2 (B, D)

Appendix-B

Table B1 Truc Bach WWTP configuration

Unit operation	Size	Unit	Qty.	Operated	Stand by	total kW	Remark
Influent pump pit							
Volume	52.1	m ³	1				assume HRT is 30 mins
Transfer pump	5.5	kw	3	2	1	11	
Grit chamber							
Grip pump	3.7	kw	2	1	1	3.7	1 operated 1 stand by
Fine Screen	0.2	kw	2	2	0	0.4	2 operated
Grit separation	2.2	kw	1	1	0	2.2	1 operated
Equalization tank							
Volume	156.25	m ³	1				assume HRT is 1.5 hrs
Agitator	2	kw	2	2	0	4	2 operated
Transfer pump	3.7	kw	3	2	1	7.4	2 operated 1 stand by
Primary sedimentation							
Volume	171.5	m ³	1				wepa n.d.
Sludge scraper	0.4	kw	1	1	0	0.4	
sludge pump	2.2	kw	2	1	1	2.2	
Anaerobic tank							
Volume	105	m ³	2				
Anaerobic mixer	1.5	kw	2	2	0	3	
Anoxic tank							
Volume	274	m ³	2				
Anoxic mixer	2.8	kw	2	2	0	5.6	
Aerobic tank							
Volume	180.4	m ³	2				
Recirculation pump	5.5	kw	2	1	1	5.5	
Coagulant dosing pump	0.2	kw	2	2	0	0.4	
Air blower	15	kw	3	2	0	30	
Secondary sedimentation							
Volume	224	m ³	2				
Sludge scraper	0.4	kw	2	2	0	0.8	
Return sludge pump	2.2	kw	1	1	1	2.2	
Disinfection							
Volume	52.1	m ³	1				assume contact time is 30 mins
Treated water discharge pump	3.7	kw	2	1	1	3.7	
Recycle water pump	3.7	kw	2	1	1	3.7	
Thickener							
Surface area	9.6	m ²					Diameter 3.5 m
Sludge scraper	0.4	kw	1	1	0	0.4	
Sludge pump	0.75	kw	1	1	0	0.75	
Dewatering	1	tank	1	1	0	1	
Sludge cake hopper	1.5	kw	2	2	0	3	
Dehydrator							
Sludge feed pump	0.75	kw	1	1	0	0.75	
Polymer dosing pump	1.5	kw	1	1	0	1.5	
Booster pump	0.75	kw	1	1	0	0.75	
Filterate return pump	1.5	kw	1	1	0	1.5	
Filtrate return pump	0.75	kw	2	1	1	0.75	
Drainage pump	0.4	kw	1	1	0	0.4	

Appendix-C

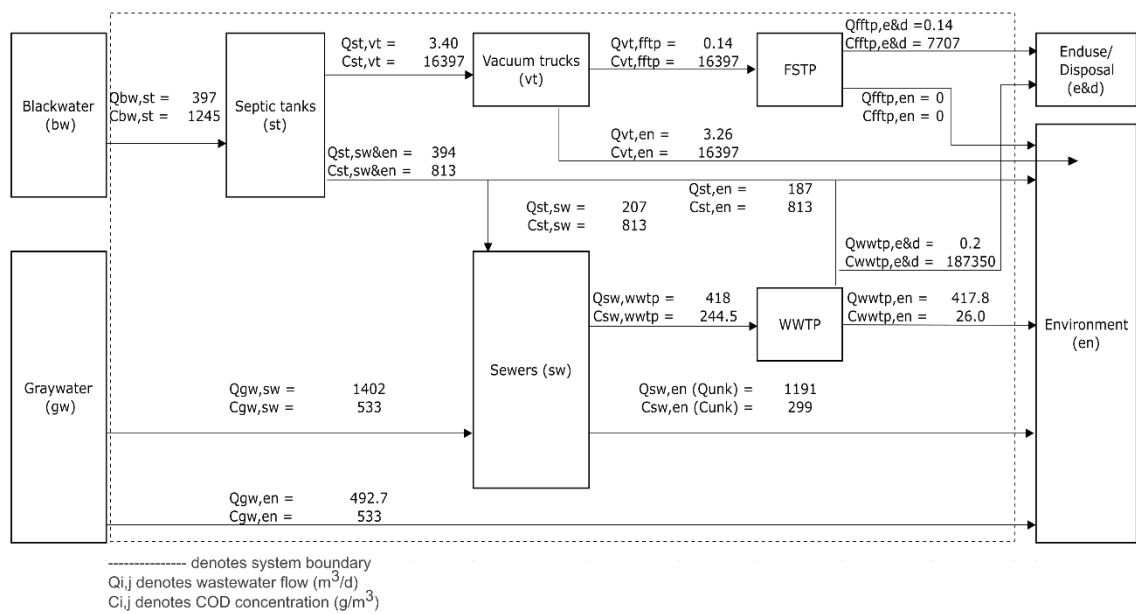


Figure C1 Mass balance diagram for baseline

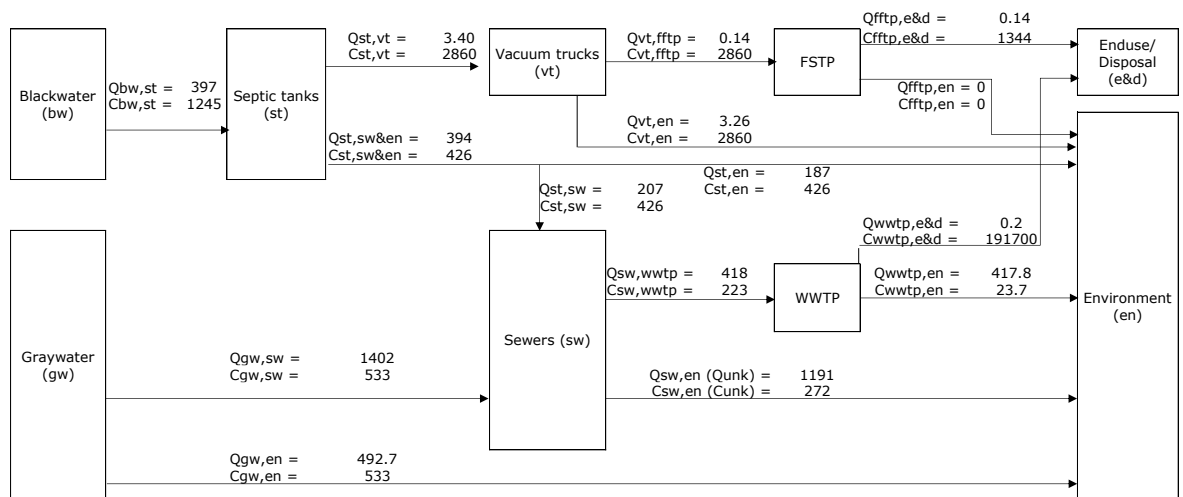


Figure C2 Mass balance diagram for scenario A

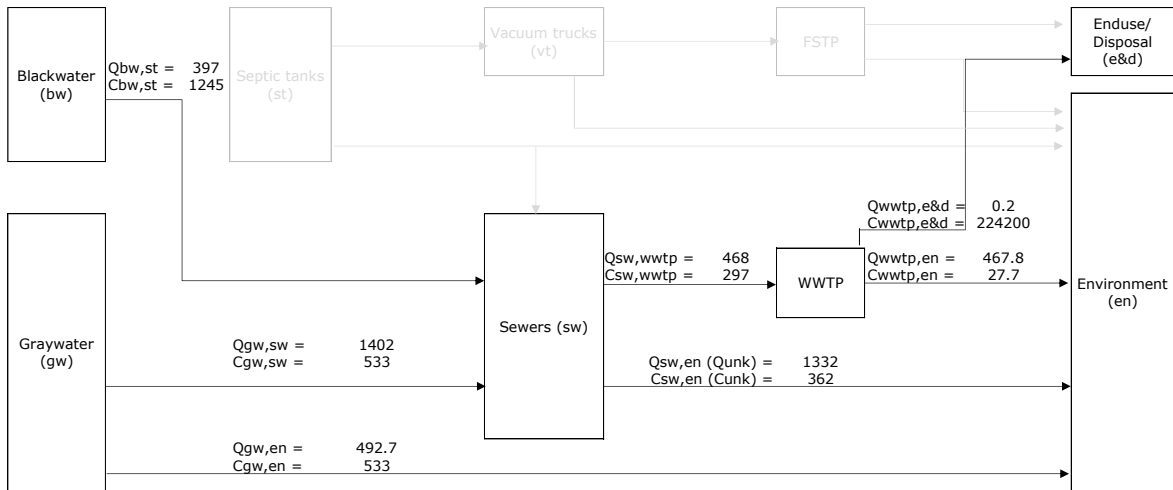


Figure C3 Mass balance diagram for scenario B

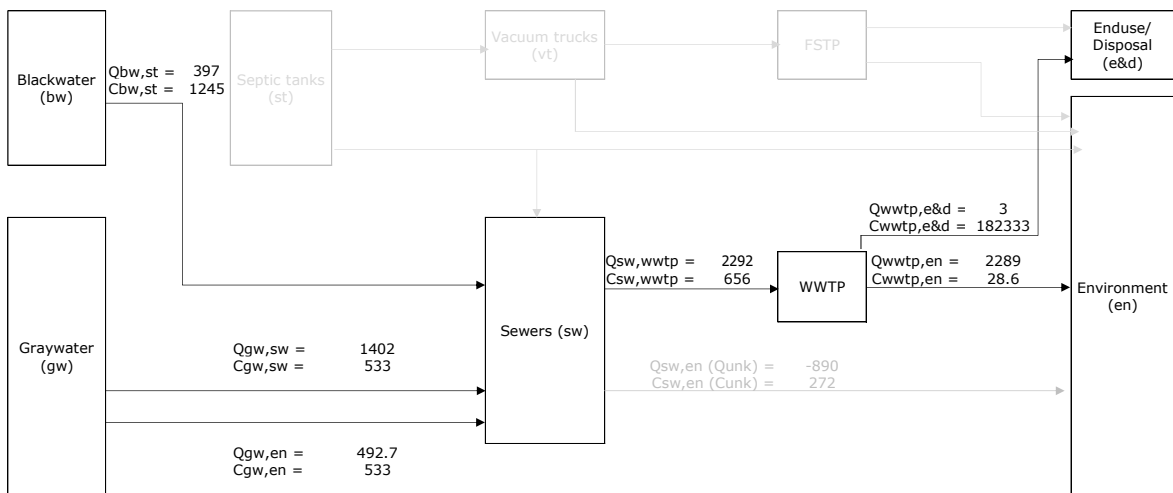


Figure C4 Mass balance diagram for scenario C

Appendix-D

Table D1 Baseline GHG emissions of WWTP obtained from GPS-X

GHG emissions (tCO ₂ e/yr)	Pump Station	Grit Chamber	EQ Tank	Primary Clarifier	Anaerobic1	Anaerobic 2	Anoxic 1	Anoxic 2	Aerobic 1	Aerobic 2	Thickener	Final Clarifier1	Final Clarifier2	Dewatering	Disinfection	Sludge Disposal	Total
Scope One CO ₂ Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.0
Scope One CH ₄ Emission	0.00	0.00	0.00	55.50	13.13	13.13	4.45	4.45	4.22	4.22	0.00	0.25	0.25	0.00	0.00	0.00	99.6
Scope One N ₂ O Emission	0.00	0.00	0.00	0.04	0.00	0.00	35.40	35.40	42.24	42.24	0.00	8.43	8.43	0.00	0.00	0.00	172.2
Scope One Emission Total	0.00	0.00	0.00	55.54	13.13	13.13	39.85	39.85	46.46	46.46	0.00	8.68	8.68	0.00	0.00	0.00	271.8
Scope Two CO ₂ Emission	60.06	50.22	32.99	20.72	23.94	23.94	44.55	44.55	52.28	52.28	41.05	23.93	23.93	45.04	58.98	0.00	598.5
Scope Two CH ₄ Emission	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.00	0.2
Scope Two N ₂ O Emission	1.44	1.21	0.79	0.50	0.57	0.57	1.07	1.07	1.25	1.25	0.99	0.57	0.57	1.08	1.42	0.00	14.4
Scope Two Emission	61.52	51.44	33.79	21.23	24.52	24.52	45.64	45.64	53.55	53.55	42.05	24.51	24.51	46.13	60.42	0.00	613.0
Scope Three Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14	0.1
Total Carbon Emission	61.52	51.44	33.79	76.77	37.65	37.65	85.48	85.48	100.01	100.01	42.05	33.19	33.19	46.13	60.42	0.14	884.9

Table D2 GHG emissions of WWTP obtained from GPS-X (Scenario A)

GHG emissions (tCO ₂ e/yr)	Pump Station	Grit Chamber	EQ Tank	Primary Clarifier	Anaerobic1	Anaerobic 2	Anoxic 1	Anoxic 2	Aerobic 1	Aerobic 2	Thickener	Final Clarifier1	Final Clarifier2	Dewatering	Disinfection	Sludge Disposal	Total
Scope One CO ₂ Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scope One CH ₄ Emission	0.00	0.00	0.00	29.97	6.32	6.32	2.29	2.29	2.17	2.17	0.00	0.13	0.13	0.00	0.00	0.00	51.79
Scope One N ₂ O Emission	0.00	0.00	0.00	0.01	0.00	0.00	13.73	13.73	24.16	24.16	0.00	7.04	7.04	0.00	0.00	0.00	89.87
Scope One Emission Total	0.00	0.00	0.00	29.98	6.32	6.32	16.02	16.02	26.33	26.33	0.00	7.17	7.17	0.00	0.00	0.00	141.66
Scope Two CO ₂ Emission	60.06	50.22	32.99	20.72	23.94	23.94	44.55	44.55	52.23	52.23	41.05	23.93	23.93	45.04	58.98	0.00	598.36
Scope Two CH ₄ Emission	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.00	0.18
Scope Two N ₂ O Emission	1.44	1.21	0.79	0.50	0.57	0.57	1.07	1.07	1.25	1.25	0.99	0.57	0.57	1.08	1.42	0.00	14.36
Scope Two Emission	61.52	51.44	33.79	21.23	24.52	24.52	45.64	45.64	53.50	53.50	42.05	24.51	24.51	46.13	60.42	0.00	612.90
Scope Three Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.15	0.15
Total Carbon Emission	61.52	51.44	33.79	51.20	30.83	30.83	61.66	61.66	79.83	79.83	42.05	31.68	31.68	46.13	60.42	0.15	754.72

Table D3 GHG emissions of WWTP obtained from GPS-X (Scenario B)

GHG emissions (tCO ₂ e/yr)	Pump Station	Grit Chamber	EQ Tank	Primary Clarifier	Anaerobic1	Anaerobic 2	Anoxic 1	Anoxic 2	Aerobic 1	Aerobic 2	Thickener	Final Clarifier1	Final Clarifier2	Dewatering	Disinfection	Sludge Disposal	Total
Scope One CO ₂ Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scope One CH ₄ Emission	0.00	0.00	0.00	40.59	9.74	9.74	4.84	4.84	4.95	4.95	0.00	0.34	0.34	0.00	0.00	0.00	80.33
Scope One N ₂ O Emission	0.00	0.00	0.00	0.02	0.00	0.00	1.18	1.18	5.94	5.94	0.00	2.24	2.24	0.00	0.00	0.00	18.73
Scope One Emission Total	0.00	0.00	0.00	40.61	9.74	9.74	6.02	6.02	10.89	10.89	0.00	2.58	2.58	0.00	0.00	0.00	99.06
Scope Two CO ₂ Emission	60.19	50.22	33.12	20.72	23.94	23.94	44.55	44.55	52.48	52.48	41.05	23.93	23.93	45.04	58.98	0.00	599.12
Scope Two CH ₄ Emission	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.01	0.02	0.00	0.18
Scope Two N ₂ O Emission	0.92	0.76	0.50	0.32	0.36	0.36	0.68	0.68	0.80	0.80	0.62	0.36	0.36	0.68	0.90	0.00	9.11
Scope Two Emission	61.13	51.00	33.63	21.05	24.31	24.31	45.24	45.24	53.29	53.29	41.69	24.30	24.30	45.73	59.90	0.00	608.41
Scope Three Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.21
Total Carbon Emission	61.13	51.00	33.63	61.65	34.05	34.05	51.26	51.26	64.18	64.18	41.69	26.87	26.87	45.73	59.90	0.21	707.68

Table D4 GHG emissions of WWTP obtained from GPS-X (Scenario C)

GHG emissions (tCO ₂ e/yr)	Pump Station	Grit Chamber	EQ Tank	Primary Clarifier	Anaerobic1	Anaerobic 2	Anoxic 1	Anoxic 2	Aerobic 1	Aerobic 2	Thickener	Final Clarifier1	Final Clarifier2	Dewatering	Disinfection	Sludge Disposal	Total
Scope One CO ₂ Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scope One CH ₄ Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Scope One N ₂ O Emission	0.00	0.00	0.00	0.52	13.59	13.59	65.25	65.25	399.83	399.83	0.00	19.77	19.77	0.00	0.00	0.00	997.41
Scope One Emission Total	0.00	0.00	0.00	0.52	13.59	13.59	65.25	65.25	399.83	399.83	0.00	19.77	19.77	0.00	0.00	0.00	997.41
Scope Two CO ₂ Emission	64.91	50.22	38.01	20.78	23.94	23.94	97.56	97.56	158.27	158.27	41.08	35.88	35.88	45.04	58.98	0.00	950.33
Scope Two CH ₄ Emission	0.02	0.02	0.01	0.01	0.01	0.01	0.03	0.03	0.05	0.05	0.01	0.01	0.01	0.01	0.02	0.00	0.29
Scope Two N ₂ O Emission	1.56	1.21	0.91	0.50	0.57	0.57	2.34	2.34	3.80	3.80	0.99	0.86	0.86	1.08	1.42	0.00	22.81
Scope Two Emission	66.49	51.44	38.93	21.28	24.52	24.52	99.93	99.93	162.12	162.12	42.08	36.76	36.76	46.14	60.42	0.00	973.43
Scope Three Emission	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.78	2.78
Total Carbon Emission	66.49	51.44	38.93	21.81	38.11	38.11	165.19	165.19	561.95	561.95	42.08	56.53	56.53	46.14	60.42	2.78	1,973.62