

Greenhouse gas emissions from blackwater septic systems in Hanoi, Vietnam

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ABBREVIATION

ADB	Asian Development Bank
BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
COD _{cr}	Chemical oxygen demand determined by dichromate potassium
DO	Dissolved oxygen
E.C.	Electrical conductivity
GDP	Gross domestic product
GNI	Gross National Income
GHG	Greenhouse gas
HH	Household
IPCC	Intergovernmental Panel on Climate Change
JICA	Japan International Cooperation Agency
MONRE	Ministry of Natural Resources and Environment
MPI	Ministry of Planning and Investment
ORP	Oxidation-reduction potential
SS	Suspended solids
ST	Septic tank
TN	Total Nitrogen
TP	Total Phosphorus
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	The United Nations Children's Fund
VSS	Volatile suspended solids
USEPA	United States Environmental Protection Agency
WB	World Bank
WHO	World Health Organization

EXCLUSIVE SUMMARY

Septic systems are one of the major onsite sanitation facilities, used by 1.5 billion people in 2017. They were widely used in urban and peri-urban areas of many developing countries. The main function of a septic system is to treat household wastewater by settling the solids of the influent and accumulating them as a sludge layer at the bottom of the tank. Due to the accumulation of organic matter under anaerobic conditions, septic systems are suspected to produce greenhouse gases (GHGs). The Intergovernmental Panel on Climate Change (IPCC), in 2007, proposed a CH₄ emission factor of septic systems as 25.5 g-CH₄/cap/day. However, the IPCC emission factor for septic systems was actually derived from an emission rate study of anaerobic lagoons, not from septic systems themselves. The information about GHG emissions from septic systems is currently limited, although a large population is using septic systems globally.

There are only 2 studies monitored GHG emissions from septic systems in the USA. The CH₄ emission rates of these two studies were substantially lower than the IPCC emission factor and suggested that IPCC emission estimation was potentially overestimated. Further, septic systems in developing countries differ from those in developed countries in terms of design and operating conditions. The septic systems in developing countries receive only blackwater, which implies a lower influent organic load because septic systems in developed countries receive domestic wastewater including black and greywater. Regarding the operating conditions, septic systems in developing countries were often under low levels of performance and functionality due to improper emptying frequency. These differences can affect the GHG emissions of septic systems in developing countries.

The CH₄ production under anaerobic conditions was affected by temperature. At low temperature, the degradation of organic matter was at slower reaction rates. Therefore, the seasonal variation of temperature had a potential impact on GHG emissions from septic systems. However, the existing studies about GHG emissions from septic tanks have a limitation in the sampling period. Diaz-Valbuena *et al.* (2011) monitored GHG emissions in the period of September – December, 2009; and Truhlar *et al.* (2016) conducted the monitoring from June to August, 2014. These studies were not able to show the seasonal variability of GHG emissions from septic systems.

This study investigated the emission rates of GHGs, namely CH₄, CO₂, and N₂O, from septic systems in Hanoi, Vietnam, which is located in a subtropical climate region. The influence of septic tank conditions such as influent, effluent characteristics, sludge compositions, non-emptying period, and HRT were also investigated, together with seasonal variability of GHG emissions and pollutant removals. To the best of our knowledge, this is the first study to measure and characterize GHG emissions from septic systems in developing countries.

Greenhouse gas emissions from septic systems in Vietnam

The first objective of this study is to estimate GHG emissions from septic systems in a developing country, with the influential factors to the emissions, as a case study of Hanoi, Vietnam. The CH₄, CO₂, and N₂O emissions from ten septic systems (ST1 – ST10) in the urban area of Hanoi, Vietnam, were measured by the floating chamber method. The monitoring was conducted in June – July, 2019.

The measured CH₄ and CO₂ emission rates were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day (Avg $\pm$ SD), respectively, whereas those of N₂O were at the negligible levels. The CH₄ emission rates were negatively correlated with septage ORP ($R = -0.68$, $p = 0.015$), and positively correlated with septage COD mass ($R = 0.71$, $p = 0.0098$) and BOD mass ($R = 0.65$, $p = 0.023$). Further, the CH₄ emission rates from septic systems with longer storage periods (more than 7 years) were significantly higher than those from septic systems with shorter storage periods (less than 7 years). Moreover, the storage periods were negatively correlated with ORP and DO, and positively correlated with COD mass and BOD mass. These results suggest that lower ORP and DO, and higher biodegradable carbon mass in association with longer septage storage periods are key conditions for CH₄ emissions from septic systems. Therefore, controlled or regular septage emptying could contribute to improve not only the removal efficiency of septic systems but also its GHG emissions. Thus, our results will contribute to estimate global GHGs emissions from septic systems in developing countries and be essential information for mitigating the emission.

The CH₄ emission rates of this study were equivalent to or even larger than those of previous studies which measured the emission rates in the USA. Beside the influent difference between septic systems in the USA (black and greywater) and septic systems in our study (only

blackwater), the equivalent or even larger CH₄ emission rates of the present study could be attributed to significant difference such as lower ORP, higher COD concentration, and longer HRT and septage storage periods. In contrast, the emission rate in this study was significantly smaller (nearly half) than the IPCC emission factor. As the IPCC emission factor is based on the correlation between removed BOD and produced CH₄, this difference can be potentially explained by the difference of influent BOD loading and removal efficiency although this study did not monitor the influent loadings.

Seasonal variability in GHG emissions and C/N/P removals of blackwater septic systems

The second objective of this study is to evaluate the septic tanks mass balance with seasonal variation. CH₄, CO₂ and N₂O emissions were monitored at twenty-five septic systems in summer and winter in the urban area of Hanoi, Vietnam. The summer survey was conducted at ten septic systems (ST1 – ST10), as shown in Chapter 3, and the winter survey monitored at fifteen septic systems (ST1, ST2, and ST11 – ST23) in December 2019 – January 2020. Together with GHG emissions from fifteen septic systems monitored in winter, the influent, effluent characteristics, and septage composition were monitored to evaluate the performance of septic systems and their impacts on GHG emissions. The average measured CH₄ and CO₂ emissions from 25 septic tanks in summer and winter in Hanoi were 14.96 ± 9.43 and 27.75 ± 14.29 g/cap/day (Avg $\pm$ SD), respectively, whereas those of N₂O were at the negligible levels.

The CH₄ and CO₂ emission rates were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day in summer, 15.52 ± 11.19 and 29.87 ± 16.03 g/cap/day in winter, respectively. The results indicated that the GHG emission rates were not significantly different between summer and winter in Hanoi. It could be attributed to the stable temperature, biological reaction rate, microbial structure, and the stable inside conditions of septic tanks (ORP, DO, organic mass). The temperature has an impact on biological reaction rate while CH₄ production was not affected. Further, this study figured out that the variability in the inside conditions of septic tanks could play a more significant role in GHG emissions. Lower ORP and higher biodegradable carbon mass (indicated by BOD or COD mass) associated with longer septage storage period are the main factors for the emission of CH₄ from septic tanks, rather than liquid temperature.

The mass balances of carbon, nitrogen and phosphorus were analyzed for ST1 and ST2. The C, N, and P removal efficiencies were 59%, 24% and 6% in ST1 and 22%, 12% and 0.5% in ST2.

Higher septage storage period of ST2 might reduce removal efficiencies of ST2. The CH₄ and CO₂ emissions were not only produced from carbon in the influent, but also from carbon in the septage because septage still contained high amount of biodegradable organic matter after long storage time. The CH₄ emission rate per-capita in the present study was 59%, smaller than IPCC emission factor. This result could be attributed to lower BOD loading and removal efficiency of septic systems in the present study as 23 ± 10 g-BOD/cap/day and $33 \pm 18\%$, respectively. Therefore, for better estimation of CH₄ emissions from septic systems, BOD loading and removal efficiency are the key factors.

Keywords: greenhouse gas; septic system; methane; nitrous oxide; inside condition; seasonal variation; septage; monitoring; removal efficiency, Hanoi.

Chapter 1 : Introduction

1.1 Research background

1.1.1 Sanitation

Domestic wastewater management is essential to achieve adequate sanitation conditions worldwide. In this context, the sewage system is one of the major sanitation facilities in developed countries but the system requires a huge expense and decades-long construction for its development (UNEP-IETC, 2002). According to the present limited coverage of sewerage in developing countries, low-cost sanitation facilities option is a suitable choice (Foster, 2001, USEPA, 2000). In 2017, 3.1 billion people relied on on-site sanitation, of which 2.9 billion lived in developing countries (WHO and UNICEF, 2017), and this number is expected to reach 5 billion by 2030 (Cairns-Smith et al., 2014). Therefore, onsite sanitation management is one of the major challenges in global sanitation.

Septic systems are one of the major onsite sanitation facilities, used by 1.5 billion people in 2017 (WHO and UNICEF, 2017). They were widely used in urban and peri-urban areas of many developing countries (Sotelo et al., 2019); for example, the proportion of households with septic systems in Hanoi, Vietnam (Brandes et al., 2016), Mandalay, Myanmar (Naing et al., 2020), Kota Surakarta, Indonesia (USAID, 2012), and Kampong Chhnang, Cambodia (Dumpert et al., 2018) are 84%, 90%, 86%, and 79%, respectively. The design of septic systems is varied by region. A typical septic system consists of a septic tank and a soil absorption field. Septic systems take responsibility for treating household wastewater by separating solids from influent wastewater. The solids were accumulated at the bottom of the tanks under anaerobic conditions. Therefore, septic systems are potential greenhouse gas (GHG) emissions sources.

1.1.2 Greenhouse gas emissions from wastewater

In 2010, GHG emissions from the waste sector accounted for 3% of total GHG emissions from all sources (1445 MtCO₂eq) (IPCC, 2014). The emissions from the waste sector were almost double from 1970–2010, while in the period 2000–2010, the increment was 13% (1278 MtCO₂-eq vs 1446 MtCO₂-eq). The main sources of waste GHG emissions were wastewater handling (51% of total waste GHG emissions in 1970 and 54% in 2010) and solid waste disposal on land

(46% of total waste GHG emissions in 1970 and 43% in 2010), waste incineration (mainly CO₂) and other sources are of minor importance (JRC/PBL, 2013).

1.1.3 Greenhouse gas emissions from septic systems

Regarding onsite sanitation facilities, onsite latrines accounted for nearly 74% of GHG emissions in China; 62% of that in India (USEPA, 2011). In the USA, for example, septic systems are estimated to be responsible for 65% of GHG emissions from domestic wastewater (USEPA, 2011). Furthermore, the increase of on-site sanitation facilities caused substantial GHG emissions. Therefore, IPCC reconsidered the default emission factors (EFs) for septic systems and pit latrines from 2000 (IPCC, 2007); however, these emission factors came from the study of anaerobic lagoons for domestic wastewater treatment in the USA (Doorn and Liles, 1999).

Currently, there are only 2 studies monitored GHG emissions from septic systems in the USA (Diaz-Valbuena et al., 2011; Truhlar et al., 2016). The CH₄ emission rates of these two studies were substantially lower than the IPCC emission factor. The CH₄ emission rates measured by these two studies, which were conducted in the USA, were substantially lower, accounting for only 43% of the IPCC emission factor. The design and operational conditions of septic systems in developing countries differ from those in developed countries. The septic systems in developing countries receive only blackwater while those of developed countries receive black and greywater (Nguyen et al., 2007; WB, 2013). These differences potentially affect to GHG emissions.

The performance of CH₄ production under anaerobic conditions was affected by temperature. At low temperature, the degradation of organic matter was at slower reaction rates (Tchobanoglous et al., 2003). Therefore, the seasonal variation of temperature had a potential impact on GHG emissions from septic systems. However, the existing studies about GHG emissions from septic tanks have a limited temporal such as Diaz-Valbuena et al. (2011) conducted in September to December, 2009, Truhlar et al. (2016) conducted in June to August, 2014. Therefore, this data was not able to show the seasonal variability of GHG emissions.

1.2 Purpose

The overall objective of the research is to estimate and mitigate GHG emissions from septic systems in developing countries.

The specific objectives of this study are:

1. To estimate GHG emissions from septic systems in a developing country, with influential factors to the emissions;
2. To evaluate the septic tanks mass balance with seasonal variation.

To fulfill the mentioned objectives, this dissertation consists of 5 chapters. The outline is as follows:

Introduction

- Introduction of this dissertation (Chapter 1);

Review on sanitation in Vietnam and GHG emissions from on-site sanitation (Chapter 2)

- Current status of sanitation in Vietnam;
- GHG emissions from the waste sector and wastewater handling sub-sector;
- The available GHG emission rates from septic systems and research gaps.

GHG emissions from septic systems in developing countries

- Characterize GHG emissions from blackwater septic systems in association with the inside conditions of septic systems. This study monitored CH₄, CO₂, and N₂O emissions from blackwater septic systems, as a case study of Hanoi, Vietnam. Together with GHG emissions, effluent characteristics and septage compositions were investigated to evaluate their effects on GHG emissions. (Chapter 3)
- Monitor GHG emissions in the summer and winter seasons to evaluate the seasonal variability. This study accessed the impact of temperature on GHG emissions, as well as confirmed the impact of the inside conditions of septic systems in winter. This study

also conducted carbon, nitrogen, phosphorus mass balance for blackwater septic systems. (Chapter 4)

Conclusions and recommendations

- Conclusions of this dissertation and recommendations for further studies. (Chapter 5)

The research framework of the dissertation is shown in Figure 1.1.

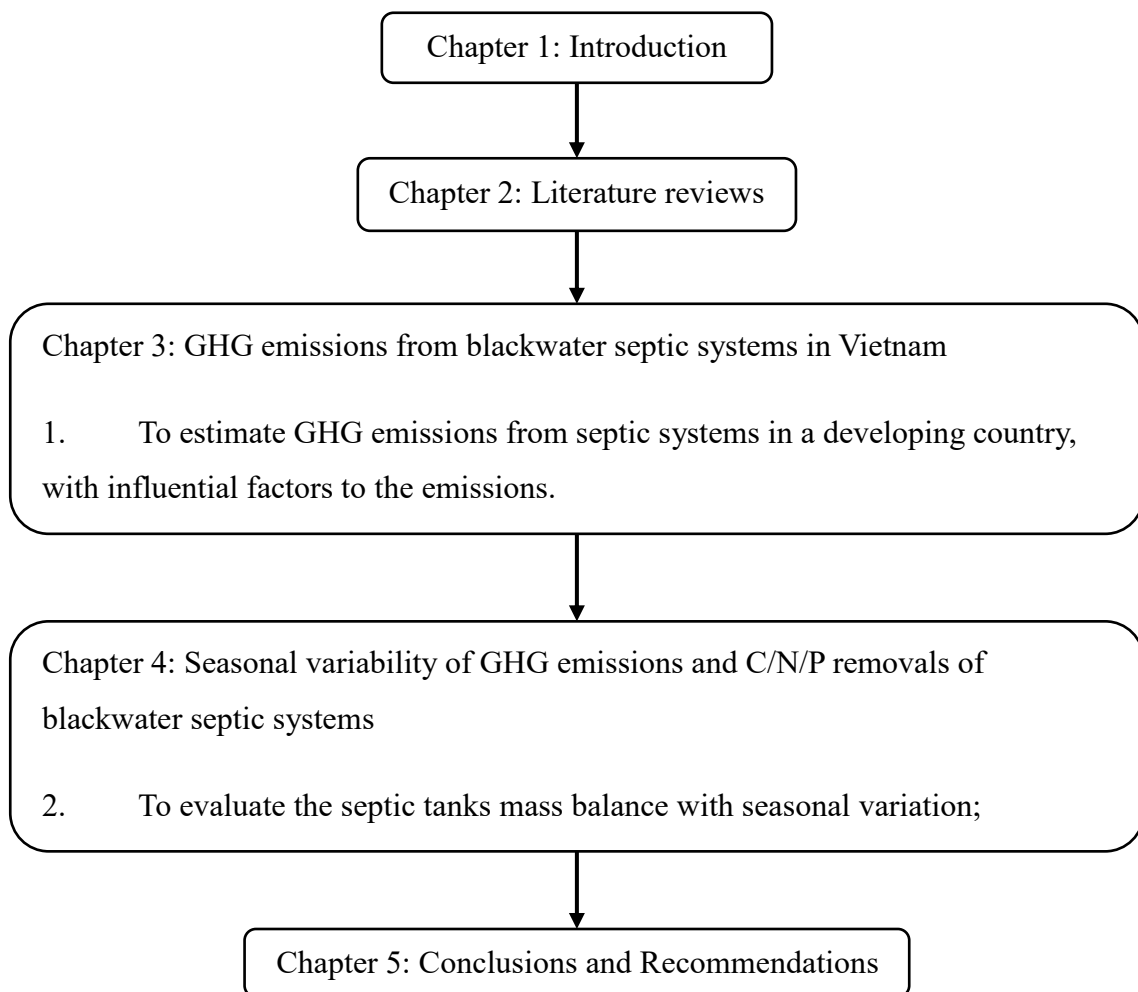


Figure 1.1 Research framework

1.3 Internship and survey in Vietnam

To complete the above-mentioned objectives, the required data were collected in Hanoi, Vietnam. The schedule and activities of the survey were listed in Table 1.1

Table 1.1 Schedule of internship and survey

Schedule	Activities	Host Institute
October 15 th – November 28 th , 2018	- Monitor GHG emissions, influent, effluent and septage from 3 septic tanks.	HUST*
December 18 th – January 26 th , 2019	- Monitor GHG emissions, influent, effluent and septage from 2 septic tanks. - Resample for influent in 2 previous septic tanks.	HUST
April 08 th – April 19 th , 2019	- Test the floating chamber for GHG emissions from septic tanks.	HUST
June 4 th – July 27 th , 2019	- Summer survey: Monitor GHG emissions, effluent and septage from 10 septic tanks.	HUST
December 04 th , 2019 – January 21 st , 2020	- Winter survey: Monitor GHG emissions, influent, effluent and septage from 15 septic tanks.	HUST

*HUST: Hanoi University of Science and Technology.

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Chapter 2 : Literature reviews

2.1 Sanitation management in Vietnam

2.1.1 General information about Vietnam

Alongside China, Laos, and Cambodia, the Socialist Republic of Vietnam is located in the eastern and southern part of the Indochinese peninsula in Southeast Asia with a long coastline bordering the South China Sea, the Gulf of Thailand, and the Gulf of Tonkin (Figure 2.1). The country is divided into 63 provinces, including the capital Hanoi. The total area of the country is 331,236 km², in which Hanoi is the largest city (335.9 km²) (GSO, 2019). The country extends for approximately 1,650 km from north to south and less than 50 km from east to west at the narrowest point. The coastline was 3,260 km, excluding islands. The terrain of Vietnam was characterized as low and flat in the north and south, as central highland in the central, and as hilly and mountain in the far north and northwest of Vietnam (Vietnam Government Portal, 2020). The general information about Vietnam is shown in Table 2.1.

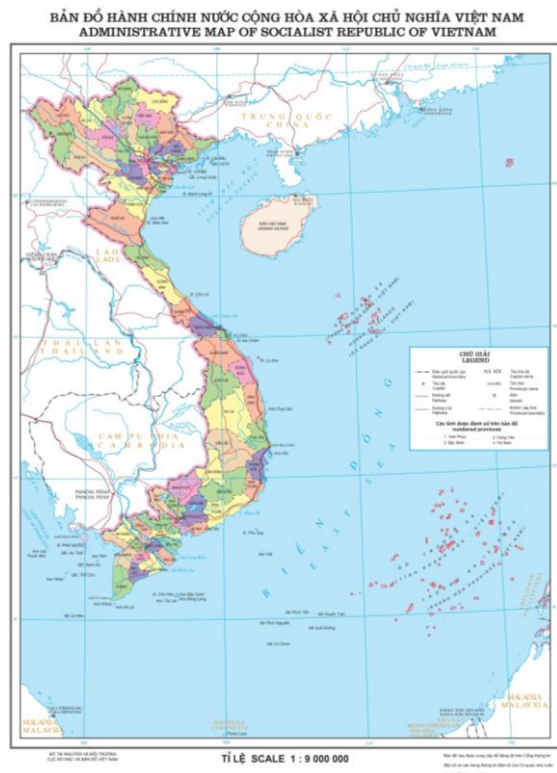


Figure 2.1 A map of Vietnam (Vietnam Department of Survey, Mapping and Geographic Information, 2020)

Table 2.1 General information about Vietnam

Items	Value	References
Surface area (km ²)	331,235.7	GSO, 2019
Population, total (million people)	94.7	GSO, 2019
Population density (people/km ²)	286	GSO, 2019
Population growth (annual %)	1.14	GSO, 2020
GDP growth rate (annual %)	6.5	WB, 2018
Inflation, GDP deflator (annual %)	3.398	WB, 2018
Increase in the population using basic drinking water service from 2000 to 2017	80.14% to 94.72%	WHO/UNICEF, 2019
Increase in the population using basic sanitation service from 2000 to 2018	52.37% to 83.52%	WHO/UNICEF, 2019

2.1.2 Sanitation in Vietnam

As population densities increased, wastewater management became a crucial issue for sanitation. Based on population and daily water consumption, generated domestic wastewater was estimated as 9,511,509 m³/day. In 2018, there are 43 domestic wastewater treatment plants (WWTPs) under operation with a capacity of 926,000 m³/day (MONRE, 2018). However, these treatment plants could treat only 10% of generated domestic wastewater due to the incomplete sewer system. The coverages of the centralized wastewater treatment system in Hanoi and Ho Chi Minh City are 33.37 and 21.59%, respectively (JICA and Nippon Koei, 2019). Therefore, the capacity of the available WWTPs in Vietnam could not meet the demand for sanitation issues.

For improving the wastewater management problem, 37 domestic WWTPs are under construction and planning with the expected capacity of 2,400,000 m³/day. In terms of centralized wastewater system development, this system requires long-decades and high investment for construction and maintenance (Sotelo et al., 2019). Therefore, the on-site

sanitation facilities were used as a substitute solution to meet the sanitation demand (WHO, 2009; Naughton and Mihelcic, 2017). Septic systems are the common on-site sanitation facilities in Vietnam, especially in urban areas.

Regarding household connection, 60% of household wastewater was discharged into the public combined drainage system (JICA and Nippon Koei, 2019). The remaining portion of septic systems is connected to the underground infiltration systems or even discharge directly into open drainage. The proportion of septic tanks connected to sewer networks, soak-pit systems, and open drainage in Danang were 12.6, 78.0, and 3.1% (Harada et al., 2015a), whereas those in Hue were 50, 30, and 20% (Anh et al., 2015). In Hanoi, the household connection to the sewer system was 80 - 90% (WB, 2013). According to the mention limited capacity of wastewater treatment plants, a large amount of household wastewater was discharged directly to water bodies and cause severe pollution problems.

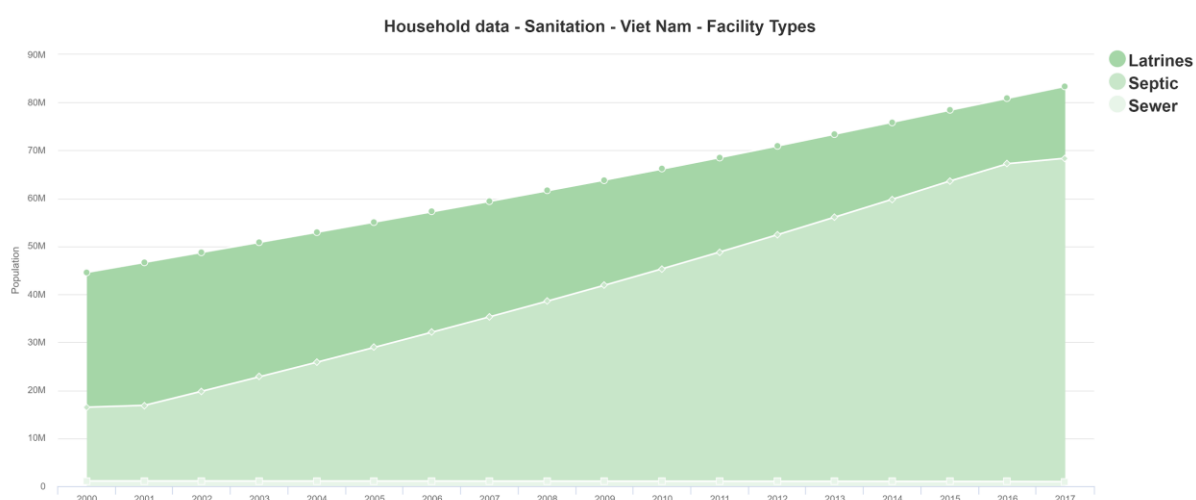


Figure 2.2 The situation of on-site sanitation in Vietnam (WHO/UNESCO, 2019)

According to the JMP database, the coverage of onsite sanitation including (1) septic, (2) improved latrine and others was changed between 2000 and 2017. The coverage of septic systems was increased by 51.43% from 2000 to 2017, while coverage of latrines was decreased from 35.03% in 2000 to 15.69% in 2017. The decrease of latrine systems was caused by the urbanization process in Vietnam and the recommendation of septic systems used for sanitation demand. According to the prediction of the Government, Vietnam can meet the target of 100% household can be served by improved on-site sanitation facilities by 2032 (MPI, 2018).

2.1.3 Sanitation in Hanoi

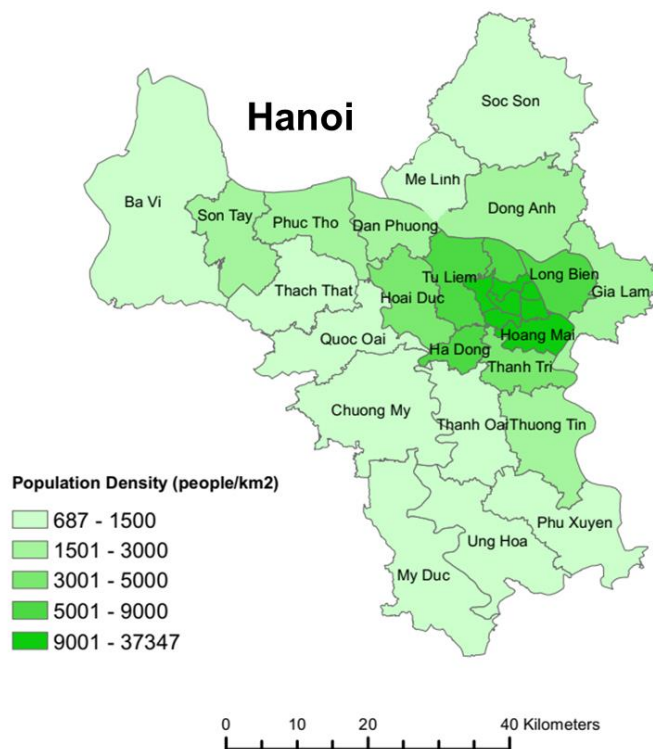


Figure 2.3 A map of Hanoi

Hanoi, which is the capital of Vietnam, is located in the Red River delta (Figure 2.3). Hanoi is the second-largest city after Ho Chi Minh City. Hanoi has an area of 3,329 km² and its population was 8.05 million in 2019 (GSO, 2019). The city is composed of 12 urban districts, one town, and 17 sub-urban districts (GSO, 2019). Hanoi has a subtropical monsoon climate with a monthly average temperature of 18.1–30.8°C (GSO, 2019).

Currently, there are 7 wastewater treatment plants, mainly concentrated in urban areas with a total capacity of 303,000 m³/day, which can treat 33.37% of generated wastewater from the city. The other 2 WWTPs were under planning and construction with a larger capacity of 354,000 m³/day, which is more than 2 times compared to the available capacity of WWTPs. JICA and Nippon Koei, (2019) reported that the inflow of these WWTPs had reached 70% of capacity. According to the performance of available WWTPs, the concentration of pollutants received at WWTPs from sewer systems is significantly lower than the initial design. Besides, the effluent quality of the available WWTPs had met the national effluent discharged standard (WB, 2013).

The proportion of households with septic systems, without septic systems, and latrines in Hanoi were 84%, 12%, and 4%, respectively (Brandes et al., 2016). Septic systems in Hanoi consist of only septic tanks. As mentioned above, septic tanks are used in urban areas, whereas pit latrines are used in peri-urban and rural areas. Latrines in Hanoi include pit latrine, single or double vault latrines (used with or without urine diversion). Single or double vault latrines are generally built above ground as fully lined tanks, whereas the pit latrines are not lined at the bottom. The waste from these latrines containment systems was used as fertilizers for agriculture (Harada et al., 2010).

The main function of septic tanks is to separate the solid part from human waste and accumulate organic matter as a bottom sludge under anaerobic conditions. Septic tanks normally connect to sewer systems, where sewer systems are available, or drain field. To avoid the negative impact of septic tanks effluent, the performance of septic tanks should be maintained. The accumulated sludge must be periodically removed (Caincron and Feachem, 2019). However, the removal of accumulated sludge was not regularly done in Vietnam and most developing countries: for example, 6.2–14.2 years in Hanoi (Harada et al., 2008; Pham, 2014), and 12.7 years in Mandalay, Myanmar (Naing et al., 2020). More than 90 and 54% of households did not regularly empty their septic tanks in Kalianda, Indonesia (ISF-UTS and SNV, 2019) and Nonthaburi, Thailand (Harada et al., 2015b), respectively. Therefore, the performance of septic tanks was low in most cases.

Septic tanks consist of two or three compartments. The first compartment is often built with two-third of the total tank volume, as the largest portion, giving space for solid accumulation under anaerobic condition. The total volume of septic tanks depends on the available land of the households. Septic tanks are required to have at least 3.0 m³ for a household with two bedrooms according to the Vietnamese National Guideline (MOC, 1999). The average volume of septic tanks in Hanoi and Hai Phong was 2.6 - 3.4 m³ and 1.9 m³ (Pham, 2014; JICA and Nippon Koei, 2019), respectively.

There are no national laws in the collection and treatment of accumulated sludge of septic tanks. The collection of septage was run mainly by the private sector in the urban area of Vietnam. There are limited disposal sites for septage, the collected septage is discharged illegally into the sewer systems, fish farms, and waterways (JICA and Nippon Koei, 2019). However, this business is not controlled by city authorities. Households are not encouraged to empty their

septic tanks regularly. Due to the position and design of septic tanks, households do not prefer to break the floor for septage emptying and willingly pay for emptying activity unless the tanks are clogged and overflowing.

2.2 Greenhouse gas emission from sanitation facilities

2.2.1 Greenhouse gas emissions from the waste sector

In 2010, GHG emissions from the waste sector accounted for 3% of total GHG emissions from all sources (1445 MtCO₂eq) (IPCC, 2014). The emissions from the waste sector were almost double from 1970–2010, while in the period 2000–2010, the increment was 13% (1278 MtCO₂eq vs 1446 MtCO₂eq). It can be explained by the waste generation that is closely related to population, urbanization, and affluence. Waste generation rates are correlated with different indicators of affluence, including GDP per capita, energy consumption per capita, and private final consumption per capita (Monni et al., 2006; Bogner et al., 2008). The main sources of waste GHG emissions were solid waste disposal on land (46% of total waste GHG emissions in 1970 and 43% in 2010) and wastewater handling (51% of total waste GHG emissions in 1970 and 54% in 2010), waste incineration (mainly CO₂) and other sources are of minor importance (JRC/PBL, 2013).

2.2.2 Greenhouse gas emissions from the wastewater handling

Greenhouse gases (i.e., GHGs) can be produced and emitted during wastewater collection, transportation, and treatment depending on technology types, age of facilities, and operating conditions (Bogner et al., 2007). IPCC 2006 guideline provides a GHG emissions inventory method for the wastewater sector focusing on methane (CH₄) based on the proportion of organic matter converted into CH₄. This method can be applied for various wastewater treatment technologies as well as on-site sanitation. According to this approach, anaerobic treatment is a major CH₄ producer (IPCC, 2007).

Regarding onsite sanitation facilities, onsite latrines accounted for nearly 74% of GHG emissions in China; 62% of that in India (USEPA, 2011). In the USA, for example, septic tanks are estimated to be responsible for 65 percent of GHG emissions from domestic wastewater. Furthermore, the increase of on-site sanitation facilities caused substantial GHG emissions.

Therefore, IPCC reconsidered the default emission factors (EFs) for septic tanks and pit latrines from 2000; however, these EFs came from the experimental results of anaerobic digestion at centralized treatment plants in the USA. That caused many challenges in GHG emissions inventory throughout the world (Scheehle, 2001; USEPA, 2011).

2.2.3 Methods for studies screening and reviewing

The review studies on GHG emission from septic systems which relevant documents were searched on Web of Science (<http://webofknowledge.com/>) by using the following keywords: “greenhouse gas” AND “onsite sanitation”; “greenhouse gas” AND “septic system”; “methane” AND “onsite sanitation”; “methane” AND “septic system”; “carbon dioxide” AND “onsite sanitation”; “carbon dioxide” AND “septic system”; “nitrous oxide” AND “onsite sanitation”; “nitrous oxide” AND “septic system”. The collected paper was primarily screened through the titles and abstracts. Then the remaining paper was chosen by reading the main texts. To provide a critical literature review on the EFs for GHGs (CH₄, CO₂, N₂O) from the septic systems, this study categorized the methods of estimation from the previous studies into different categories such as the estimation approaches by default EFs, practical approaches by monitoring in the field or laboratory experiments. By synthesizing existing results in term of GHGs EFs from the septic systems, this paper identified research gaps and influential factors on uncertainties to recommend better GHG emission approaches in further studies.

2.2.4 The available emission factors of septic systems

Currently, GHG emissions were mostly estimated by the EFs from IPCC guidelines 2006 (Bogner et al., 2007). However, when IPCC considered the EFs of onsite sanitation technologies, septic systems and various pit latrines were given attention. Moreover, the estimation from IPCC only focused on CH₄. EFs from IPCC derived from research on GHG emissions of domestic wastewater treatment plants under anaerobic conditions in the USA (IPCC, 2007).

In terms of CO₂, IPCC and EPA guidelines assume it is a biogenic emission as a part of the ecosystem (IPCC, 2007). Thus, CO₂ was not considered widely in GHG emissions studies. However, the substantial CO₂ quantity should be assessed for actual GHG emissions. Moreover, CO₂ emission might usefully participate in carbon mass balance analysis. As regarded by N₂O,

it was most prominent GHGs with the global warming potential of 298 times greater than CO₂ on a 100-year timescale. Moreover, N₂O is also an ozone-depleting substance (IPCC, 2007). Therefore, CO₂ and N₂O were essential to investigate. The GHG emission factors are listed in Table 2.2.

Table 2.2 The summarized GHG emission rates from reviewed studies

Study area	Influent	CH ₄ (g/cap/day)	CO ₂ (g/cap/day)	Notes	References
Septic systems					
		26	-	Estimation by IPCC	IPCC, 2007
		27	-	method	US.EPA, 2011
USA	Black + greywater	39 L-biogas/m ³		CH ₄ :CO ₂ of 75.2%:5.9%	Kinnicut et al., 1910
		11 (σ = 2.2)	33.3 (σ = 2.7)	Onsite measurement by floating chamber, inside septic tank	Leverenz et al., 2010
USA	Black + greywater	11 (σ = 1.7)	335 (σ = 2.1)	Onsite measurement from vent pipe (septic tanks + sand field)	Diaz-Valbuena et al., 2011
		11 (σ = 12)	160 (σ = 3.2)	Onsite measurement from vent pipe	
USA	Black + greywater	0.0072 (σ = 0.047)	120 (σ = 83)	Onsite measurement by static chamber from sand field	Truhlar et al., 2016
Ireland	Black + greywater		155 (σ = 208)	Onsite measurement by static chamber from soak away	Somlai-Haase et al., 2017
Other onsite sanitation facilities					
Japan	Black + greywater	5.03	0.23	Onsite measurement for Johkasou treating domestic wastewater	Ebie et al., 2014
South Africa		3.01 (σ = 0.69)		Laboratory incubation with the assumptions of 50% CH ₄ of biogas composition - Pit latrines	Reid et al., 2014

The methane EFs from IPCC 2006 guideline in Table 2.2 was calculated by the following equation:

$$EF = B_o \times MCF \times BOD \text{ production rate} \quad (\text{Eq. 1})$$

Where: B_o : maximum CH_4 producing capacity, $\text{kg CH}_4/\text{kg COD}$ ($0.25 \text{ kg CH}_4/\text{kg COD}$ or $0.6 \text{ kg CH}_4/\text{kg BOD}$); MCF: methane conversion factor, in case of septic tank, $\text{MCF} = 0.5$; The BOD production rate using in this EF is 85 g-BOD/cap/day .

The existing emission rates were measured for septic systems in developed countries, where septic systems consist of septic tanks and soil absorption fields. Septic systems in these studies received both black and greywater. Firstly, Kinnicut et al. (1910) reported the biogas production from a closed municipal septic tank in the USA as 39 L-biogas/m^3 of treated sewage which ratio of $\text{CH}_4:\text{CO}_2$ of $75.2\%:5.9\%$. Leverenz et al. (2010) and Diaz-Vulbuena et al. (2011) investigated CH_4 , CO_2 and N_2O emissions from eight septic systems in the USA; they figured out that the primary source of CH_4 emissions was septic tanks, soil absorption fields emitted major CO_2 , while N_2O was negligible. In 2016, Truhlar et al., (2016) measured CH_4 and N_2O emissions from roof vent, sand filter and soil absorption fields at eight septic systems in NY, USA. The majority of GHG emissions escaped through the roof vent, the soil absorption field was found to be a negligible source of CO_2 but potentially releases N_2O .

The empirical methane emission factor was approximately half of the IPCC and USEPA factors. The difference was explained by the BOD loading value in IPCC and USEPA approaches. From the study of Diaz-Valbuena et al., (2011), the MCF was proposed to change the methane correction factor (MCF) of IPCC from 0.5 to 0.22. Then, another study applied the MCF is 0.35 – the average of 0.5 of IPCC and 0.22 for their estimation in Ireland GHG emissions inventory from the septic system (Dubber & Gill, 2014).

Regarding other onsite sanitation facilities, the previous studies figured out GHG emission rates from pit latrines and Japanese onsite sanitation facilities, known as Johkasou. Reid et al., (2014) reported that the empirical emission factor of pit latrine in South Africa was $1.10 \pm 0.25 \text{ kg-CH}_4/\text{cap/year}$. This emission factor was estimated according to the biogas production from laboratory incubation with the assumptions of 50% CH_4 of biogas composition and fresh surficial sludge generation rate as 400g/cap/day . Another study estimated N_2O emissions from pit latrines in India by the N_2O conversion factor from nitrate loading resulted from the investigation of the denitrification process in pit latrines (Rao et al., 2015). According to Ebie

et al. (2014), this study reported that the measured CH₄ and N₂O emission factors of Johkasou treating domestic wastewater as 1,835 and 83.1 g/cap/year, respectively.

2.2.5 The uncertainties of the current emission factors

In IPCC estimation, the BOD₅ production rate could influence the uncertainty of the calculation because it could be different for different countries as well as had a wide range for each country. Furthermore, the data availability of BOD₅ is also one of the challenges. Moreover, the Bo calculation from IPCC was estimated from COD and BOD monitored in the centralized treatment plant. Therefore, it was likely to be high uncertainty when IPCC EF was applied on septic systems. IPCC assumed that MCF is 0.5, the maximum value of conversion rate for organic matter (Diaz-Valbuena et al., 2011). Therefore, some studies convinced that IPCC EF estimation seemed to be overestimated (Diaz-Valbuena et al., 2011; Dubber & Gill, 2014; Orner & Mihelcic, 2018).

Although USEPA used IPCC calculation, it changed the BOD₅ value for the USA from 85 to 90 g-BOD/cap/day, where the standard range of BOD₅ for the USA is 50-120 g-BOD/cap/day (IPCC, 2007). Therefore, the EF estimated from USEPA and IPCC was different.

Similarly, Truhlar (2016) and Somlai-Haase (2017) also investigated GHGs EF by using gas analyzers which need periodical monitoring for the samples and uncertainty might come from sample handling. Moreover, Truhlar (2016) and Diaz-Valbuena (2011) sampled in the drained field where GHGs can inhomogeneously distribute (Truhlar et al., 2016). Therefore, the uncertainty could properly rely on choosing a sampling site. Moreover, in the case of developing countries, the drain field is difficult to place in the urban areas, consequently, the EF estimation methods which need to sample at the drain fields are not appropriate.

As mentioned before, not only CH₄ but also CO₂ and N₂O also were considered as major contributors of GHGs in the wastewater sector. However, IPCC and USEPA could estimate only CH₄ while other studies (Diaz-Valbuena et al., 2011; Truhlar et al., 2016) tried to investigate CH₄, CO₂, and N₂O. IPCC, as well as the previous studies, were conducted in developed countries. To the best of our knowledge, there is no study conducted in developing countries. Therefore, there was still high uncertainty to use EF from the previous studies including IPCC to estimate GHG emissions in developing countries. Consequently, this study

recommended the further feasible study in developing countries that can be represented by using convenient and appropriate methods to reduce uncertainty.

2.2.6 The variability of GHG emissions from septic systems

The CO₂ emission from the septic systems could decrease by the hardness of supply water (Diaz-Valbuena et al., 2011) due to calcium carbonate reaction. This study concluded that CO₂ concentration was more sensitive to site-specific conditions more than CH₄ and N₂O.

Truhlar et al., (2016) estimated that the GHG emissions measured from vent pipe were significantly larger than of drain field because of gas diffusion to the environment from the drain field; representing 74 times, 7.6 times, and 1.4 times for CH₄, N₂O, and CO₂, respectively.

Moreover, Diaz-Valbuena et al. (2011) and Truhlar et al. (2016) proposed the N₂O emission can be affected by the microbial community in the environment if the emission was measured at the drain field. Besides, CO₂ emission from the drain field was significantly affected by air and soil temperature (Elmitwalli, 2013).

CH₄ emission can be affected significantly by wastewater temperature in the septic tank in the first year of operation, and slightly affect the CH₄ production process due to the long septage storage period (Elmitwalli, 2013). However, Diaz-Valbuena et al. (2011) mentioned that temperature had no significant impact on CH₄ emissions from septic tanks. Organic loading could play an important role in CH₄ emissions; therefore, organic loading was suggested to investigate for further understanding (Diaz-Valbuena et al., 2011).

2.2.7 Research gaps

- According to the methodology, these two studies in the USA could collect gases from vent pipe or roof vent due to no leakage of gas from septic tanks. However, septic tanks in developing countries have not confirmed gas leakage. Therefore, to monitor GHG emissions from septic tanks under gas leakage situations should be considered.
- Regarding the purpose of septic systems, most septic systems in developing countries receive only blackwater whereas septic systems in developed countries receive black and greywater. The characteristics of blackwater and domestic wastewater are potentially

different, therefore, the organic loading of blackwater might be smaller than those of domestic wastewater. Subsequently, the difference in GHG emissions should be identified.

- The existing studies about GHG emissions from septic tanks have a limited temporal such as Diaz-Valbuena et al. (2011) conducted in September to December, 2009, Truhlar et al. (2016) conducted in June to August, 2014. Therefore, this data was not able to show the seasonal variability of GHG emissions.
- According to the previous studies, they were focused on the impact of physical environmental factors on GHG emissions such as temperature, wind speed. However, the impact of septic tanks conditions as well as the organic loading have not been assessed. Therefore, these influential factors should be investigated and figured out the impact of those to GHG emissions in further studies.

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Proceeding

1. Loi Tan Huynh, Hidenori Harada, Shigeo Fujii, (2018). A review of greenhouse gas emissions from septic systems. Proceeding of the 27th Joint KAIST-KU-NTU-NUS (KKNN) Symposium on Environmental Engineering, Japan (July 5-7).

Chapter 3 : Greenhouse gas emissions from septic systems in Vietnam

3.1. Introduction

Septic systems are one of the major onsite sanitation facilities, used by 1.5 billion people in 2017 (WHO and UNICEF, 2017). They were widely used in urban and peri-urban areas of many developing countries (Sotelo et al., 2019); for example, the proportion of households with septic systems in Hanoi, Vietnam (Brandes et al., 2016), Mandalay, Myanmar (Naing et al., 2020), Kota Surakarta, Indonesia (USAID, 2012), and Kampong Chhnang, Cambodia (Dumpert et al., 2018) are 84%, 90%, 86%, and 79%, respectively. The design of septic systems can change throughout different regions, but they typically consist of a septic tank and a soil absorption field also known as an infiltration field. The main function of a septic system is to treat household wastewater by settling the solids of the influent and accumulating them as a sludge layer at the bottom of the tank (Cairncross and Feachem, 2018). Due to the accumulation of organic matter under anaerobic conditions, septic systems are suspected to produce greenhouse gases (GHGs) including methane (CH_4) and carbon dioxide (CO_2).

The waste sector represented 3% (1,446 $\text{MtCO}_2\text{-eq}$) of global GHG emissions sources in 2010, and the domestic wastewater sub-sector was the most significant contributor, accounting for 54% of this sector's emissions (IPCC, 2014). In 1999, the United States Environmental Protection Agency (USEPA) estimated the global CH_4 emissions from septic systems as 3.0 $\text{Tg-CH}_4/\text{year}$, which accounted for 10.4% of the global CH_4 emissions from domestic wastewater (28.8 $\text{Tg-CH}_4/\text{year}$) (Doorn and Liles, 1999). This result indicated that the emissions from septic systems are not negligible. Based on this estimation, the Intergovernmental Panel on Climate Change (IPCC), in 2007, proposed a CH_4 emission factor of septic systems as 25.5 $\text{g-CH}_4/\text{cap/day}$, which allows the inclusion of GHG emissions from septic systems into global GHG emissions (IPCC, 2007). This emission factor assumed a stoichiometric relationship between total biochemical oxygen demand (BOD) loading in domestic wastewater and CH_4 emission from septic systems, and it is currently used to estimate GHG emissions from the wastewater sector worldwide (UNFCCC, 2019). However, the stoichiometric relationship used in the IPCC emission factor for septic systems was actually derived from an emission rate study of anaerobic lagoons (Doorn et al., 2000), not from septic systems themselves. The information about GHG emissions from septic systems is currently limited, although a large population are using septic systems globally.

Flux chambers, also known as dynamic chambers, have been used to monitor GHG emissions from agricultural soils (Hutchinson and Livingston, 1993; Parkin et al., 2010) and aeration tanks of wastewater treatment plants (Bao et al., 2016; Hwang et al., 2016). Diaz-Valbuena et al. (2011) investigated GHG emissions by using a flux chamber. The obtained emission rates of septic tanks were 11 g-CH₄/cap/day and 0.005 – 0.2 g-N₂O/cap/day, whereas those from infiltration fields were negligible. Truhlar et al. (2016) also measured CH₄ and N₂O emission rates from septic systems in the USA as 11 g-CH₄/cap/day and 0.12 g-N₂O/cap/day, respectively, whereas the levels from infiltration fields were within the range of the background level. The CH₄ emission rates measured by these two studies, which were conducted in the USA, were substantially lower, accounting for only 43% of the IPCC emission factor.

Septic systems in developing countries differ from those in developed countries in terms of design and operating conditions. Typical septic systems in developing countries consist of a septic tank only or a septic tank connected to an underground infiltration tank. They receive only blackwater, which implies a lower influent organic load because septic systems in developed countries receive domestic wastewater including black and greywater. Regarding the operating conditions, septic systems in developing countries were often under low levels of performance and functionality due to improper emptying frequency (UNICEF and WHO, 2019). For example, in Hanoi, Vietnam, the average non-emptying period was 8.1 years, and some households had not emptied the tanks for 20 years, which resulted in poor pollutant removal (Harada et al., 2008). Further, most septic systems in developing countries are located in tropical climates, whereas in developed countries they are mostly under temperate climates. These differences can affect the GHG emissions of septic systems in developing countries, where a majority of septic tanks is used.

Thus, septic systems in developing countries were potentially a significant source of GHGs. However, little is known about the GHG emission from septic systems in developing countries. This study investigated the emission rates of GHGs, namely CH₄, CO₂, and N₂O, from septic systems in Hanoi, Vietnam, which is located in a tropical climate region. Ten septic tanks receiving only blackwater were investigated by on-site monitoring of GHG emissions. As gases leaked from septic tanks through somewhere other than vent pipes, this study applied the floating chamber method for measuring GHG emissions. The influence of septic tank

conditions such as effluent characteristics, sludge compositions, non-emptying period, and HRT were also investigated. To the best of our knowledge, this is the first study to measure and characterize GHG emissions from septic systems in developing countries.

3.2. Materials and methods

3.2.1 Study area

Hanoi, the capital of Vietnam, is located in the northern part of the country, in the Red River delta, and it has a population of 8.05 million (GSO, 2019). Hanoi has a subtropical monsoon climate with a monthly average temperature of 18.1 – 30.8°C (GSO, 2019). Owing to urbanization, wastewater management is a crucial concern. The proportion of household connection to sewer systems in Hanoi was 80 – 90% (WB, 2013). The sewage treatment coverage is limited, approximately 33.4% of the city's population (JICA and Nippon Koei Co., Ltd., 2019). Septic tanks are the main type of on-site sanitation facility in Hanoi as they present in 84% of the households (Brandes et al., 2016).

Typically, most septic systems in Hanoi consist only of septic tanks and receive only blackwater (Nguyen et al., 2007; WB, 2013). Septic tanks are required to have at least 3.0 m³ for a household with two bedrooms according to the national guideline (MOC, 1999). Pham (2014) reported that the average septic tank size in Hanoi was 3.4 ± 1.2 m³ with three compartments, and the average number of users was 5 ($n = 46$). Moreover, the septage storage period was more than 7 years (Harada et al., 2008; Pham, 2014). Therefore, the performance of septic tanks was low in most cases (ISF-UTS and SNV, 2019).

Table 3.1 Characteristics of surveyed septic tanks

ID	Household size	Year of construction	Years since septic tank emptied	No. of septic tank's compartment	Volume of septic tank (m ³)	Volume of 1 st compartment (m ³)
ST1	5	2000	3.9	3	2.6	1.8
ST2	5	2005	10.0	3	1.6	1.0
ST3	4	2005	14.0	3	2.2	1.0
ST4	4	2012	7.0	3	3.2	2.3
ST5	3	2001	18.0	3	2.5	1.6
ST6	4	2000	4.0	2	1.6	1.1
ST7	3	2010	9.0	3	3.0	2.1
ST8	6	2000	19.0	3	2.0	1.3
ST9	5	2005	14.0	3	3.0	2.3
ST10	6	2010	4.0	3	1.4	0.8
Avg	4.5		10.3		2.3	1.5
SD	1.1		5.7		0.7	0.6

3.2.2 Surveyed septic tanks

Ten septic tanks (ST1–ST10) were investigated in the urban area of Hanoi. The characteristics of the surveyed septic tanks are shown in Table 1. The surveyed septic tanks receive only blackwater and the households use cistern-flush toilets with water guns, which are used for cleaning after using the toilet. According to manufacturers' catalog, the water volume per flush is 4.0 – 8.0 L/flush for a big flush, and 2.5 – 3.0 L/flush for a small flush. These septic tanks have two to three compartments. The average effective volume is $2.3 \pm 0.7 \text{ m}^3$ with a septage storage period of 3.9 – 19.0 years. The effluent of these septic tanks is discharged into the sewer system. These septic tanks are in line with previous studies in Hanoi (Pham, 2014). In this study, ST1 and ST2 were used to monitor water flow, septage, effluent, and emitted gas; and ST3 – ST10 were used to monitor septage and emitted gas.

3.2.3 Monitoring of water flow, septage, and effluent

Experimental set up

The experimental set-up used for ST1 and ST2 is shown in Figure 3.1. As septic tanks in developing countries are often suspected for leakage (Crites and Tchobanoglous, 1998; WB, 2013). The present study, therefore, checked the water balance by quantifying the influent and effluent with water flow rate sensors (FD-M5AT, Keyence) installed at the inlet of every toilet water tank including water guns (sensor A), and at the outlet of septic tanks (sensor B).

A temporary tank was installed at the septic tank outlet for effluent online monitoring and sampling. The dimensions of the temporary tank were 200 x 150 x 150 mm (L x W x H; 4.5 L). After passing the water flow rate sensor (B), the effluent was overflowed from the cone ($V = 0.37$ L) to the temporary tank. Electrical conductivity (E.C.) and water temperature were continuously monitored by an E.C. logger (U-24, HOBO). The cone was cleaned several times per day to avoid the settling of solids.

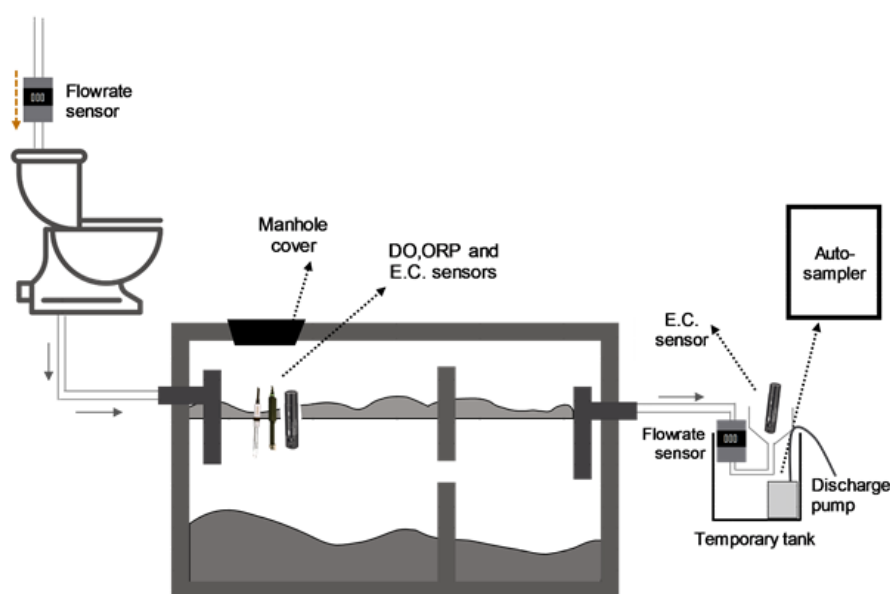


Figure 3.1 Experimental set up in ST1 and ST2

To observe the biochemical reactions inside a septic tank, dissolved oxygen (DO) (HQ30D, HACH-LDO), oxidation-reduction potential (ORP) (9300-10D, HORIBA) and other E.C

sensors (U-24, HOBO) were installed inside the first compartment of the septic tank at 25 cm below water surface, under the manhole cover used for inspection. An auto-sampler with cooling preservation by ice inside the bottle container (3700, Teledyne ISCO) was connected to the temporary tank to collect effluent samples. The sampling tube head of the sampler was submerged to the bottom of the temporary tank.

Effluent samples

Two sampling campaigns of effluent were conducted: daily composite samplings and hourly samplings. Daily composite sampling was performed from June 18 to July 3, 2019 (16 days) for ST1; and from July 13 to July 20, 2019 (7 days) for ST2 during summer season. Hourly samples were obtained on July 5 and 19, 2019 for ST1 and ST2, respectively. For daily composite sampling, 500 ml of effluent wastewater was collected by the auto-sampler at two-hour intervals, and a composite was produced. All samples were kept on ice for transportation to the laboratory.

Septage samples

In this study, septage was defined as the total of bottom sludge, liquid and scum layers in the septic tanks. To avoid changing the conditions inside the septic tanks, the septage sampling was conducted after the gas sampling mentioned below. Septage was sampled by a transparent cylinder equipped with a one-way valve at the bottom which allows only the septage to enter without escape. The cylinder slowly sank into the septage until the bottom. After it was confirmed that the water level in the cylinder was the same as the outside level, the cylinder containing the septage was carefully lifted above the ground. After settling for 30 min, the depths of each layer were recorded. Septage in the cylinder was then collected.

Sample analysis of effluent and septage

At the laboratory, effluent and septage samples were divided into two bottles: with and without acid preservation ($\text{pH} < 2$); and these samples were stored in a refrigerator ($< 4^{\circ}\text{C}$). The water quality of the effluent wastewater was analyzed using standard methods (APHA, 2005) for the following parameters: pH, E.C., BOD₅, suspended solids (SS), volatile suspended solids (VSS),

NO₃-N, NO₂-N, T-P, PO₄-P. COD_{Cr}, T-N, and NH₄-N were analyzed by Hach methods. The dissolved gases in the effluent were analyzed separately, as described in Section 3.2.4.

3.2.4 Monitoring of emitted gas

Gas sample collection

Although there were ventilation pipes in the septic tanks, the gas inside the tanks leaked through somewhere other than the pipes. Flux or floating chambers have been used to measure GHG emissions from isolated surface areas of agricultural soils with an enclosure and fixed volume device (Hutchinson and Livingston, 1993, Parkin et al., 2010), and they have also been used for aeration tanks in wastewater treatment plants (Bao et al., 2015; Hwang et al., 2016) and septic tanks (Diaz-Valbuena et al., 2011). Based on the above-mentioned studies, the floating chamber used in this study was designed, as shown in Figure 3.2. The chamber was constructed from a PVC pipe of 0.15 m diameter and height, and 2.65 L inner volume, inserted in a 0.15 m diameter cap. A sampling tube ($\phi = 5.0$ mm) and a vent pipe ($\phi = 1.5$ mm) were located on top of the chamber. A small fan, used to mix the air, was mounted inside the top of the chamber. Styrofoam was used to keep the chamber floating. To ensure the chamber was airtight, 5.0 mm of the chamber's height was maintained under water.

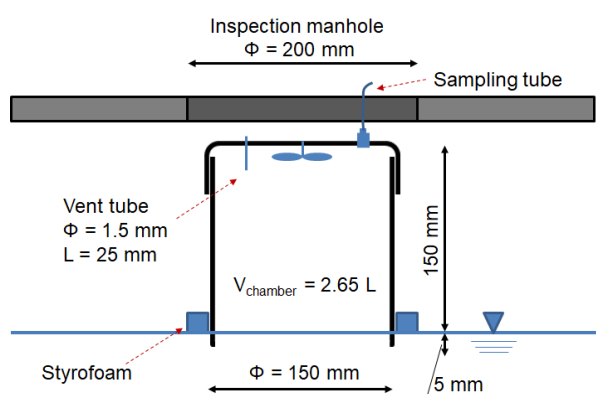


Figure 3.2 Floating chamber design

The floating chamber was inserted on the septage surface in the first compartment of the septic tank through inspection/emptying hole before emptying the septage. Once the chamber was in place, 24 mL of gas were withdrawn from the chamber through the sampling tube connected

by a syringe at 10-min intervals, for 60 min. The fan inside the chamber was activated for 5 sec right before sampling. These gas samples were used to analyze CO₂ and CH₄. At the last sampling (t = 60 min), 12-mL of sample and 1-L were additionally collected; the former was collected by a syringe for N₂O analysis, and the latter by using a pump in a Teflon bag for NH₃ analysis. After the sampling, CO₂, CO, and CH₄ concentrations were analyzed by using a portable gas analyzer (PG300, HORIBA) connected to the chamber for cross-checking. All syringes and Teflon bags with gas were sealed with parafilm and transported on ice to the laboratory. The sample gas was transferred into serum vials, kept in a refrigerator, and analyzed within 24 h. Gas sampling was conducted with a one-week interval for ST1 and ST2. For ST3 to ST10, gas sampling was performed one time. For the dissolved gas analysis, effluent samples were collected directly from the outlet pipes of ST1 and ST2.

Calculation of gas emission

The gas emissions rates (mg/m³-gas/min) were determined based on the flux chamber measurements by plotting $[X]_t$ against time, where $[X]_t$ is the inner gas concentration of the floating chamber (mg/m³) at time t (min). The slope of a linear fit of the data provides the emission rate (mg/m³-gas/min), as shown in Figure 3.3.

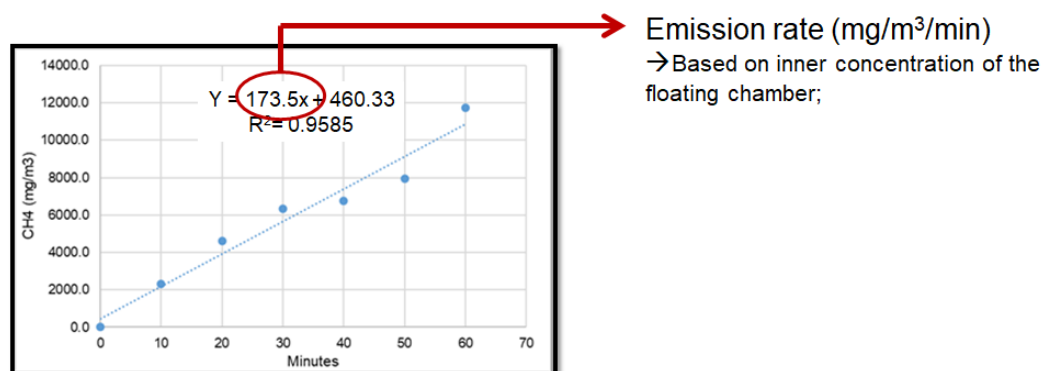


Figure 3.3 An example of linear regression analysis for emission rate based on the increase of inner concentration in the floating chamber

These emissions rates based on the inner concentration of the floating chamber were converted to emission rates per capita (g/cap/day) through Eq. (1):

$$E = \frac{m \times 60 \times 24 \times 10^{-3} \times V_{FC} \times A_{comp}}{A_{FC} \times n} \quad (1)$$

where E is the emission rate per capita (g/cap/day);

m is the emission rate based on the inner concentration of the floating chamber (mg/m³-gas/min);

n is the household size (person);

V_{FC} is the chamber volume (m³) – 2.65L;

A_{comp} is the area of the compartment (m²); and

A_{FC} is the area covered by the floating chamber (m²).

The septic tanks typically used in Hanoi present two or three compartments. The present study monitored the emission from the first compartment, and estimated the emissions from the second and third ones. According to a previous study,¹⁵ the ratio between the emission rates per area from the first and the second compartments was 0.42 and 0.55 for CH₄ and CO₂, respectively. Assuming the same ratio between the first compartment and the second/third compartment in our study, the emission from all compartments was calculated by Eq. (2).

$$E_{Total} = E_{1st} + E_{1st} \times R \times \frac{A_{2nd\&3rd}}{A_{1st}} \quad (2)$$

where E_{Total} is the emission from all compartments (g/cap/day);

E_{1st} is the emission rate from the first compartment (g/cap/day);

R is the ratio between the emission rates per area from the first and the second compartments (-);

$A_{2nd\&3rd}$ is the total area of the second and the third compartments (m²); and

A_{1st} is the area of the first compartment (m²).

Sample analysis

Concentrations of CH₄, CO₂, and N₂O in the collected samples were determined using a gas chromatograph (Shimadzu GC-2014) with a flame ionization detector (FID), thermal conductivity detector (TCD), and electron capture detector (ECD), respectively. The operating temperature of these detectors was 200°C. The retention times for CH₄, CO₂ and N₂O were

5.251, 8.976, and 10.617 min, respectively. The NH_3 concentration was analyzed by the acid absorption method (EPA method 17).

Monitoring gas dissolved in effluent

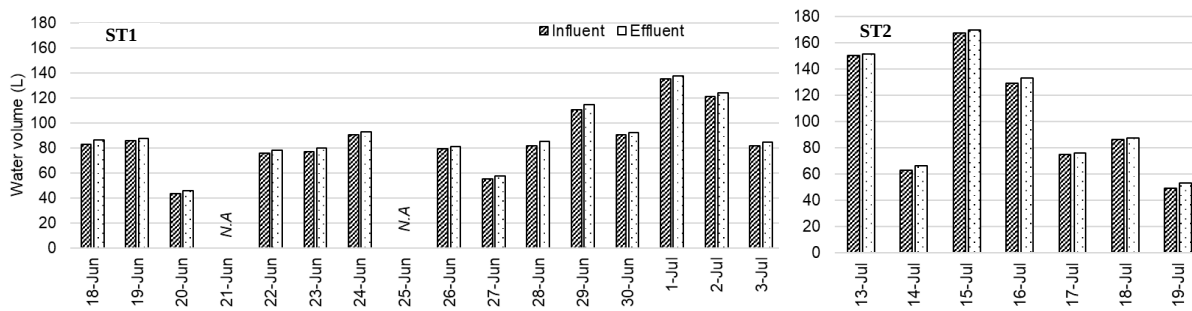
The present study also screened the amount of dissolved gas in the effluent by using a portable gas analyzer. For extracting dissolved gas, the salting-out method of Daelman et al. (2012) was slightly changed. Before each extraction, a serum bottle of 590 mL was filled with 160 g NaCl. Subsequently, the serum bottle was filled with 400 ml of the effluent sample which was collected directly from the outlet pipe of the septic tanks, and the bottle was sealed by a rubber stopper and a plastic cap. The sealed bottle was shaken vigorously to quickly dissolve the salt. The headspace volume was recorded. The CH_4 and CO_2 concentrations in headspace were analyzed by the portable gas analyzer (PG300, HORIBA) by connecting it to the serum bottle. The amounts of CH_4 and CO_2 were determined, and they were completely dissolved into the liquid before the sample was saturated with salt. By dividing their amount for the volume of the sample, the CH_4 and CO_2 concentrations in the liquid were established.

3.3. Results and discussion

3.3.1 Septic tank conditions

Water balance

According to the water volume recorded by the water flow rate sensors in ST1 and ST2, the influent from toilets to septic tanks was 92.1 ± 32.6 L/day (18.4 ± 6.5 L/cap/day; Avg $\pm$ SD), which is similar to a previous survey that reported 18.6 L/cap/day in Hanoi (Otaki et al., 2013). The effluent, which was monitored at the outlet of septic tanks, was 94.6 ± 32.5 L/day (18.9 ± 6.5 L/cap/day). Accordingly, the ratio between influent and effluent was 0.95–0.98. This small gap between influent and effluent flows can represent the volume of human waste, we concluded that these two septic tanks presented no water leakage, as shown in Figure 3.4. Excluding the volume of bottom sludge layers, the hydraulic retention times (HRTs) based on the effective volume of the septic tanks was 17.1 and 5.2 days for ST1 and ST2, respectively. The great difference between these HRTs stemmed from the different effective volume of the septic tanks (1.42 m^3 for ST1 and 0.47 m^3 for ST2).



Note: N.A = Not available

Figure 3.4 Influent and effluent wastewater volume of ST1 and ST2.

Effluent and septage composition

The effluent characteristics and pollutant loadings of ST1 and ST2 are summarized in Table 3.2. The average COD, BOD₅, and SS concentrations of ST1 were 564, 389 and 39 mg/L, whereas those of ST2 were 803, 544 and 173 mg/L, respectively. Higher pollutant concentrations in the effluent of ST2 could be explained by the longer septage storage period and shorter HRTs in ST2 compared to ST1. Despite these differences, these obtained values are within the range presented by Pham (2014) and JICA and Nippon Koei Co., Ltd. (2019). Similar to previous studies (Crites and Tchobanoglous, 1998; JICA and Nippon Koei, 2019), NH₄-N accounted for a major part of nitrogen in the effluent, thus indicating that nitrification was not a dominant process in the septic tanks.

Table 3.3 shows the septage composition of ST1 – ST10. The surveyed septic tanks were under anaerobic conditions as clearly indicated by DO (0.02 – 0.34 mg/L) and ORP (–230 to –489 mV). Moreover, pH (7.21 – 7.99) and liquid temperature (30.6 – 31.7 °C) of these septic tanks were within the range for optimum mesophilic anaerobic digestion (neutral pH; 25 – 35 °C) (Tchobanoglous et al., 2003). The septage composition in the present study was comparable to Pham (2014) and Gold et al. (2017). Similar to the effluent, NH₄-N (172 – 584 mg/L) was a major form of nitrogen in the septage, again indicating that nitrification was not a dominant process in the septic tanks. The average HRT for ST1 and ST2 was 13.1 days, HRT was investigated only for ST1 and ST2 due to the time limitation and difficulty in setting up water flow rate sensors.

Table 3.2 Effluent characteristics of ST1 and ST2

Items	ST1	ST2	ST1	ST2	Crites & Tchobanoglous (1998) Conc, mg/L	Pham, 2014 (Vietnam) Conc, mg/L	JICA and Nippon Koei, 2019 (Vietnam) Conc, mg/L
	Conc, mg/L		Loading, g/cap/day				
pH	7.5 ± 0.2	7.7 ± 0.2				6.9 - 8.8	6.0 - 8.0
E.C. (mS/cm)	3.0 ± 0.1	2.8 ± 0.1					
COD _{Cr}	564 ± 28	803 ± 12	10.2 ± 3.2	16.9 ± 7.3	250 - 500	91 - 3525	173 - 2112
BOD ₅	389 ± 29	544 ± 25	7.0 ± 2.3	11.4 ± 4.8	150 - 250	60 - 2350	96 - 1259
SS	39 ± 4	173 ± 7	0.7 ± 0.3	3.7 ± 1.6	40 - 140	12 - 2030	53 - 1447
VSS	31 ± 4	148 ± 2	0.6 ± 0.2	3.1 ± 1.4	-	-	-
T-N	356 ± 23	370 ± 10	6.4 ± 1.8	7.8 ± 3.4	50 - 90*	1.3 - 691.6*	77 - 483
NH ₄ -N	261 ± 17	286 ± 7	4.7 ± 1.3	6.0 ± 2.6	30 - 50	-	49 - 174
T-P	32 ± 4	36 ± 5	0.6 ± 0.2	0.8 ± 0.4	20 - 12	0.9 - 145.5	24 - 110

Note: average ± standard deviation; *: TKN.

Table 3.3 Septage composition and of ST1 – ST10

Parameters		This study	Pham, 2014 (Vietnam)	Gold et al., 2017 (Vietnam)
Liquid temperature	°C	31.1 ± 0.4	-	-
COD _{cr} septage	mg/L	12,328 ± 4,900	20,290 ± 15,200	24,900 ± 14,200
COD _{cr} mass of septage	g/tank	18,256 ± 9,190	-	-
BOD ₅ septage	mg/L	8,956 ± 4,216	13,290 ± 9,300	-
BOD ₅ mass of septage	g/tank	13,856 ± 8,485	-	-
COD _{cr} supernatant	mg/L	1,035 ± 390	-	-
SS	mg/L	7,729 ± 1,652	14,420 ± 11,800	-
VSS	mg/L	5,752 ± 1,577	13,070 ± 11,430	-
T-N	mg/L	1,458 ± 664	297.6 ± 267.0 ³	-
NH ₄ -N	mg/L	370 ± 148	-	184 ± 77
T-P	mg/L	305 ± 172	153.8 ± 284.6	-
DO	mg/L	0.15 ± 0.11	-	-
ORP ¹	mV	-373 ± 88	-	-
HRT ²	day	13.1 ± 7.2	-	-
Septage storage period	year	14	10.2	-

Note: Numbers show average ± standard deviation except septage storage period that shows only median;

¹ORP_{SHE} (mV) = ORP + 206 - 0.7(*t* - 25), *t* is temperature (°C); ²HRT of ST1 and ST2; ³TKN.

3.3.2 Nitrogen and carbon gas concentrations

The emitted gases were monitored for ST1–ST10 based on the floating chamber method. Inner CH₄, and CO₂ concentrations of the chamber were plotted against time for each septic tank, and a linear regression analysis was conducted. The *R*² values of the regression analysis for ST1–ST10 were within 0.93–0.99, thus indicating that inner gas concentrations successfully increased and there was no unexpected leakage inside the floating chamber during the 60-min monitoring. The concentrations of CH₄, CO₂, CO, N₂O, and NH₃ accumulated in the floating chamber at *t* = 60 min are shown in Table 3.4. The accumulated CH₄ and CO₂ concentrations were 6,537–25,579 and 4,577–13,541 ppm, respectively. In contrast, CO, NH₃, and N₂O were at negligible levels. CO concentration was approximately similar to ambient concentration, NH₃ concentration was almost less than 0.5 ppm, and N₂O concentration was smaller than 1.0 ppm.

N₂O concentration was comparable to a previous study on septic tanks in the USA (Diaz-Valbuena et al., 2011). Due to this negligible concentration, the following discussion excludes CO, NH₃ and N₂O.

Table 3.4 Average concentrations of CH₄, CO₂, CO, N₂O, and NH₃ accumulated in the floating chamber at t = 60 min.

	CH ₄	CO ₂	CO	N ₂ O	NH ₃
	ppm	ppm	ppm	ppm	ppm
Avg.	14,516	8,881	0.3	0.6	0.4
SD.	5,202	2,870	0.5	0.3	0.5
Range	6,537 – 25,579	4,577 – 13,541	0 - 1	<0.1 - 1.015	<0.5 - 1.87

3.3.3 CH₄ and CO₂ emission rates

Based on the slope of increasing gas concentration in the floating chamber, CH₄ and CO₂ emission rates per capita from septic tanks were calculated according to Eq. 2. As shown in Figure 3.5, the CH₄ and CO₂ emissions from septic tanks were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day (Avg $\pm$ SD), respectively. Coefficients of variation and ratio between maximum and minimum were 34.4% and 3.8 for CH₄, and 40.0% and 4.0 for CO₂, respectively. These results indicate a large variability of GHG emissions from individual septic tanks, which is potentially reflected by the large variability of inside conditions of septic tanks, as summarized in Table 3.2. The average C-CO₂:C-CH₄ ratio in this study was 0.38:0.62. Assuming the substrates inside septic tanks can be represented by C₆H₁₂O₄ or C₆H₁₂O₆, the theoretical ratio of C-CO₂:C-CH₄ for anaerobic digestion is 0.4:0.6 or 0.5:0.5, respectively (Tchobanoglous et al., 2003). Therefore, the ratio in this study is in line with theoretical ratios, which indicates that organics in septic tanks were mainly decomposed by anaerobic digestion.

The CH₄ emission rates obtained in this study were compared to other emission values from previous studies, as shown Table 3.5. The obtained CH₄ emission rates of this study were equivalent to or even larger than those obtained for the USA by Diaz-Valbuena et al. (2011) and Truhlar et al. (2016) (11 g/cap/day), and they were nearly half the IPCC (25.5 g/cap/day, $p = 0.03964$, IPCC, 2007) and USEPA (27.1 g/cap/day, $p = 0.0224$, USEPA, 2010) emission

factors. The potential reasons for these significant differences and the variability within our samples are discussed in Section 3.4.

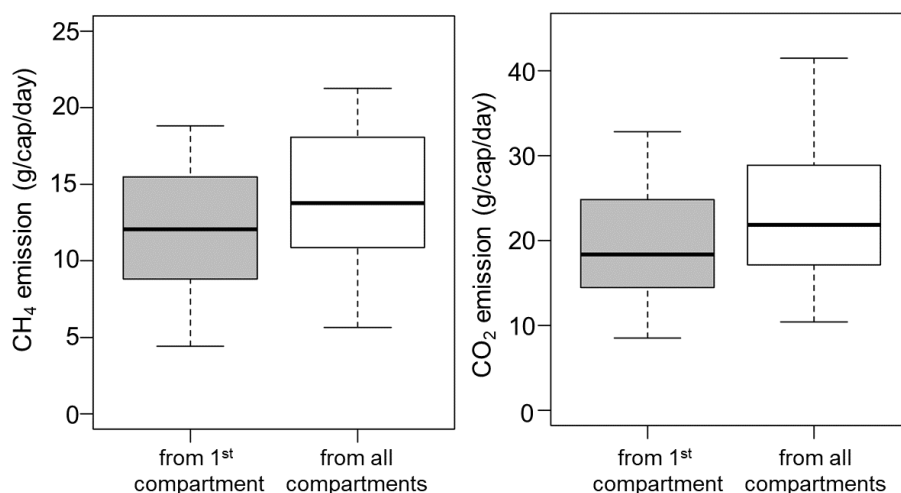


Figure 3.5 CH₄ and CO₂ emission rates from blackwater septic tanks in Hanoi (boxplots indicate the median and interquartile ranges (IQRs) with whiskers extend up to $1.5 \times \text{IQR}$ (IQR from the median)).

Among ten surveyed septic tanks, effluent was collected from ST1 and ST2, for which dissolved CH₄ in the effluent was monitored with effluent flow rate. The average dissolved CH₄ concentration was 0.22 mg/L for ST1 and ST2. Based on the solubility of CH₄ in distilled water (0.0009 mg/L) (Lewin et al., 1990), CH₄ was oversaturated in the effluent by 24,444% to enable comparison with other anaerobic digestion studies in lagoons (260 - 128,420% of saturation) (Koné et al., 2010) and septic tanks (325,000% saturation) (Leverenz et al., 2010). According to the flow rate of the effluent, 18.9 L/cap/day for ST1 and ST2, this dissolved CH₄ concentration was converted to discharged CH₄ rate in the effluent, at 3.68 mg-dissolved/cap/day. These dissolved CH₄ in the effluent accounted for only 0.03 and 0.04% of the total CH₄ emitted and discharged in the effluent of ST1 and ST2, respectively. Therefore, the amount of dissolved CH₄ was negligible, although dissolved CH₄ is potentially emitted to the atmosphere after the effluent is discharged to the environment. Further digestion and CH₄ emission might occur after the effluent is discharged to the environment. However, this was not included in the scope of the present study.

Table 3.5 CH₄ and CO₂ emission rates of septic tanks from the present study and previous studies

Study area	Influent of septic tanks	CH ₄ (g/cap/day)	CO ₂ (g/cap/day)	Notes	References
Hanoi, Vietnam	Blackwater	11.11 ($\sigma = 1.53$)	17.97 ($\sigma = 1.50$)	Geometric mean and (σ) standard deviation; Onsite measurement by the floating chamber, inside 1 st compartments of septic tanks	This study
		13.01 ($\sigma = 1.49$)	21.99 ($\sigma = 1.50$)	Geometric mean and standard deviation; from all compartments	
		11.96 ($\sigma = 4.33$)	19.30 ($\sigma = 7.27$)	Arithmetic mean and standard deviation; Onsite measurement by the floating chamber, inside 1 st compartments of septic tanks	
		13.89 ($\sigma = 4.78$)	23.69 ($\sigma = 9.48$)	Arithmetic mean and standard deviation; from all compartments	
		25.5	-	Estimation by IPCC method	
USA	Black + greywater	27.1	-		USEPA, 2010
		11.0 ($\sigma = 2.2$)	33.3 ($\sigma = 2.7$)	Geometric mean and standard deviation; Onsite measurement by the floating chamber, inside septic tanks	Diaz-Valbuena et al., 2011
		10.7 ($\sigma = 1.7$)	335 ($\sigma = 2.1$)	Geometric mean and standard deviation; Onsite measurement from vent pipe	
USA	Black + greywater	11.0 ($\sigma = 12$)	160 ($\sigma = 3.2$)	Onsite measurement from vent pipe	Truhlar et al., 2016
		0.0072 ($\sigma = 0.047$)	120 ($\sigma = 83$)	Onsite measurement by static chamber from sand field	

Considering the population using septic tanks in Hanoi (8.002 million), the CH₄ emission from all septic tanks in Hanoi was calculated as 40.59 kt-CH₄/year based on the average emission factor of this study (13.89 g/cap/day). This CH₄ emission was converted to CO₂-equivalent at 1,014.8 ktCO₂-eq/year, following IPCC (1995). In Hanoi, GHG emissions (focus on CH₄ emission) from several major sectors were reported as 525 ktCO₂-eq/year for livestock (Truong et al., 2018), 1,700 ktCO₂-eq/year for paddy fields (Pandey et al., 2014), and 2,973 ktCO₂-eq/year for landfills for municipal solid waste (Thanh et al., 2015), as shown in Figure 3.6.

Therefore, based on those emissions, septic tanks can be considered a major source of GHG emissions in Hanoi.

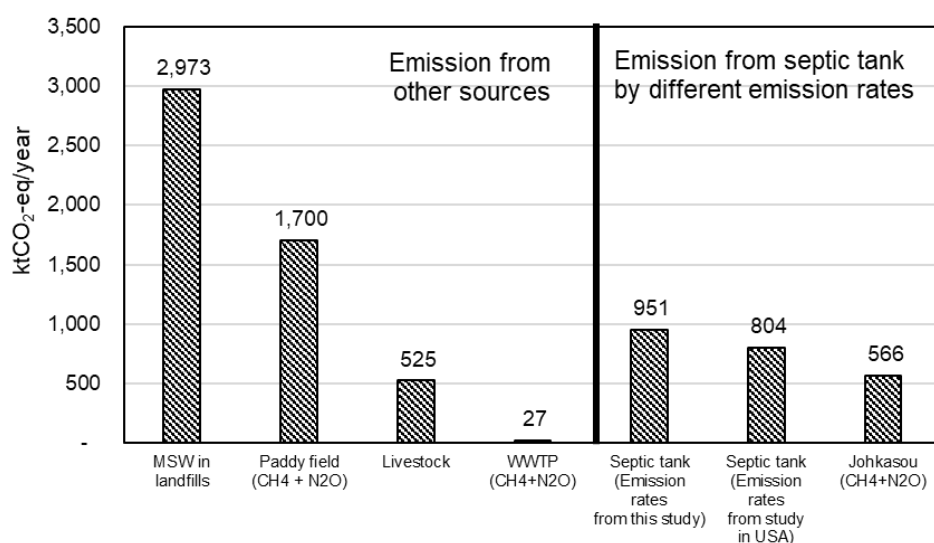


Figure 3.6 The CH₄ emissions from several sectors in Hanoi (ktCO₂-eq/year).

3.3.4 Variability in methane emission

Methane emissions can be affected by the conditions inside the septic tanks. As shown in Table 3.2, liquid temperature, ORP, DO, and septage COD mass of the septic tanks surveyed in this study were 30.6 – 31.7 °C, -434 to -237 mV, 0.025 – 0.340 mg/l, and 5,110 – 34,822 g/tank, respectively. The obtained ORP values were comparable to the operational ORP range for sewage sludge fermentation (-200 to -500 mV) (WEF, 2005). Regardless of poor operational conditions such as unscheduled septage emptying (3.9 – 19.0 years), low ORP and high COD amount of septage, the inside conditions of septic tanks in this study were suitable for anaerobic digestion with high accumulated organic.

The CH₄ emission rates were correlated with septage composition. Among 12 parameters, ORP, DO, BOD, and COD presented significant correlation with CH₄ emissions, with *R* values of -0.68 (*p* = 0.015), -0.55 (*p* = 0.064), 0.65 (*p* = 0.023), and 0.71 (*p* = 0.0098), respectively, as shown in Figure 3.7. These correlations indicate that lower ORP and DO, and higher biodegradable carbon mass (indicated by BOD or COD mass) in association with longer septage storage period are key conditions for the emission of CH₄ from septic tanks.

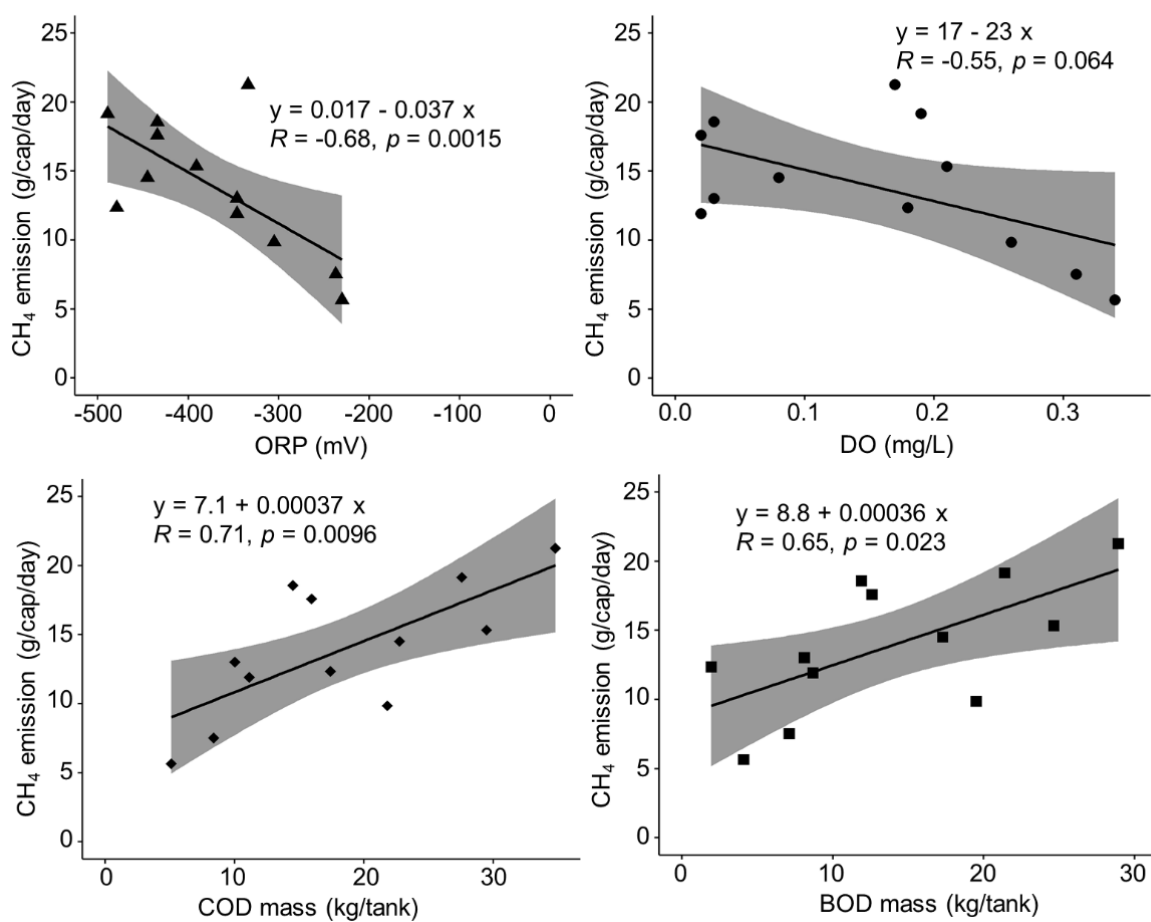


Figure 3.7 Correlation between CH₄ emission rate and ORP, DO, septage's COD mass, and BOD mass of septic tanks in Hanoi. Black lines show linear trend and gray zones show confidence interval.

The changes of ORP, DO, COD mass and BOD mass can be partly explained by the septage storage period, as shown in Figure 3.8. Septage storage period was strongly correlated with ORP ($R = -0.82$, $p = 0.0012$) and moderately correlated with COD mass of septage ($R = 0.65$, $p = 0.022$), whereas septage storage was not significantly correlated with DO ($R = -0.12$, $p = 0.7$) or BOD mass ($R = 0.43$, $p = 0.16$). These correlations indicate that, the longer septage is stored, the more COD accumulates under highly reduced conditions, possibly causing a positive impact on CH₄ production.

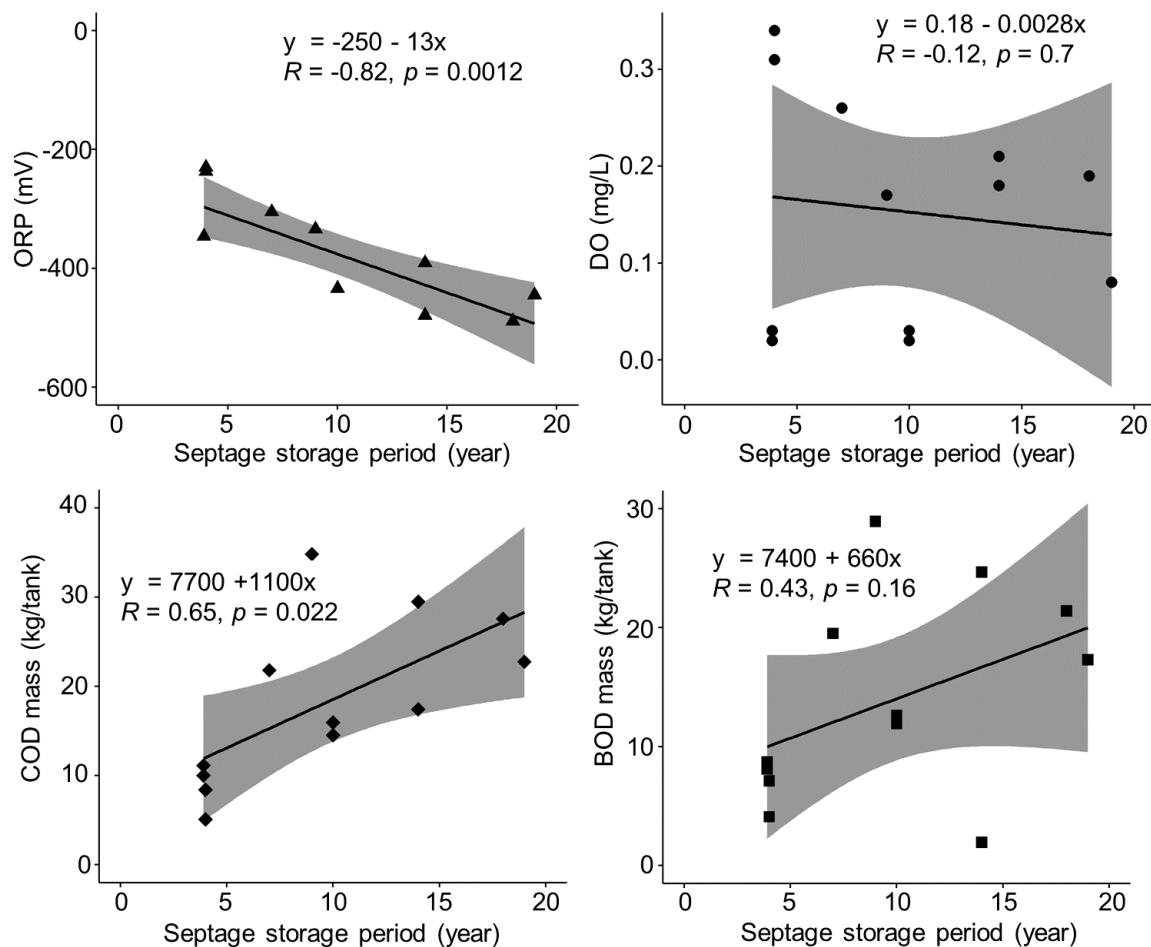


Figure 3.8 Correlation between septage storage period (years) and ORP (mV), DO (mg/l), and COD and BOD mass of septage (g/tank). Black lines show linear trend and gray zones show confidence interval.

The correlation between emission rate and storage period was not significant ($R = 0.54$, $p = 0.068$) as the storage periods were classified into two groups. CH_4 emission rates from septic tanks with longer storage periods (more than 7 years) were significantly higher than those from septic tanks with shorter storage periods (less than 7 years) ($p = 0.002$, t-test) as shown in Figure 3.9. Together with the correlation between septage composition and storage period, this result implies that longer storage periods lead to larger CH_4 emissions. The storage period of septic tanks in South East Asia were long in many cases: for example, 6.2 – 14.2 years in Hanoi (Harada et al., 2008; Pham, 2014), and 12.7 years in Mandalay, Myanmar (Naing et al., 2020). More than 90 and 54% of households did not regularly empty their septic tanks in Kalianda, Indonesia (ISF-UTS and SNV, 2019) and Nonthaburi, Thailand (Harada et al., 2015),

respectively. These poor operating conditions, especially no regular emptying, primarily deteriorate the removal efficiency of organic pollutants. Furthermore, they would increase CH₄ emissions. In other words, if septic tanks are regularly emptied, they will present improved pollutant removal and reduced GHG emissions.

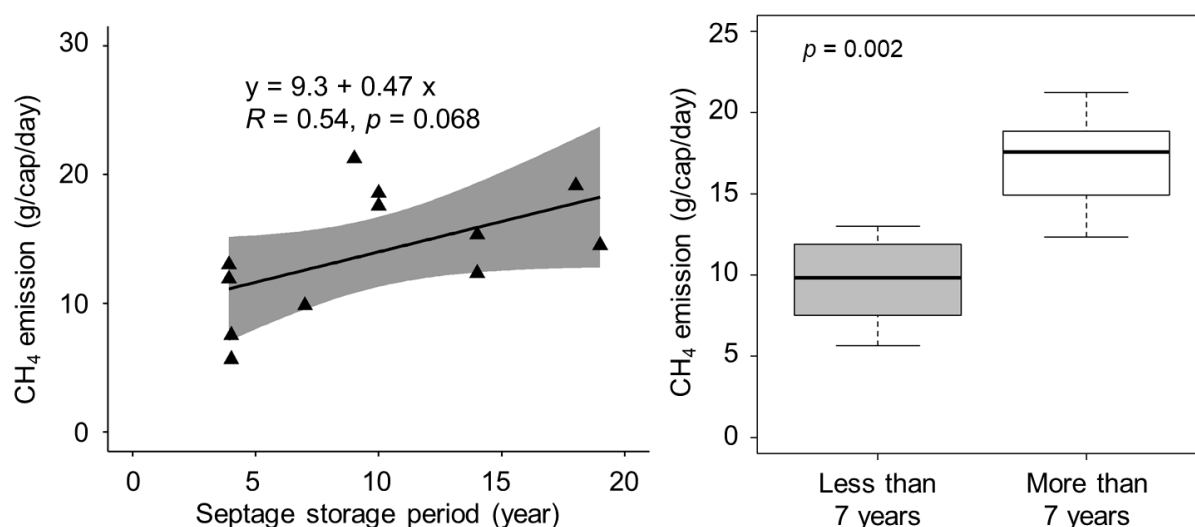


Figure 3.9 CH₄ emission rates for shorter (less than 7 years) and longer (more than 7 years) storage periods. Black line shows linear trend and gray zone shows confidence interval; and boxplots indicate the median and IQRs with whiskers extend up to $1.5 \times \text{IQR}$.

The CH₄ emission rates in this study was equivalent to or even larger than Diaz-Valbuena et al. (2011) in the USA (11 ± 2.2 g/cap/day). A notable difference between the septic tanks from the USA and Hanoi is the type of influent: the former received domestic water including black and greywater, whereas the latter received only blackwater. This difference likely caused the greater organic loading input to the septic tanks in the USA compared to those in Hanoi. However, the comparable or even larger CH₄ emission rate in this study can be explained by the different conditions inside the septic tanks, as shown in Figure 3.10. ORP in this study was significantly lower ($p < 0.001$), and liquid temperature ($p < 0.001$) and COD concentration of liquid layer ($p < 0.001$) were significantly higher in the present study. Therefore, these conditions of this study may have contributed to a larger CH₄ production. However, liquid temperature was not significantly correlated to CH₄ emission rates (Diaz-Valbuena et al., 2011). These conditions in the septic tanks could be caused by long septage storage conditions, long HRTs and high ambient temperature. The median septage storage period, average HRT, and ambient

temperature in this study were 9.5 years, 13.1 days (only ST1 and ST2) and 34 – 39 °C, respectively, whereas those in Diaz-Valbuena et al. (2011) were 6.5 years, 8.5 days, 6 – 20 °C. Therefore, the more suitable conditions inside septic tanks potentially caused the equivalent and larger emission from blackwater septic tanks in this study than those from domestic-wastewater septic tanks in Diaz-Valbuena et al. (2011). These results indicate that the emission rate per unit organic loading of this study is potentially higher despite the lack of influent organic loading values for Diaz-Valbuena et al. (2011) and the present study.

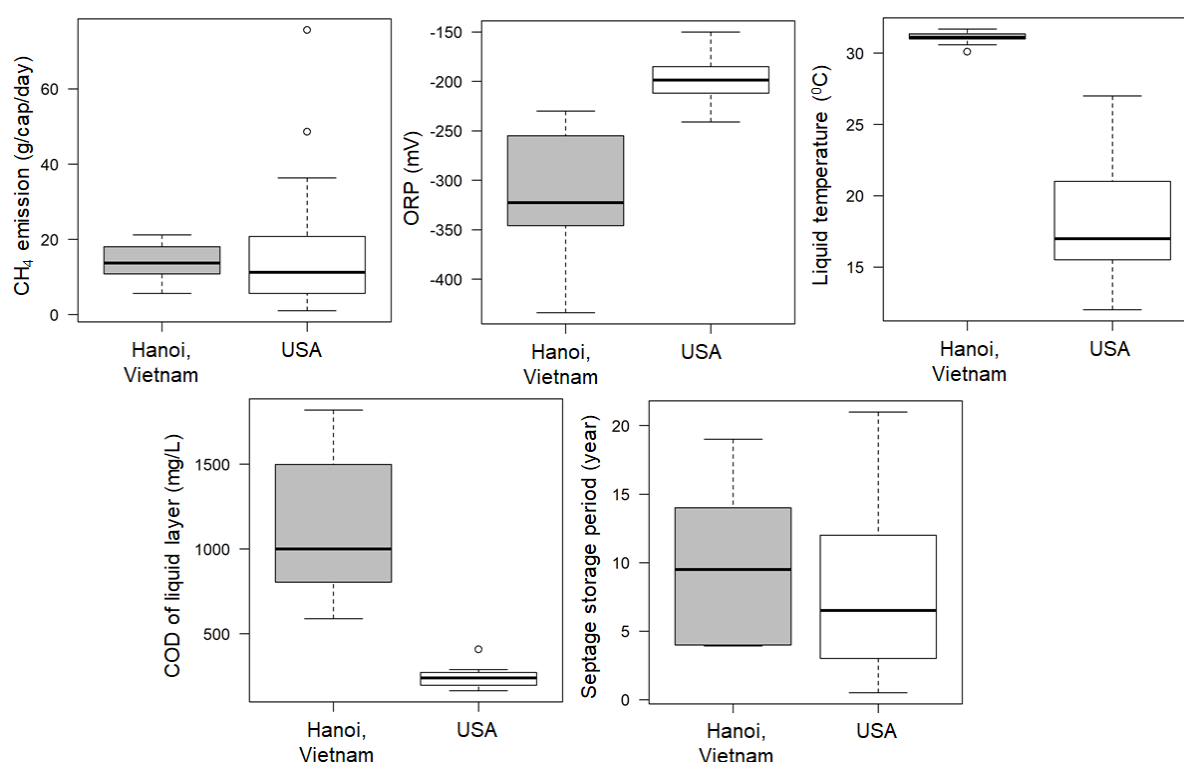


Figure 3.10 Septic system parameters of this study and of Diaz-Valbuena et al. (2011) in the USA: CH₄ emission rate, liquid temperature, ORP, COD concentration of liquid layer, and septage storage periods. Boxplots indicate the median and IQRs with whiskers extend up to 1.5 × IQR.

The IPCC emission factors are presented as per-capita (25.5 g-CH₄/cap/day) and per-BOD-removed (0.6 g-CH₄/g-BOD) (IPCC, 2007). The CH₄ emission rate obtained in this study was 13.89 g-CH₄/cap/day, almost half of the IPCC's value. The IPCC emission factors were originally estimated as per BOD-removed emission factors, and then converted to per-capita emission factors based on an 85 g/cap/day BOD loading of domestic wastewater into an

anaerobic tank and a 50% BOD removal. However, as previously mentioned septic tanks in Hanoi and in most South East Asia regions received only blackwater. Previous studies reported BOD loading of blackwater or excreta as 11.2 g/cap/day (JICA and Nippon Koei, 2019) and 45 g/cap/day (Montangero and Strauss, 2002). Although the reported values have a large gap, they are still much smaller than the BOD loading used for the IPCC per-capita emission factor. Furthermore, in Hanoi, BOD removal efficiency of septic tanks changes significantly according to the septage storage period (Harada et al., 2008). Long storage periods might result in removal efficiency 50% lower than those used by IPCC (2007) to convert emission factors. Although this study did not obtain influent loading and BOD removal values, these factors might cause around 2 times difference between this study and IPCC (2007). Further studies are required to investigate the correlation between BOD loading and removal, and emission rates.

3.4. Conclusions

The present study studied GHG emissions from septic systems in developing countries that receive only blackwater, under tropical climate. We investigated the CH₄, CO₂ and N₂O emissions from ten septic systems in Hanoi, Vietnam by installing floating chambers into septic tanks, in association with septic tank conditions. The measured CH₄ and CO₂ emission rates were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day, respectively, whereas those of N₂O were at the negligible levels. To the best of our knowledge, this is the first study to directly measure GHGs emission from septic systems in developing countries. CH₄ emission rates were significantly negatively correlated with septage ORP and DO, and positively correlated with septage COD mass and BOD mass. Further, the CH₄ emission rates from septic systems with longer storage periods (more than 7 years) were significantly higher than those from septic systems with shorter storage periods (less than 7 years). Moreover, the storage periods were negatively correlated with ORP and DO, and positively correlated with COD mass and BOD mass. These results suggest that lower ORP and DO, and higher biodegradable carbon mass in association with longer septage storage periods are key conditions for CH₄ emissions from septic systems. Therefore, controlled or regular septage emptying could contribute to improve not only the removal efficiency of septic systems but also its GHG mitigation capability. Thus, our results will contribute to estimate global GHGs emissions from septic tanks in developing countries and be essential information for mitigating the emission.

The CH₄ emission rates of this study were equivalent to or even larger than those of previous studies which measured the emission rates in the USA. Beside the influent difference between septic systems in the USA (black and greywater) and septic systems in our study (only blackwater), the equivalent or even larger CH₄ emission rates of the present study could be attributed to significant difference such as lower ORP, higher COD concentration, and longer HRT and septage storage periods. In contrast, the emission rate in this study was significantly smaller (nearly half) than the IPCC emission factor. As the IPCC emission factor is based on the correlation between removed BOD and produced CH₄, this difference can be potentially explained by the difference of influent BOD loading and removal efficiency although this study did not monitor the influent loadings.

This study presents some limitations, such as the above-mentioned lack of monitoring of influent organic loading due to the difficulty in sampling. Therefore, for a more detailed comparison with the IPCC emission factor, the emission rates should be associated with influent loadings in future studies. Moreover, the present study was conducted only in summer, and the seasonal variability might affect the GHG emissions of septic systems. As the design and operating conditions of septic systems vary according to regions and there are other types of anaerobic on-site sanitation technologies in developing countries, GHG emission rates should be studied in different regions with different technologies for a broader understanding of GHG emission from onsite sanitation in the world. Nevertheless, our successful measurement of GHGs emissions rates contributes to the society by providing the first monitoring data of GHGs from septic systems in developing countries.

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Publications

Reviewed paper

1. Loi Tan Huynh, Hidenori Harada, Shigeo Fujii, Lien Nguyen Pham Hong, Thu-Huong Thi Hoang, Hai Trung Huynh (2020). Greenhouse gas emissions from blackwater septic systems. *Environmental Science and Technology* (Under reviewed).

Proceeding

1. Loi Tan Huynh, Hidenori Harada, Shigeo Fujii, Lien Nguyen Pham Hong (2020). Evaluation of Greenhouse Gas Emission from Septic Tank under Tropical Climate: A Case Study in Hanoi, Vietnam. Proceeding of the 54th Annual Conference of Japan Society on Water Environment, (March 16 - 18).

Chapter 4 : Seasonal variability in GHG emissions and C/N/P removals of blackwater septic systems

4.1. Introduction

Globally, 3.1 billion people rely on onsite sanitation, and this number is expected to grow to 5 billion by 2030 (Strande et al., 2014, WHO and UNICEF, 2017). Septic systems are one of the major on-site sanitation facilities. The population used septic systems was increased from 0.8 to 1.5 billion people between 2000 and 2017 (WHO and UNICEF, 2017). The main function of a septic system is to separate the solids of the influent and accumulating them as a sludge layer at the bottom of the tank under the anaerobic condition (Cairncross and Feachem, 2018). Septic systems were confirmed that they produce greenhouse gases, as shown in Chapter 3.

The CH₄ production under anaerobic conditions was affected by temperature. At low temperature, the degradation of organic matter was at slower reaction rates (Tchobanoglous et al., 2003). Therefore, the seasonal variation of temperature had a potential impact on GHG emissions from septic systems. However, the existing studies about GHG emissions from septic tanks have a limited sampling period. Diaz-Valbuena et al. (2011) monitored GHG emissions in the period of September – December, 2009; and Truhlar et al. (2016) conducted the monitoring from June to August, 2014. These studies were not able to show the seasonal variability of GHG emissions from septic systems.

According to the lack of information about seasonal variability of GHG emissions from septic systems, this study investigated the CH₄, CO₂, and N₂O emissions from blackwater septic systems in summer and winter in Hanoi, Vietnam. Chapter 3 presented the GHG emissions from ten septic systems in the summer. Fifteen septic systems receiving blackwater were monitored GHG emissions in winter by the floating chamber method. Together with GHG emissions, the performance of septic systems in C, N, P removals was also evaluated.

4.2. Materials and methods

4.2.1 Study area

Hanoi is the capital city of Vietnam, located in the Red River Delta. Hanoi has a subtropical monsoon climate with four different seasons as spring (from March to May), summer (from May to September), autumn (from September to November) and winter (from November to March) which classified by weather conditions and temperature. The present study was conducted in summer and winter in Hanoi. During the sampling period, the temperature in summer and winter in Hanoi was 26 – 33°C and 14 – 19°C, respectively. Summer and winter seasons in Hanoi are corresponding to rain and rainy seasons. The rainfalls in summer and winter were 188.5 – 427.8 mm and 8.3 – 89.4 mm (GSO, 2019), respectively.

4.2.2 Surveyed septic tanks

The monitoring was done at twenty-five septic tanks in the urban area of Hanoi in summer (June – July 2019) and winter (December 2019 – January 2020). Ten septic tanks (ST1 – ST10) were monitored in summer and 15 septic tanks (ST1, ST2, ST11 – ST23) in winter. Ten septic tanks monitored in summer were mentioned in Chapter 3. ST1 and ST2 were monitored for both seasons.

The characteristics of 25 septic tanks are shown in Table 4.1. These surveyed septic tanks receive only blackwater. These households have 1 to 3 toilets and use cistern-flush toilets with water guns. These septic tanks consist of 2 – 3 compartments with the effective volume are $2.1 \pm 0.9 \text{ m}^3$, and the septage storage period is 11.7 ± 6.5 years. The effluent of these septic tanks is discharged into the sewer system. In this study, ST1 and ST2 were used the same purpose with chapter 3, including monitor water flow, septage, influent, effluent, and emitted gas; and ST11 – ST23 (winter septic tanks) were used to monitor influent, effluent, septage, and emitted gas.

Table 4.1 Characteristics of surveyed septic tanks in the summer and winter surveys in Hanoi

Items	Summer (<i>n</i> = 10)	Winter (<i>n</i> = 15)	Average (<i>n</i> = 25)
Household size (people)	4.5 ± 1.1	4.3 ± 0.8	4.4 ± 0.9
Year since septic tank emptied (year)	10.3 ± 5.7	12.6 ± 7.0	11.7 ± 6.5
Septic tank volume (m ³)	2.3 ± 0.7	2.0 ± 1.1	2.1 ± 0.9
The first compartment volume (m ³)	1.5 ± 0.6	1.1 ± 0.7	1.3 ± 0.7

Note: Average ± Standard deviation

4.2.3 Monitoring of water flow, septage, influent and effluent

Experimental set up

The experiment set-up used for ST1 and ST2 is mentioned in section 3.2.3 (Chapter 3). The water flow was monitored by flow rate sensors (FD-M5AT, Keyence). Electrical conductivity (E.C.) and water temperature were continuously monitored by an E.C. logger (U-24, HOBO) which was located in the temporary tank collected effluent of ST1 and ST2. Other sensors such as DO (HQ30D, HACH-LDO), ORP (9300-10D, HORIBA), and other E.C sensors (U-24, HOBO) were installed in the first compartment to observe biochemical reaction inside ST1 and ST2 in winter to compare to septic tanks conditions in summer.

Effluent samples

In the winter survey, daily composite effluent samples were collected. Daily composite samples were collected from December 06 to December 12, 2019 (7 days) for ST1; and from December 16 to December 22, 2019 (7 days) for ST2. For daily composite sampling, 500 ml of effluent wastewater was sampled by the auto-sampler at two-hour intervals, and a composite was produced. All samples were kept on ice for transportation to the laboratory.

Septage samples were collected for 25 septic tanks with 10 septic tanks in summer (Chapter 3) and 15 septic tanks in winter. The method and procedure of sampling were mentioned in section 2.3.3 in Chapter 3. After septage sampling, 15 septic tanks surveyed in winter were

emptied by vacuum truck, and the first compartment of septic tanks was cleaned carefully before using for influent sampling.

Influent samples

After emptying and cleaning out of septic tanks, influent samples were collected after 1-day use toilet for 15 septic tanks in the winter survey. The height of blackwater inside the first compartment was measured and recorded. A long stick was used to mix the blackwater inside the first compartment. After 5 minutes of mixing, 500 ml sample was collected by 1-L bucket. The influent samples were collected from December 14 to December 16, 2019 (3 days) for ST1, and from December 24 to December 26, 2019 (3 days) for ST2. For the other septic tanks, influent sampling was conducted one time (1 day) due to the permission of the house owner.

Sample analysis of wastewater and septage

At the laboratory, effluent and septage samples were divided into two bottles: with and without acid preservation ($\text{pH} < 2$), and these samples were stored in a refrigerator ($< 4^{\circ}\text{C}$). The water quality of the effluent wastewater was analyzed using standard methods (APHA, 2005) for the following parameters: pH, E.C., BOD_5 , suspended solids (SS), volatile suspended solids (VSS), $\text{NO}_3\text{-N}$, $\text{NO}_2\text{-N}$, T-P, $\text{PO}_4\text{-P}$. COD_{Cr} , T-N, and $\text{NH}_4\text{-N}$ were analyzed by Hach methods. The dissolved gases in the effluent were analyzed separately, as described in Section 3.2.4 in Chapter 3.

4.2.4 Monitoring of emitted gas

For the emitted gases, the floating chamber was used for monitoring. The detail of the floating design and procedure of sampling were mentioned in section 3.2.4 in Chapter 3. In the winter survey, to reduce the number of samples, the gas sampling duration was reduced from 60 mins (in the summer survey) to 40 mins. The emitted gas samples were collected from December 11 to December 15, 2019 (5 days) for ST1, and from December 19 to December 22, 2019 (5 days) for ST2. The gas monitoring for ST11 – ST23 was conducted one time before emptying septic tanks. For the dissolved gas analysis, effluent samples were collected directly from the outlet pipes of ST1, ST2. The method for screening dissolved gas in the effluent was mentioned in section 3.2.4 in Chapter 3.

4.3. Results and discussion

4.3.1 Performance of septic tanks in Hanoi

According to the recorded influent volume, the influent volume in septic tanks was 62.7 – 169.5 L/day (or 15.7 – 42.4 L/cap/day), which is similar to a previous study in Hanoi (Otaki et al., 2013). The effective HRTs (hydraulic retention times) of ST1 – ST15 were 9.9 ± 7.3 days. The influent and effluent characteristics and pollutant loadings are summarized in Table 2. The average of influent COD_{Cr}, BOD₅, SS and VSS of 15 septic tanks (ST1, ST2, and ST11 – ST23) were 1215 ± 265 , 919 ± 216 , 1038 ± 351 , and 829 ± 281 mg/L, respectively. The ratio of BOD₅/COD was in the range of 0.69 – 0.81, indicated biodegradable matter. The majority of nitrogen was in NH₄⁺, accounted for 64 – 84% of T-N concentration. The COD_{Cr}, BOD₅, TN and TP loadings of the influent (blackwater) were 31 ± 13 , 23 ± 10 , 11 ± 4 and 0.9 ± 0.2 g/cap/day. The pollutant loadings of blackwater in this study were comparable to those in a previous study in Hanoi which COD_{Cr}, BOD₅, TN and TP loadings are 8.1 – 35.0, 5.8 – 24.1, 5.2 – 10.4, and 1.07 – 2.44 g/cap/day (JICA and Nippon Koei, 2019), respectively.

Table 4.2 Influent and effluent characteristics of ST1, ST2, and ST11 – ST23

Parameters	Influent (Blackwater)		Effluent	
	Concentration mg/L	Loading g/cap/day	Concentration mg/L	Loading * g/cap/day
pH	8.1 ± 0.4		7.6 ± 0.2	
E.C. (mS/cm)	2.8 ± 0.3		2.6 ± 0.5	
COD _{Cr}	$1,215 \pm 265$	31 ± 13	711 ± 177	15 ± 6
BOD ₅	919 ± 216	23 ± 10	498 ± 123	9 ± 4
SS	$1,038 \pm 351$	26 ± 12	109 ± 71	2.1 ± 1.8
VSS	829 ± 281	21 ± 9	94 ± 63	1.8 ± 1.6
T-N	451 ± 136	11 ± 4	365 ± 24	7.8 ± 2.6
NH ₄ -N	344 ± 115	9 ± 4	280 ± 24	6.0 ± 2.1
T-P	35 ± 8	0.9 ± 0.2	37 ± 6	0.7 ± 0.3

Note *: effluent loadings of ST1 and ST2; Average $\pm$ Standard deviation.

The effluent characteristics of ST1, ST2, and ST11 – ST23 are shown in Table 4.2. According to the average influent concentrations, the COD_{Cr}, BOD₅, SS, and VSS removal efficiencies were 34.2%, 33.0%, 86.3%, and 84.8%, respectively. The COD and BOD removals were low

in performance due to the long septage storage period, whereas SS and VSS achieved higher removal efficiency because these septic tanks consist of 2 – 3 compartments. The effluent characteristics and removal efficiency were correlated to the septage storage period, as shown in Figure 4.1. The effluent concentrations and removal of COD_{Cr}, BOD₅, SS and VSS were strongly correlated to septage storage period, with *R* values of 0.93 (*p* < 0.001), 0.91 (*p* < 0.001), 0.95 (*p* < 0.001) and 0.95 (*p* < 0.001), respectively. Together with septage storage periods, HRT was also strongly correlated to effluent characteristic such as BOD₅ (*R* = -0.61, *p* = 0.016), COD_{Cr} (*R* = -0.61, *p* = 0.015), SS (*R* = -0.74, *p* = 0.002), and VSS (*R* = -0.73, *p* = 0.002), as shown in Figure 4.2. These results indicate that the septage storage period is longer and HRT is shorter, the higher concentrations of COD_{Cr}, BOD₅, SS, and VSS are discharged, or the lower removals of septic tanks are performed.

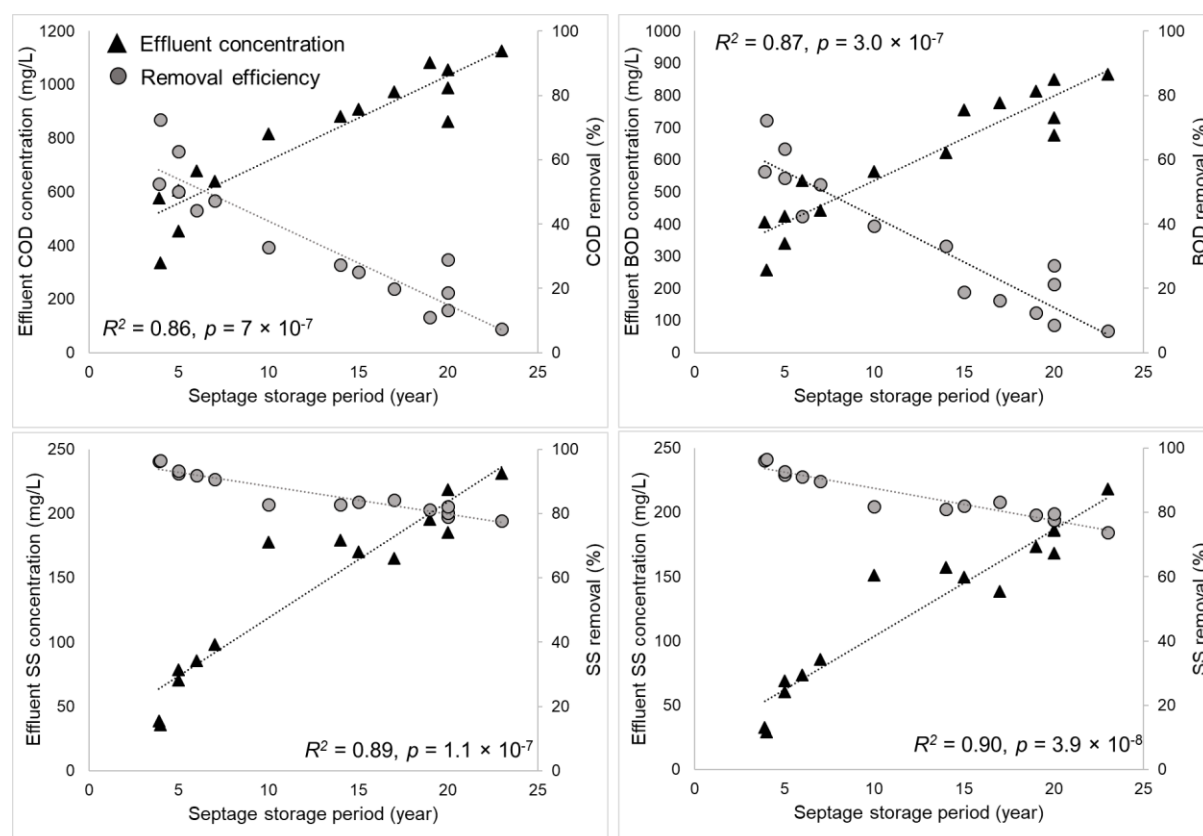


Figure 4.1 The correlation between effluent concentration and removal efficiency with septage storage period.

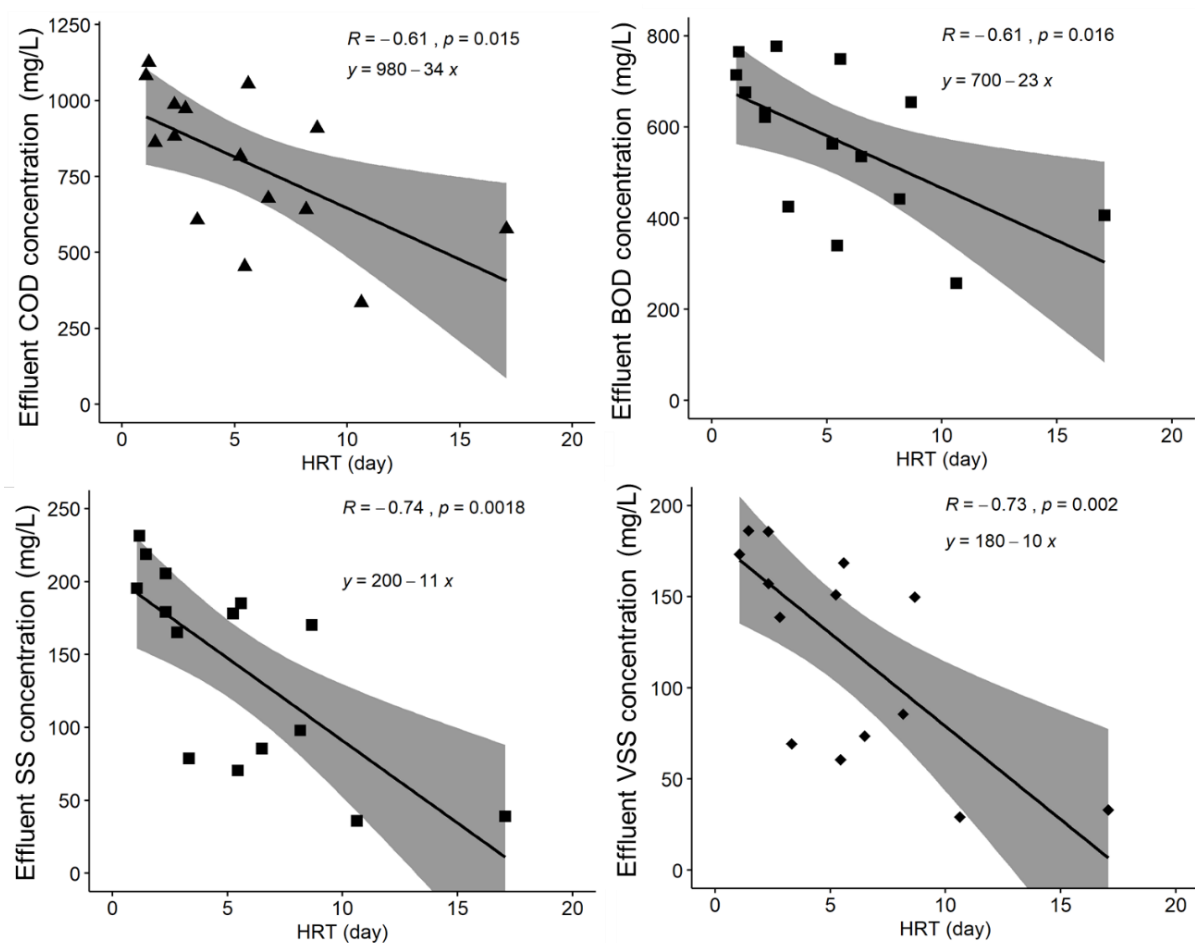


Figure 4.2 The correlation between effluent concentration with HRT. Black lines show linear trend and gray zones show confidence interval.

Table 4.3 shows the effluent characteristics from septic systems in summer and winter in Hanoi. There were not significantly different in effluent characteristic of ST1 and ST2 between summer and winter in Hanoi. These results were comparable to a previous study (Luostarinen et al., 2006). Luostarinen et al. (2006) reported that the 10°C difference in ambient temperature had no impact on the performance and the effluent characteristics from the anaerobic process for domestic wastewater treatment.

Table 4.3 Effluent characteristics of ST1 and ST2 in summer and winter in Hanoi

Parameters	Summer				Winter			
	ST1	ST2	ST1	ST2	ST1	ST2	ST1	ST2
	(Concentration, mg/L)		(Loading, g/cap/day)		(Concentration, mg/L)		(Loading, g/cap/day)	
pH	7.5 ± 0.2	7.7 ± 0.2			7.6 ± 0.1	7.8 ± 0.1		
E.C. (mS/cm)	3.0 ± 0.1	2.8 ± 0.1			2.9 ± 0.1	2.1 ± 0.1		
COD _{cr}	564 ± 28	803 ± 12	10.2 ± 3.2	16.9 ± 7.3	602 ± 47	861 ± 102	16.0 ± 2.6	20.4 ± 6.3
BOD ₅	389 ± 29	544 ± 25	7.0 ± 2.3	11.4 ± 4.8	471 ± 25	681 ± 51	13.0 ± 2.0	16.1 ± 4.6
SS	39 ± 4	173 ± 7	0.7 ± 0.3	3.7 ± 1.6	40 ± 2	182 ± 9	1.1 ± 0.2	4.4 ± 1.5
VSS	31 ± 4	148 ± 2	0.6 ± 0.2	3.1 ± 1.4	37 ± 2	155 ± 8	1.0 ± 0.2	3.7 ± 1.2
T-N	356 ± 23	370 ± 10	6.4 ± 1.8	7.8 ± 3.4	348 ± 11	371 ± 11	9.6 ± 1.2	8.9 ± 3.0
NH ₄ -N	261 ± 17	286 ± 7	4.7 ± 1.3	6.0 ± 2.6	269 ± 15	299 ± 13	7.4 ± 1.0	7.2 ± 2.4
T-P	32 ± 4	36 ± 5	0.6 ± 0.2	0.8 ± 0.4	33 ± 2	36 ± 4	0.9 ± 0.1	0.9 ± 0.2

Note: Average ± Standard deviation.

4.3.2 Septage composition

Septage composition of 25 septic tanks is shown in Table 4.4, which is similar to previous studies (Pham, 2014; Gold et al., 2017). These septic tanks were under the anaerobic condition indicated by DO (0.2 ± 0.2 mg/L) and ORP (-351 ± 89 mV) values. According to the septic tanks' conditions, nitrification was not a dominant process when the majority of nitrogen was in NH_4^+ . The variation of ORP, DO, BOD mass and COD mass can be partly explained by the septage storage period. Septage storage period was strongly correlated with ORP ($R = -0.65$, $p < 0.001$), COD mass of septage ($R = 0.66$, $p < 0.001$), BOD mass of septage ($R = 0.63$, $p < 0.001$), whereas septage storage was not significantly correlated with DO ($R = -0.43$, $p = 0.026$), as shown in Figure 4.3. These correlations indicate that the longer septage is stored, the more biodegradable organic mass accumulates under highly reduced conditions, possibly causing a positive impact on CH_4 production.

Table 4.4 Septage composition of 25 septic tanks

Parameters	Unit	Summer	Winter	Average
Liquid temp	°C	31.1 ± 0.4	21.8 ± 1.2	25.9 ± 4.8
COD _{cr}	mg/L	12,329 ± 4,900	19,245 ± 9,894	16,171 ± 8,668
COD _{cr} mass	g/tank	18,256 ± 9190	24,133 ± 25,486	21,521 ± 19,858
BOD ₅	mg/L	8,956 ± 4,217	15,953 ± 8,886	11,345 ± 11,727
BOD ₅ mass	g/tank	13,856 ± 8,485	20,173 ± 21,968	19,732 ± 39,535
sCOD _{cr}	mg/L	1,035 ± 390	1,083 ± 380	1,062 ± 378
SS	mg/L	7,404 ± 1,298	7734 ± 2011	7,587 ± 1,708
VSS	mg/L	5,994 ± 1,439	5127 ± 1451	5,512 ± 1,484
T-N	mg/L	1,458 ± 664	1,940 ± 887	1,726 ± 818
NH ₄ -N	mg/L	370 ± 148	429 ± 183	403 ± 168
T-P	mg/L	305 ± 172	165 ± 86	227 ± 147
DO	mg/L	0.15 ± 0.12	0.18 ± 0.16	0.2 ± 0.2
ORP	mV	-328 ± 68	-370 ± 101	-351 ± 89
Effective HRT	days	-	-	9.9 ± 7.3
Septage storage period	years	9.7 ± 5.5	12.6 ± 7	11.3 ± 6.4

Note: Average ± Standard deviation

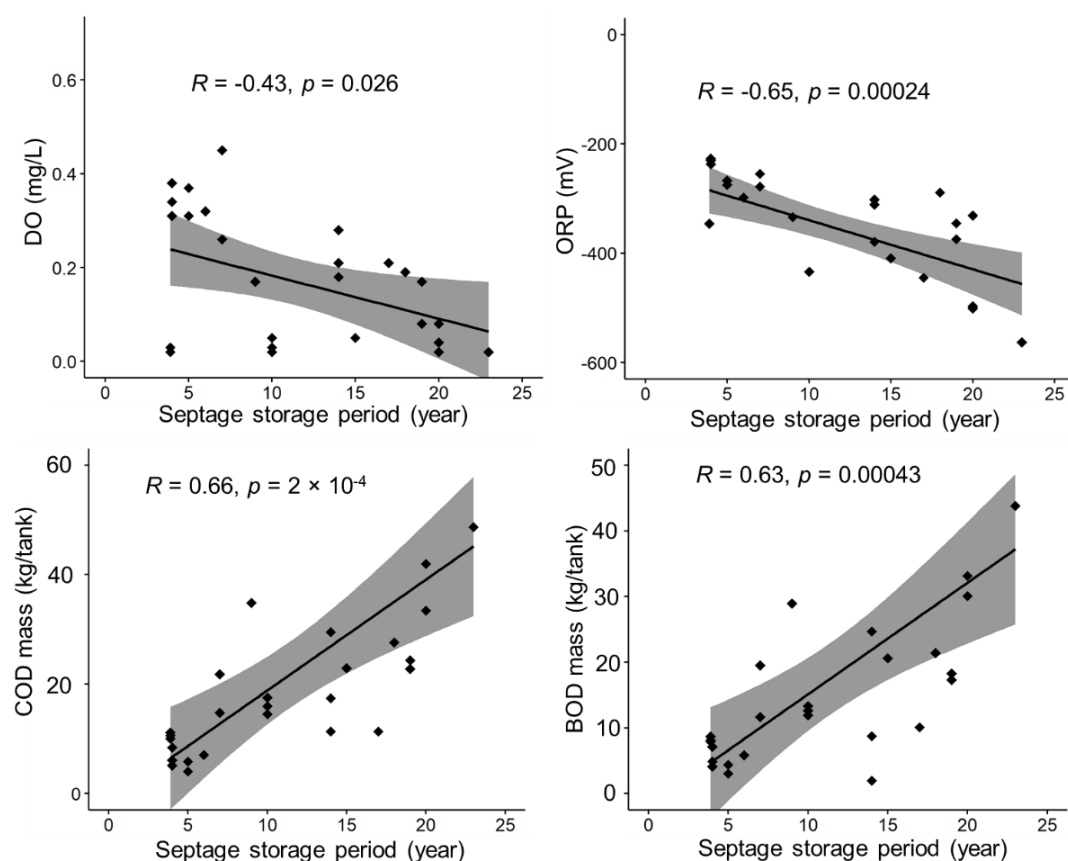


Figure 4.3 Correlation between septage storage period (years) and ORP (mV), DO (mg/L), and COD and BOD mass of septage (kg/tank). Black lines show linear trend and gray zones show confidence interval.

Regarding the difference in ambient and liquid temperatures between summer and winter in Hanoi, the inside conditions of septic tanks in Hanoi was not significantly different between summer and winter, as shown in Figure 4.4. The previous studies also figured out that there was not significantly different in septage characteristics between summer ($18.4 \pm 1.6^{\circ}\text{C}$) and winter ($21.9 \pm 3.3^{\circ}\text{C}$) in Jordan (Halalsheh et al., 2011). Bassan et al. (2013) and Krithika et al. (2017) reported that septage variability was due to storage period while season had a low influence in Ouagadougou and Chennai City, respectively. Similarly, the septage storage period is the key factor of the variability of septage characteristics in the present study, as mentioned above.

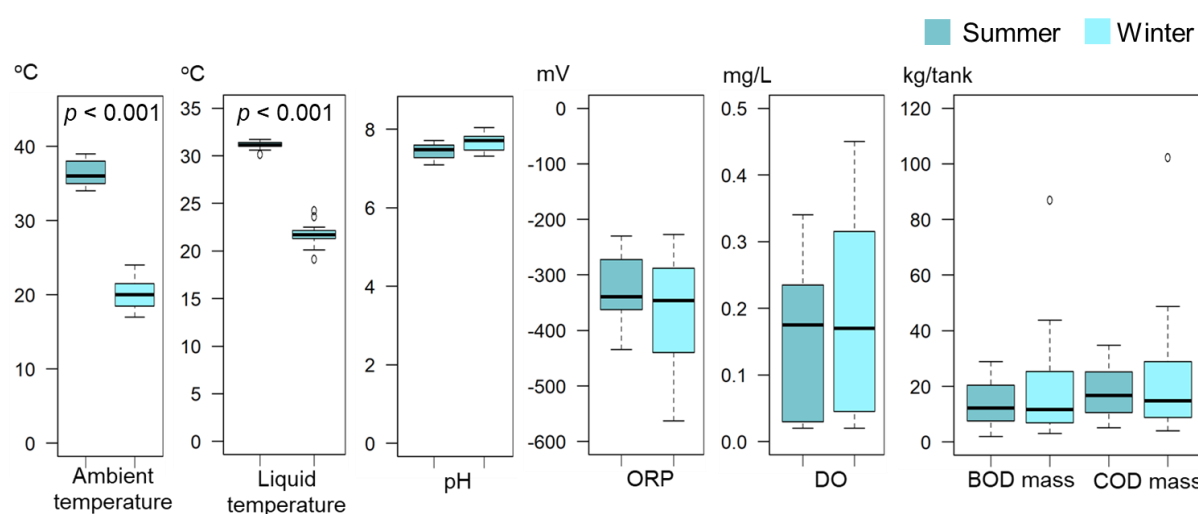


Figure 4.4 Seasonal variation of septage composition in Hanoi

4.3.3 Seasonal variability of GHG emissions from septic systems

Emitted gases concentrations

The emitted gases were monitored at 25 septic tanks in total, which 10 septic tanks in summer and 15 septic tanks in winter in Hanoi. The accumulated CH_4 and CO_2 concentrations were 3,433 – 22,571 and 2,263 – 15,678 ppm, respectively, whereas CO , NH_3 , and N_2O concentrations were at negligible levels. Therefore, CO , NH_3 , and N_2O were excluded in the following discussion. Table 4.5 shows the accumulated gas concentrations in summer and winter from 25 septic tanks in Hanoi.

Table 4.5 Accumulated CH₄, CO₂, CO, N₂O and NH₃ concentration at t = 40-min in summer and winter in Hanoi

		CH ₄ ppm	CO ₂ ppm	CO ppm	N ₂ O ppm	NH ₃ ppm
Summer	Avg.	10,362	5,957	0	1	1
(n = 10)	SD.	4,088	2,220	0	0	1
Winter	Avg.	11,107	7,948	2	1	1
(n = 15)	SD.	4,609	3,112	1	0	0

CH₄ and CO₂ emission rates

According to the slope of linear fits for the gas concentrations in the floating chamber, CH₄ and CO₂ emission rates were calculated and illustrated in Figure 4.5. The average CH₄ and CO₂ emission rates of 25 septic tanks in Hanoi were 14.96 ± 9.43 and 27.75 ± 14.29 g/cap/day (Avg $\pm$ SD), respectively. Coefficients of variation were 63% for CH₄ and 52% for CO₂ emissions. These results indicate a large variability of emissions, which is potentially reflected by the larger variability of inside conditions of septic tanks. The carbon ratio of C-CH₄:C-CO₂ was not significantly different between summer (0.38:0.62) and winter (0.43:0.57), as shown in Figure 4.6. Among fifteen surveyed septic tanks, the effluent was collected from ST1 and ST2, for which dissolved CH₄ in the effluent was monitored with effluent flow rate. The average dissolved CH₄ concentration in winter was 0.22 mg/L for ST1 and ST2, corresponding to 24,444% of saturation, this result was same as that in the summer survey. The amount of dissolved CH₄ was negligible, although dissolved CH₄ is potentially emitted to the atmosphere after the effluent is discharged to the environment.

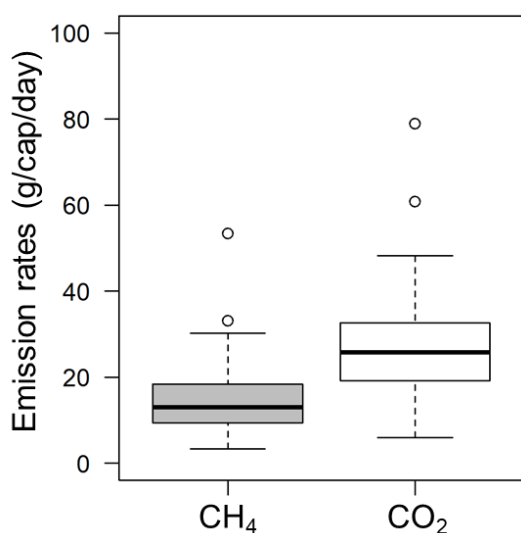


Figure 4.5 CH₄ and CO₂ emission rates of 25 septic tanks in Hanoi. Boxplots indicate the median and interquartile ranges (IQRs) with whiskers extend up to $1.5 \times \text{IQR}$.

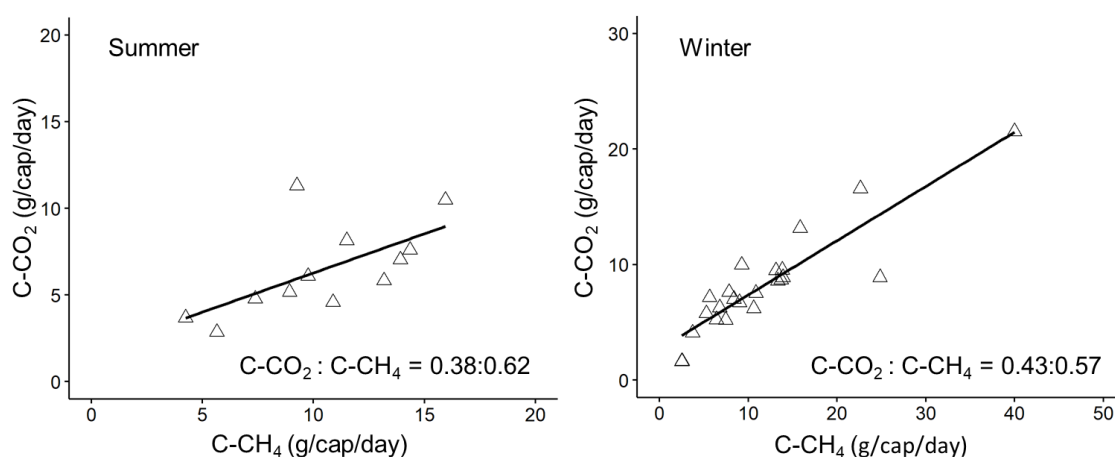


Figure 4.6 The ratios of C-CO₂:C-CH₄ in summer and winter in Hanoi.

Seasonal variation of CH₄ and CO₂ emissions

This study monitored CH₄ and CO₂ emissions from septic tanks in summer and winter in Hanoi. The CH₄ and CO₂ emission rates were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day in summer, 15.52 ± 11.19 and 29.87 ± 16.03 g/cap/day in winter, respectively. No clear correlations between liquid temperature and emission rates of CH₄ and CO₂ were found, as shown in Figure 4.7, indicated that the range of temperature 19.1 – 31.7 °C had no impact on CH₄ and CO₂ emissions. This result was similar to the previous study in the USA and Brazil (Diaz-Valbuena et al., 2011; Resende et al., 2016). Diaz-Valbuena et al. (2011) showed temperature (12 – 27 °C) was not

significantly affected to GHG emissions from septic systems in the USA, and Resende et al. (2016) reported that the change of ambient temperature from 24 – 35 °C (summer) to 14 – 25 °C (winter) in Brazil had no impact on CH₄ production of anaerobic reactors. These results could be explained by the range of liquid temperature inside septic systems. The liquid temperature in the present study was in the mesophilic range (20 – 45°C). The mesophilic temperature range are generally preferred to support the biological reaction rates, and to provide a more stable process (Tchobanoglous et al., 2003). A notable point is that temperature has an impact on the biological reaction rate while the CH₄ production amount was not affected. Further, the difference in temperature at the bottom of septic tanks was not significantly which is potential by the difference in soil temperature at 0.5 m depth between summer and winter was <6°C in the sub-tropical area (Rodríguez et al., 2010; Kosugi et al., 2007). The previous study figured out that the temperature of anaerobic digester was affected to microbial structures. However, the change of microbial structure had no significant impact on CH₄ production because all microbial groups have the same role in producing CH₄ and CO₂ (Resende et al., 2016; Pussayanavin et al., 2015).

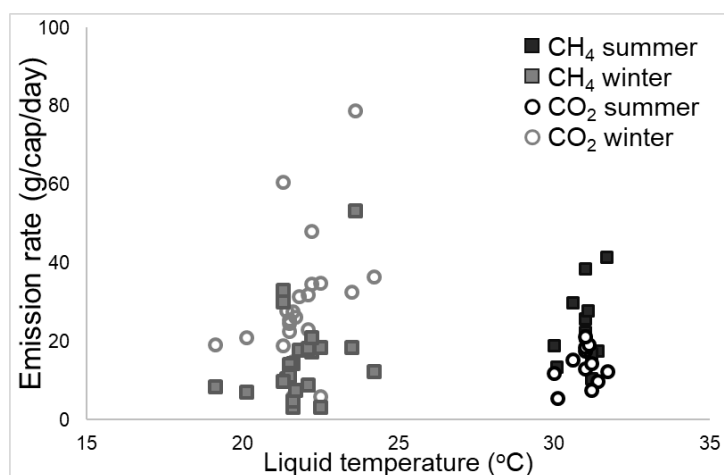


Figure 4.7 The relationship between liquid temperature and CH₄, CO₂ emissions

Further, the variability in other factors could play a more significant role in GHG emissions. Regarding the variability of the inside conditions of septic tanks, as shown in Table 4.4, the average ORP, DO, BOD mass and COD mass were -351 ± 89 , 0.2 ± 0.2 , $19,732 \pm 39,535$ g/tank and $21,521 \pm 19,858$ g/tank, respectively. The CH₄ emission rates might be affected by the inside conditions of septic tanks, as shown in Figure 4.8. ORP, DO, BOD and COD mass presented significant correlation with CH₄ emissions, with *R* values of -0.63 ($p < 0.001$), -0.61

($p < 0.001$), 0.92 ($p < 0.001$), and 0.92 ($p < 0.001$), respectively. Further, CH₄ emission rates from septic tanks with longer septage storage period were higher than those from septic tanks with shorter septage storage period, as shown in Figure 4.9. These correlations indicate that lower ORP and higher biodegradable carbon mass (indicated by BOD or COD mass) associated with longer septage storage periods are the main factors for the emission of CH₄ from septic tanks, rather than liquid temperature.

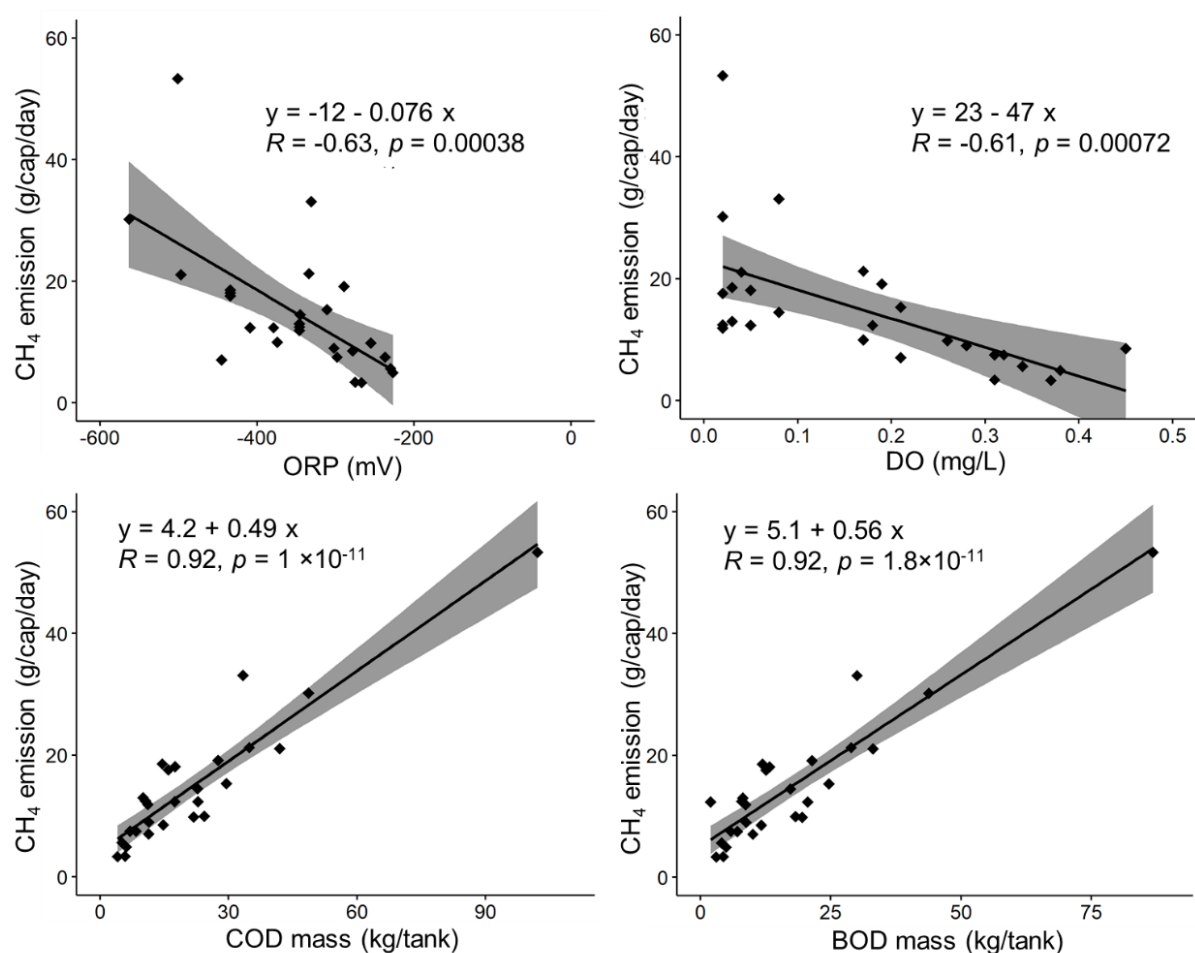


Figure 4.8 Correlation between septic tanks conditions and CH₄ emission rates. Black lines show linear trend and gray zones show confidence interval.

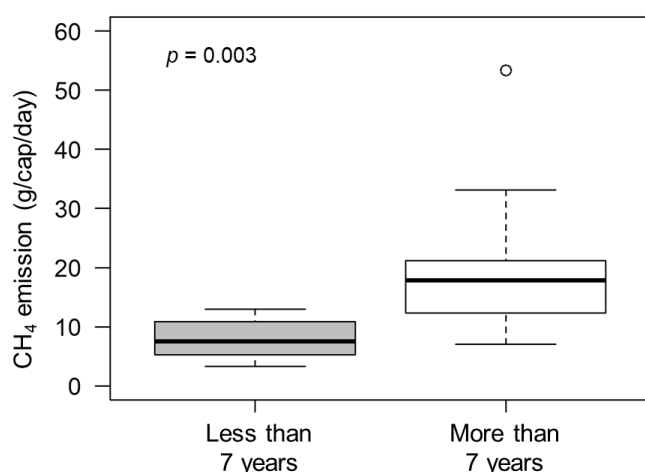


Figure 4.9 CH₄ emission rates for shorter (less than 7 years) and longer (more than 7 years) storage periods. Boxplots indicate the median and IQRs with whiskers extend up to $1.5 \times \text{IQR}$.

4.3.4 Mass balance analysis for carbon, nitrogen, and phosphorus for ST1 and ST2

Figure 4.10 shows the carbon, nitrogen, and phosphorus mass balance for ST1 and ST2. According to the difference in the septage storage period of ST1 (3.9 years) and ST2 (10 years), the C/N/P emission in the gas phase and effluent from ST2 is higher than that from ST1. Together with higher emissions in gas and liquid, more C/N/P was accumulated in septage in ST2 compared to ST1. The C, N, and P removal efficiencies were 59%, 24% and 6% in ST1 and 22%, 12% and 0.5% in ST2. According to low performance in N and P removal, it could be explained by the function of septic tanks that mostly used for separating solids from the influent by gravity settlement. Further, nitrogen and phosphorus removal were not dominant processes in septic tanks due to anaerobic condition of septic tanks indicated by low ORP (-346 to -434 mV) and DO (0.02 – 0.03 mg/L). A notable of these mass balance analyses are represented at the monitoring period because the performance could be changed according to the septage storage period.

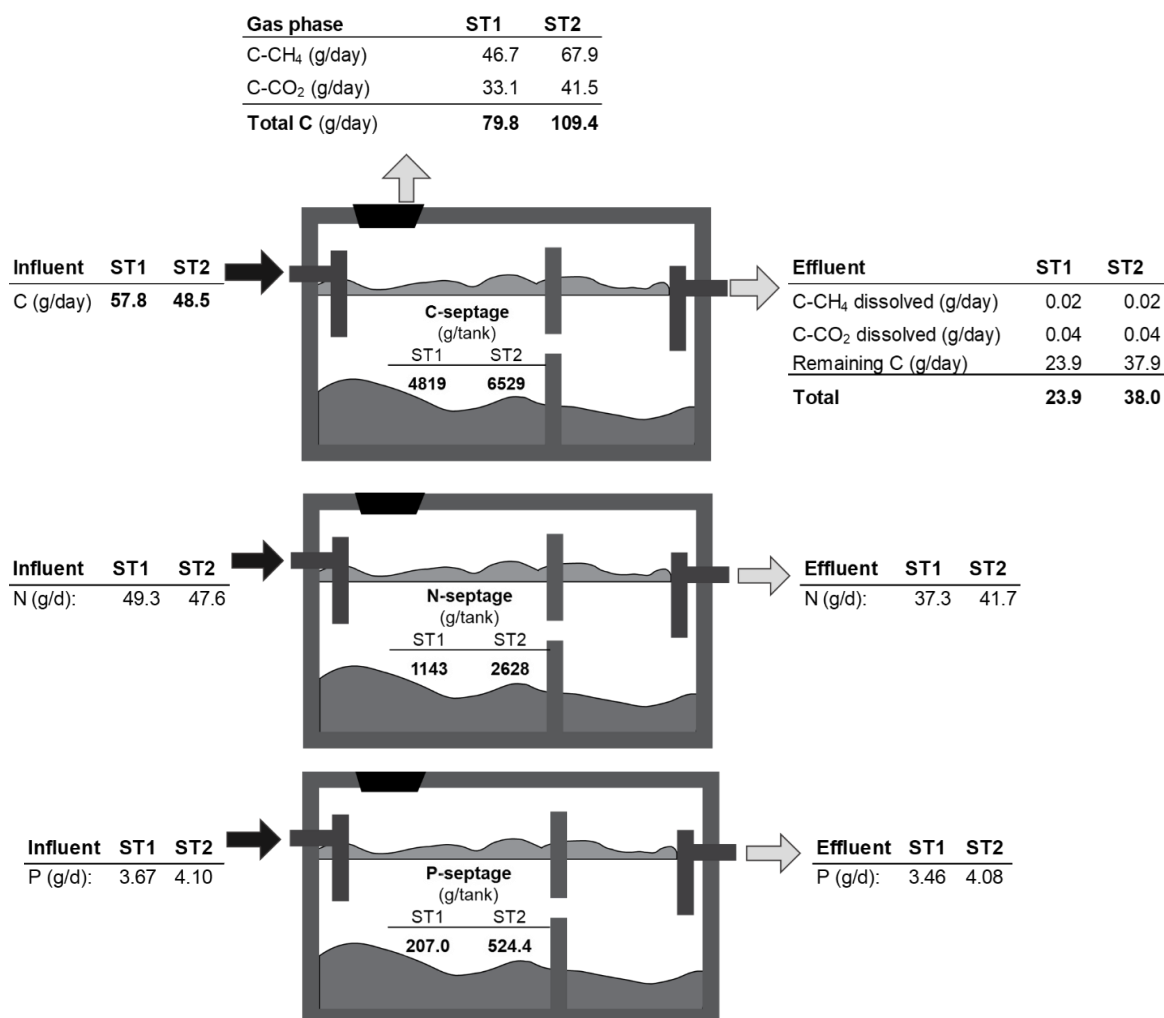


Figure 4.10 Carbon, Nitrogen, Phosphorus mass balance of ST1 and ST2

Regarding organic source of the CH₄ and CO₂ productions, the carbon mass balance shows the carbon mass in gas phase was higher than that in the influent of ST1 and ST2, as shown by the ratio as 1.14 ± 0.70 g C-CH₄/g C_{inf}. This result indicated that CH₄ and CO₂ emissions were not only produced from carbon in the influent, but also from carbon in the septage. This result could be explained by the biodegradable organic matter contained in the septage. The BOD₅ mass of the septage was $19,732 \pm 39,535$ g/tank indicating septage still contained high amount of biodegradable organic matter after long storage time. This result was same as the previous study about septage composition in Vietnam (Pham, 2016; Gold et al., 2017).

The CH₄ emission rates in the present study were significantly smaller than the IPCC CH₄ emission factor. The CH₄ emission rates in the present study were 14.96 g/cap/day or 3.3 ± 4.9 g-CH₄/g-BOD_{removed}. In IPCC estimation, the CH₄ emission per-biodegradable organic loading was suggested as 0.6 ± 0.1 g-CH₄/g-BOD_{removed} or 0.3 ± 0.1 g-CH₄/g-COD_{removed}, based on

expert judgment. The CH₄ emission per-biodegradable organic loading of IPCC was lower than that of the present study. This result indicated that the CH₄ conversion of blackwater septic systems in the present study is better than IPCC suggestion due to the suitable conditions (ORP, DO, retention time) of the anaerobic process in septic systems. HRT (23.8 ± 10.6 days) and septage storage period (11.7 ± 6.5 years) are longer than HRT (20 – 24 days) and sludge retention time (50 – 100 days) (Tchobanoglous et al., 2003) of the anaerobic lagoon process which IPCC emission factor archived. According to long HRT and septage storage period, the CH₄ production process in septic systems had sufficient time for converting biodegradable organic matter into CH₄ (Tchobanoglous et al., 2003; Resende et al., 2016; Andersson et al., 2020). However, the IPCC emission factor per-capita is significantly higher than that in the present study. This higher emission could be attributed to the biodegradable organic loading and methane conversion factor, assumed the same as removal efficiency. In the present study, the BOD loading of blackwater influent of septic tanks in Hanoi as 23.4 ± 9.9 g/cap/day (Avg $\pm$ SD) was significantly smaller than BOD loading recommended in IPCC as 85 (50 – 120) g/cap/day for USA or 40 (35 – 45) g/cap/day for Asia (IPCC, 2006; Tchobanoglous et al., 2003). Further, IPCC assumed that the removal efficiency of septic tanks as 50%. This assumption derived from a well-maintained system and it is higher than the current removal efficiency of septic tanks under poor operating condition in the present study as $33 \pm 18\%$ (Avg $\pm$ SD). These indicated that IPCC emission factors were overestimated in most cases. For better estimate CH₄ emissions from septic systems, BOD loading and removal efficiency are the key factors.

Table 4.6 Comparison between the present study and IPCC

Parameters	This study	IPCC, 2006
g-CH ₄ /capita/day	14.96	25.50
g-CH ₄ /g-COD _{removed}	2.4 (0.17 – 16.66)	0.3
g-CH ₄ /g-COD _{inf}	0.55 (0.12 – 1.22)	0.96 (0.26 – 2.0)
g-CH ₄ /g-BOD _{inf}	0.71 (0.16 – 1.6)	1.6 (0.43 – 3.4)
g-C-CH ₄ /g-C _{inf}	1.14 (0.30 – 2.90)	-
g-COD _{inf} /capita/day	31.0 (17.9 – 60.5)	-
g-BOD _{inf} /capita/day	23.4 (13.2 – 46.6)	85 (50 – 120) *
COD removal efficiency	$34 \pm 20\%$	-
BOD removal efficiency	$33 \pm 18\%$	50 – 88%

Note: * IPCC suggestion for BOD production

4.4. Conclusions

The present study studied seasonal variability of GHG emissions from septic systems in Hanoi, Vietnam that receive only blackwater, under subtropical climate. CH₄, CO₂, and N₂O emissions were monitored at 10 septic tanks in summer (Chapter 3) and 15 septic tanks in winter in Hanoi by the floating chamber method. The influent, effluent characteristics, and septage composition were also monitored to evaluate the performance of the septic systems and their impacts on GHG emissions. The average measured CH₄ and CO₂ emissions from 25 septic tanks in Hanoi were 14.96 ± 9.43 and 27.75 ± 14.29 g/cap/day (Avg $\pm$ SD), respectively, whereas those of N₂O were at the negligible levels.

The CH₄ and CO₂ emission rates were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day in summer, 15.52 ± 11.19 and 29.87 ± 16.03 g/cap/day in winter, respectively. The range of liquid temperature 19.1 – 31.7 °C had no significant impact on CH₄ and CO₂ emission rates. It could be attributed to the stable temperature at the bottom of septic tanks, biological reaction rate, microbial structure, and the stable inside conditions (ORP, DO, organic mass). The temperature has an impact on biological reaction rate while CH₄ production was not affected. Further, this study figured out that the variability in the inside conditions of septic tanks could play a more significant role in GHG emissions. Lower ORP and higher biodegradable carbon mass (indicated by BOD or COD mass) associated with longer septage storage period are the main factors for the emission of CH₄ from septic tanks, rather than liquid temperature.

The mass balance of carbon, nitrogen and phosphorus was analyzed for ST1 and ST2. The C, N, and P removal efficiencies were 59%, 24% and 6% in ST1 and 22%, 12% and 0.5% in ST2. According to the higher in septage storage period of ST2, the C/N/P emissions and removal efficiencies of ST1 were higher than those of ST2. The CH₄ and CO₂ emissions were not only produced from carbon in the influent, but also from carbon in the septage because septage still contained high amount of biodegradable organic matter after long storage time. The CH₄ emission rates per-biodegradable organic loading in the present study was 2.4 g-CH₄/g-COD_{removed} or 1.14 ± 0.70 g C-CH₄/g C_{inf}, and 8.0 times higher than that in IPCC guideline as 0.3 g-CH₄/g-COD_{removed}. The higher emission rate could be explained by the more suitable anaerobic condition of septic systems (indicated by ORP), longer HRT and septage storage periods. However, the IPCC CH₄ emission factor per-capita was significantly higher than that in the present study. This result could be attributed to lower BOD loading and removal

efficiency of septic systems in the present study as 23 ± 10 g-BOD/cap/day and $33 \pm 18\%$, respectively. Therefore, for better estimate CH₄ emissions from septic systems, BOD loading and removal efficiency are the key factors.

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Publications

Proceeding

1. Loi Tan Huynh, Hidenori Harada, Shigeo Fujii, Lien Nguyen Pham Hong, Thu-Huong Thi Hoang, Hai Trung Huynh (2020). Seasonal Variation of GHG emissions from septic systems in Hanoi. Proceeding of the 42nd Symposium of Kyoto University Environmental and Sanitary Engineering Research, (July 30, 2020).

Chapter 5 : Conclusions and Recommendations

5.1 Conclusions

The present study studied seasonal variability of GHG emissions from septic systems in Hanoi, Vietnam that receive only blackwater, under subtropical climate. CH₄, CO₂, and N₂O emissions were monitored at 10 septic tanks in summer and 15 septic tanks in winter by the floating chamber method. The influent, effluent characteristics, and septage composition were also monitored to evaluate the performance of the septic systems and their impacts on GHG emissions. The average measured CH₄ and CO₂ emissions from 25 septic tanks in Hanoi were 14.96 ± 9.43 and 27.75 ± 14.29 g/cap/day (Avg $\pm$ SD), respectively, whereas those of N₂O were at the negligible levels. To the best of our knowledge, this is the first study to directly measure GHGs emission from septic systems in developing countries.

CH₄ emission rates were negatively correlated with septage ORP and DO, and positively correlated with septage COD mass and BOD mass, while water temperature was not significantly correlated. Further, the CH₄ emission rates from septic systems with longer storage periods (more than 7 years) were significantly higher than those from septic systems with shorter storage periods (less than 7 years). Moreover, the storage periods were negatively correlated with ORP and DO, and positively correlated with COD mass and BOD mass. These results suggest that lower ORP and DO, and higher biodegradable carbon mass in association with longer septage storage periods are key conditions for CH₄ emissions from septic systems. Therefore, controlled or regular septage emptying could contribute to improve not only the removal efficiency of septic systems but also its GHG mitigation capability. Thus, our results will contribute to estimate global GHGs emissions from septic tanks in developing countries and be essential information for mitigating the emission.

The CH₄ emission rates of this study were equivalent to or even larger than those of previous studies which measured the emission rates in the USA. Beside the influent difference between septic systems in the USA (black and greywater) and septic systems in our study (only blackwater), the equivalent or even larger CH₄ emission rates of the present study could be attributed to significant difference such as lower ORP, higher COD concentration, and longer HRT and septage storage periods.

The CH₄ emission rates per-biodegradable organic loading in the present study was 2.4 g-CH₄/g-COD_{removed} or 1.14 ± 0.70 g C-CH₄/g C_{inf}, and 8.0 times higher than that in IPCC guideline as 0.3 g-CH₄/g-COD_{removed}. The higher emission rate could be explained by the more suitable anaerobic condition of septic systems (indicated by ORP), longer HRT and septage storage periods. However, the IPCC CH₄ emission factor per-capita was significantly higher than that in the present study. This result could be attributed to lower BOD loading and removal efficiency of septic systems in the present study as 23 ± 10 g-BOD/cap/day and $33 \pm 18\%$, respectively. Therefore, for better estimate CH₄ emissions from septic systems, BOD loading and removal efficiency are the key factors.

The CH₄ and CO₂ emission rates were 13.89 ± 4.78 and 23.69 ± 9.48 g/cap/day in summer, 15.52 ± 11.19 and 29.87 ± 16.03 g/cap/day in winter, respectively. The range of liquid temperature 19.1 – 31.7 °C had no significant impact on CH₄ and CO₂ emission rates. It could be attributed to the biological reaction rate, microbial structure, and the stable inside conditions of septic tanks (ORP, DO, organic mass). The temperature has an impact on biological reaction rate while CH₄ production was not affected. Further, this study figured out that the variability in the inside conditions of septic tanks could play a more significant role in GHG emissions. Lower ORP and higher biodegradable carbon mass (indicated by BOD or COD mass) associated with longer septage storage period are the main factors for the emission of CH₄ from septic tanks, rather than liquid temperature.

The mass balance of carbon, nitrogen and phosphorus was analyzed for ST1 and ST2. The C, N, and P removal efficiencies were 59%, 24% and 6% in ST1 and 22%, 12% and 0.5% in ST2. According to the higher in septage storage period of ST2, the C/N/P emissions and removal efficiencies of ST1 were higher than those of ST2. The CH₄ and CO₂ emissions were not only produced from carbon in the influent, but also from carbon in the septage because septage still contained high amount of biodegradable organic matter after long storage time.

5.2 Recommendations

Due to the difficulty in accessing septic tanks in Hanoi, the present study was monitored GHG emissions from the first compartments of septic tanks. The total emissions were calculated based on the GHG emission ratios of the first compartment and the second compartment of

septic tanks obtained from the previous study. To represent the GHG emissions for the septic systems, the measurement from all the compartment should be considered for more accuracy.

To measure GHG emissions, this study was focused on the septic systems with only septic tanks and receiving only blackwater in the sub-tropical region. Since types of on-site sanitation facilities, and the designs and operating conditions of septic systems are different by regions, the investigation of GHG emissions for different operating conditions from different regions is recommended for a broader understanding of global GHG emissions from on-site sanitation facilities.

The manual monitoring of septic systems to understand the inside conditions, removal efficiency, and GHG emissions from septic systems was time, money and labor-intensive work. The monitoring of septic systems was, however, very important to improve waste management practice in developing countries, where mostly rely on on-site sanitation facilities. For the further development of advanced septic systems monitoring, to develop IoT-based on-site monitoring system is highly recommended for further studies.

Appendix

Appendix A Influent characteristics

ID	pH	E.C. mS/cm	Cl- mg/L	COD _{cr} mg/L	BOD ₅ mg/L	SS mg/L	VSS mg/L	T-N mg/L	NH ₄ -N mg/L	NO ₃ -N mg/L	NO ₂ -N mg/L	T-P mg/L	PO ₄ -P mg/L
ST1	8.05	3.1	162	1576	1277	1300	903	355	228	1.10	0.57	37.5	26.3
ST1	8.16	2.3	79	897	691	698	530	365	274	1.30	0.21	20.4	14.9
ST1	8.24	2.9	145	1192	822	1299	965	475	346	1.78	0.35	29.9	22.1
ST2	8.04	3.2	223	1347	1010	616	488	375	280	1.95	0.33	34.7	23.9
ST2	8.77	2.5	133	873	655	608	520	400	300	0.99	0.39	31.2	20.9
ST2	8.91	2.9	137	987	750	738	632	405	304	0.75	0.74	36.7	24.2
ST11	7.71	2.8	157	971	777	750	667	675	564	0.57	0.88	37.1	26.7
ST12	8.40	2.7	78	1024	768	1188	920	370	286	1.12	0.49	33.2	23.2
ST13	7.76	3.2	167	1631	1256	1113	877	385	268	1.07	0.57	27.3	19.4
ST14	7.74	2.9	62	1368	1040	924	728	310	233	0.99	0.26	33.4	24.1
ST15	7.56	3.2	137	1574	1149	1588	1274	775	631	0.93	0.37	29.7	19.9
ST16	8.21	2.6	124	1128	914	1077	907	400	312	0.88	0.26	38.1	25.2
ST17	7.81	3.0	167	1327	1022	1387	1075	360	270	0.83	0.37	41.7	29.6
ST18	7.94	2.3	262	1299	974	1071	807	355	266	0.94	0.48	28.6	20.9
ST19	8.75	2.3	89	887	648	662	577	580	435	0.97	0.44	32.2	23.9
ST20	8.55	2.4	241	991	733	690	583	325	269	1.03	0.41	27.9	19.2
ST21	7.62	2.9	229	1229	873	1375	1079	415	336	1.05	0.34	52.5	35.7
ST22	7.87	2.5	201	1093	765	857	657	670	503	1.01	0.33	41.3	28.1
ST23	8.45	3.3	270	1693	1337	1785	1557	575	431	0.87	0.17	51.6	34.1

Appendix B. Effluent characteristics

ID	Sample date	Flushing water L	Eff water L	pH	E.C. mS/cm	Cl- mg/L	COD _{cr} mg/L	BOD ₅ mg/L	SS mg/L	VSS mg/L	T-P mg/L	PO ₄ -P mg/L	T-N mg/L	NH ₄ -N mg/L	NO ₃ -N mg/L	NO ₂ -N mg/L
ST1	06/18/2019	83.04	86.63	7.21	2.9	86.1	549	367	38.5	36.0	35.6	23.2	370	285	6.55	2.69
ST1	06/19/2019	85.98	87.72	7.30	2.9	106	533	362	36.5	30.5	38.2	22.4	355	247	6.32	2.76
ST1	06/20/2019	43.56	45.9	7.22	3.0	99.6	529	365	35.5	26.5	32.0	21.1	375	267	6.32	2.64
ST1	06/22/2019	76.11	78.33	7.29	3.2	140	567	400	39.5	32.0	41.2	20.5	380	273	6.77	2.58
ST1	06/23/2019	77.34	80.16	7.30	3.1	138	583	419	40.5	35.0	31.3	19.1	315	245	6.32	2.75
ST1	06/24/2019	90.82	93.08	7.34	3.2	134	593	420	43.5	35.0	28.7	18.9	330	249	6.10	2.54
ST1	06/26/2019	79.25	81.20	7.34	3.3	120	536	360	34.5	28.0	31.6	17.6	340	253	5.65	2.8
ST1	06/27/2019	55.41	57.77	7.67	3.0	99.2	527	342	35.5	24.5	29.7	17.0	350	247	5.42	1.97
ST1	06/28/2019	81.87	85.1	7.70	3.0	97	544	360	34.5	29.0	33.2	16.2	355	250	5.65	2.16
ST1	06/29/2019	110.73	114.51	7.72	3.0	112	588	400	34.5	29.0	29.3	17.2	325	239	7.00	2.34
ST1	06/30/2019	90.61	92.52	7.70	3.0	109	573	395	34.5	29.5	26.4	17.1	385	280	6.77	2.23
ST1	07/01/2019	135.40	137.66	7.64	3.2	148	611	420	47.0	34.0	30.5	17.0	390	284	6.77	2.62
ST1	07/02/2019	121.01	124.38	7.59	3.0	131	598	430	46.0	34.0	31.7	14.8	355	252	8.35	2.91
ST1	07/03/2019	81.75	84.66	7.77	2.8	140	575	414	39.5	35.0	33.5	13.8	365	285	8.35	1.85
ST2	07/13/2019	150.42	151.60	7.85	1.8	123	805	531	180.5	146.5	38.8	16.7	370	291	8.13	0.69
ST2	07/14/2019	63.12	66.31	7.63	1.8	133	814	553	167.5	145.5	37.0	18.4	380	285	8.81	0.55
ST2	07/15/2019	167.57	169.84	7.67	1.8	137	793	530	173.5	151.5	44.8	16.7	370	281	8.56	0.67
ST2	07/16/2019	129.09	132.98	7.99	2.0	132	803	554	165.2	150.0	33.2	19.4	380	289	7.23	0.61
ST2	07/17/2019	74.85	76.27	7.24	1.7	137	784	501	168.6	148.6	32.4	18.8	355	275	8.58	0.78
ST2	07/18/2019	86.17	87.50	7.74	1.8	137	819	573	175.7	147.0	31.3	19.4	360	284	10.16	0.55
ST2	07/19/2019	49.22	53.00	7.74	1.9	133	805	567	181.9	145.7	35.8	17.3	375	297	9.75	0.69
ST1	12/06/2019	145.37	148.18	7.61	2.7	119	555	395	42.0	39.3	35.0	16.5	330	277	7.23	1.12
ST1	12/07/2019	106.91	108.99	7.52	2.9	149	613	459	38.0	34.7	33.0	17.3	347	264	6.77	1.25
ST1	12/08/2019	148.75	151.64	7.52	3.0	141	657	485	40.0	38.0	36.0	17.5	350	255	7.45	1.37
ST1	12/09/2019	154.32	156.93	7.60	2.9	163	613	454	40.0	36.0	33.3	15.8	348	262	7.68	1.21
ST1	12/10/2019	141.27	143.53	7.59	3.1	140	547	387	38.0	33.3	32.1	16.7	367	298	7.68	1.09

ID	Sample date	Flushing water	Eff water	pH	E.C.	Cl-	COD _{cr}	BOD ₅	SS	VSS	T-P	PO ₄ -P	T-N	NH ₄ -N	NO ₃ -N	NO ₂ -N
ST1	12/11/2019	118.29	121.88	7.55	3.0	117	569	401	39.3	37.3	32.4	17.7	352	262	7.23	1.11
ST1	12/12/2019	134.39	137.88	7.62	3.0	134	660	496	44.0	41.3	31.5	15.1	339	261	7.90	1.05
ST2	12/16/2019	77.82	80.20	7.82	2.2	101	773	575	183.2	150.2	35.6	17.6	360	291	7.52	1.02
ST2	12/17/2019	151.72	154.22	7.91	2.1	143	820	566	165.3	140.5	36.5	14.8	365	289	7.98	0.97
ST2	12/18/2019	85.36	88.92	7.75	2.2	141	895	665	175.5	154.4	40.5	17.6	359	287	8.05	0.91
ST2	12/19/2019	105.32	109.04	7.73	2.0	121	810	547	189.3	164.7	35.6	15.7	379	309	8.06	1.03
ST2	12/20/2019	77.21	80.12	7.85	2.1	135	870	620	185.7	157.7	40.8	16.6	380	305	7.38	0.85
ST2	12/21/2019	146.98	150.01	7.82	2.2	144	887	591	190.6	162.1	31.5	14.9	388	321	7.97	0.90
ST2	12/22/2019	171.23	175.18	7.81	2.2	109	762	508	187.5	153.8	32.7	18.7	365	290	7.83	0.95
ST11				7.96	3.0	121	641	442	98.0	85.6	37.8	15.6	377	297	6.71	0.57
ST12				7.38	3.3	168	1126	765	231.3	218.0	34.7	14.9	350	263	5.90	0.54
ST13				7.73	2.6	138	862	576	218.7	186.2	55.5	27.6	420	319	7.48	0.40
ST14				8.04	2.1	88	1082	714	195.4	173.3	43.6	16.2	325	247	6.52	0.46
ST15				7.71	2.7	128	987	631	205.5	185.8	40.5	23.7	322	249	5.95	0.92
ST16				7.31	2.3	92	607	425	78.7	69.3	54.2	31.4	360	284	5.98	1.10
ST17				7.86	2.6	101	882	621	179.2	157.2	45.6	28.3	410	325	6.35	1.17
ST18				7.50	3.0	153	1055	749	185.1	168.5	47.1	22.7	409	343	6.51	1.03
ST19				7.41	2.0	65	454	340	70.5	60.6	39.1	18.5	384	292	8.27	1.17
ST20				7.44	1.80	112	335	257	35.9	29.1	35.7	18.7	377	275	6.63	1.02
ST21				7.65	2.10	71	678	535	85.5	73.5	40.7	19.8	402	303	6.98	0.93
ST22				7.71	2.70	119	973	777	165.1	138.7	45.9	21.7	394	320	9.27	1.26
ST23				7.83	2.70	75	909	654	170.2	149.8	46.1	24.1	389	290	8.90	1.08

Appendix C. Septage compositions

ID	Liquid temp °C	DO mg/L	ORP mV	COD _{cr} mg/L	sCOD _{cr} mg/L	BOD ₅ mg/L	T-N mg/L	NH ₄ -N mg/L	NO ₃ -N mg/L	NO ₂ -N mg/L	T-P mg/L	SS mg/L	VSS mg/L
ST1_1	31.1	0.03	-346	5,500	567	4,455	400	250	4.1	2.1	74	5880	3570
ST1_2	31.1	0.02	-346	6,100	611	4,758	500	267	5.1	1.9	69	5910	3760
ST2_1	31.4	0.02	-434	16,660	958	13,161	1400	292	6.3	1.5	341	7760	6940
ST2_2	31.4	0.03	-434	15,124	980	12,402	1600	264	7.2	2.2	357	7850	7020
ST3	31.7	0.18	-479	17,576	1,032	14,964	1800	478	5.3	3.5	363	9264	6484
ST4	31.4	0.26	-305	9,584	1,504	8,571	2200	584	4.7	3.1	397	8830	6064
ST5	31.1	0.19	-489	16,758	1,498	13,001	2100	533	6.7	1.8	521	9870	7983
ST6	31.2	0.31	-237	7,820	805	6,621	700	175	7	1.9	89	6020	4418
ST7	31.0	0.17	-334	16,286	818	13,529	1800	532	5.7	2.1	457	6788	4730
ST8	31.0	0.08	-445	17,220	1,820	13,076	2100	451	6.7	2.5	375	9934	7679
ST9	30.6	0.21	-391	13,068	1,126	10,924	2000	440	4.9	2.5	507	9067	6373
ST10	30.1	0.34	-230	6,250	703	5,013	900	172	7.7	2.7	108	5573	4004
ST1	21.6	0.02	-346	5,800	600	4,350	588	242	4.2	2.0	69	5472	3874
ST2	22.1	0.05	-434	18,280	678	13,893	1540	290	6.5	1.9	368	7944	4446
ST11	19.1	0.45	-278	16,740	1,284	13,225	1325	353	7.5	2.7	77	6800	4815
ST12	21.3	0.02	-563	37,135	1,762	33,422	1300	230	6.3	1.9	110	10860	6078
ST13	22.2	0.04	-497	29,340	1,206	23,179	2625	700	5.7	1.5	213	9822	7137
ST14	21.3	0.17	-374	23,840	914	17,880	2150	315	5.9	2.1	126	8166	6182
ST15	21.3	0.08	-331	28,441	1,478	25,597	3625	620	4.8	2.5	236	9382	6456
ST16	21.6	0.31	-275	10,830	907	8,123	1425	570	6.2	2.6	98	5216	3206

ID	Liquid temp	DO	ORP	COD_{cr}	sCOD_{cr}	BOD₅	T-N	NH₄-N	NO₃-N	NO₂-N	T-P	SS	VSS
ST17	22.1	0.28	-302	22,080	1,238	17,002	2150	500	5.7	1.7	189	8854	5673
ST18	23.6	0.02	-501	29,592	1,535	25,153	3075	360	6.7	1.6	203	9594	5633
ST19	22.5	0.37	-267	7,245	653	5,434	1218	225	6.9	2.1	172	5307	3730
ST20	21.6	0.38	-227	5,190	553	4,152	915	235	6.5	2.2	61	4855	2447
ST21	21.7	0.32	-298	9,024	798	7,490	1569	425	6.4	2.6	85	5682	4129
ST22	20.1	0.21	-445	23,200	1,337	20,648	3025	750	5.1	1.7	251	9637	7296
ST23	24.2	0.05	-409	21,945	1,309	19,751	2567	615	5.7	1.9	215	8422	5796

Appendix D. Gases concentrations

ID	Time	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppm)
ST1_1	0	10	394	
ST1_1	10	2821	2007	
ST1_1	20	3522	3520	
ST1_1	30	5809	4381	
ST1_1	40	7098	5179	
ST1_1	50	10125	6605	
ST1_1	60	12550	7502	0.625
ST1_2	0	5	459	
ST1_2	10	2055	1827	
ST1_2	20	4278	2274	
ST1_2	30	5257	3607	
ST1_2	40	7115	4173	
ST1_2	50	9639	5819	
ST1_2	60	11027	6707	0.784
ST2-1	0	9	421	
ST2-1	10	4152	3009	
ST2-1	20	8518	6650	
ST2-1	30	13468	7485	
ST2-1	40	17914	8591	
ST2-1	50	19916	9556	
ST2-1	60	23379	11069	0.619
ST2-2	0	15	450	
ST2-2	10	4579	2975	
ST2-2	20	7067	7029	
ST2-2	30	14861	8012	
ST2-2	40	16607	9127	
ST2-2	50	20077	10657	
ST2-2	60	25579	13541	0.559
ST3	0	10	367	
ST3	10	2703	2053	
ST3	20	3971	5897	
ST3	30	5957	6806	
ST3	40	8234	9116	
ST3	50	9925	11815	
ST3	60	11151	12315	1.015
ST4	0	9	455	
ST4	10	1709	876	
ST4	20	2576	1103	
ST4	30	3541	2087	
ST4	40	4218	2597	
ST4	50	5729	3087	
ST4	60	6537	4577	0.527
ST5	0	15	557	

ID	Time	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppm)
ST5	10	2877	1131	
ST5	20	6005	3507	
ST5	30	9073	4781	
ST5	40	9905	5972	
ST5	50	11017	6259	
ST5	60	15561	7640	0.862
ST6	0	11	359	
ST6	10	2027	803	
ST6	20	3697	1131	
ST6	30	5043	2008	
ST6	40	6588	2263	
ST6	50	7023	3379	
ST6	60	9276	4816	0.496
ST7	0	7	487	
ST7	10	3006	1048	
ST7	20	5658	4281	
ST7	30	6527	5687	
ST7	40	8364	6257	
ST7	50	12074	7473	
ST7	60	14043	8870	0.445
ST8	0	5	321	
ST8	10	3057	2072	
ST8	20	8058	3524	
ST8	30	12435	4475	
ST8	40	15911	5027	
ST8	50	18377	7755	
ST8	60	20865	9630	0.523
ST9	0	7	403	
ST9	10	2550	1274	
ST9	20	5729	3754	
ST9	30	6252	4138	
ST9	40	8843	5671	
ST9	50	10447	8127	
ST9	60	14506	9521	ND
ST10	0	9	457	
ST10	10	2305	2529	
ST10	20	4982	5206	
ST10	30	8775	6907	
ST10	40	10097	7513	
ST10	50	11465	10738	
ST10	60	14085	12031	0.437
ST1-1	0	9	359	
ST1-1	10	2500	2009	
ST1-1	20	4192	3579	
ST1-1	30	6487	5010	

ID	Time	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppm)
ST1-1	40	8784	6064	0.221
ST1-2	0	7	427	
ST1-2	10	2061	2078	
ST1-2	20	3716	4237	
ST1-2	30	5071	5221	
ST1-2	40	6271	6692	0.511
ST1-3	0	5	407	
ST1-3	10	2138	2067	
ST1-3	20	4023	3041	
ST1-3	30	7171	3508	
ST1-3	40	8004	5627	0.421
ST1-4	0	11	311	
ST1-4	10	2289	1190	
ST1-4	20	4867	3069	
ST1-4	30	6145	4548	
ST1-4	40	7023	5072	0.448
ST1-5	0	9	409	
ST1-5	10	2055	942	
ST1-5	20	3902	2076	
ST1-5	30	5048	3709	
ST1-5	40	6795	5743	0.338
ST2-1	0	10	355	
ST2-1	10	4013	4109	
ST2-1	20	8417	6863	
ST2-1	30	12720	8617	
ST2-1	40	14824	11372	0.657
ST2-2	0	11	376	
ST2-2	10	4798	3777	
ST2-2	20	6586	5178.6	
ST2-2	30	13373	8579	
ST2-2	40	15161	9981	0.661
ST2-3	0	9	401	
ST2-3	10	5049	4071	
ST2-3	20	8889	5741	
ST2-3	30	14009	9411	
ST2-3	40	15770	11081	0.775
ST2-4	0	10	377	
ST2-4	10	6042	3913	
ST2-4	20	9975	5450	
ST2-4	30	13008	8587	
ST2-4	40	16941	10524	0.661
ST2-5	0	7	352	
ST2-5	10	4912	3884	
ST2-5	20	7817.6	7017	
ST2-5	30	13722	7949	

ID	Time	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppm)
ST2-5	40	15628	10482	0.939
ST11	0	5	321	
ST11	10	2074	1561	
ST11	20	5544	2501	
ST11	30	7313	5041	
ST11	40	9083.3	7482	1.067
ST12	0	6	319	
ST12	10	7645	5841	
ST12	20	12881	9987	
ST12	30	18629	13818	
ST12	40	22571	15678	0.505
ST13	0	7	347	
ST13	10	3016	3043	
ST13	20	7632	4760	
ST13	30	10227	8756	
ST13	40	13243	10413	0.156
ST14	0	7	381	
ST14	10	3094	2710	
ST14	20	6481	4383	
ST14	30	7648	5056	
ST14	40	9955	7287	0.754
ST15	0	2	326	
ST15	10	3563	1707	
ST15	20	7524	2433	
ST15	30	9885	3787	
ST15	40	11846	4357	0.268
ST16	0	3	317	
ST16	10	1354	1354	
ST16	20	2507	1791	
ST16	30	3255	2422	
ST16	40	4199	2866	0.216
ST17	0	5	351	
ST17	10	2583	2920	
ST17	20	6059	5209	
ST17	30	9563	8160	
ST17	40	11514	10628	0.556
ST18	0	5	367	
ST18	10	5438	3585	
ST18	20	8261	5348	
ST18	30	15239	7782	
ST18	40	16317	9240	0.428
ST19	0	4	357	
ST19	10	2394	1006	
ST19	20	2785	2256	
ST19	30	4575	2805	

ID	Time	CH ₄ (ppm)	CO ₂ (ppm)	N ₂ O (ppm)
ST19	40	5566	3355	0.642
ST20	0	4	388	
ST20	10	1531	1573	
ST20	20	2088	2778	
ST20	30	3045	3143	
ST20	40	3433	3928	0.758
ST21	0	10	364	
ST21	10	2462	1854	
ST21	20	3514	5984	
ST21	30	5566	8525	
ST21	40	9618	10244	0.879
ST22	0	6	409	
ST22	10	3357	3961	
ST22	20	6713	7513	
ST22	30	9966	9665	
ST22	40	11420	12417	0.387
ST23	0	5	367	
ST23	10	3213	2395	
ST23	20	5061	4053	
ST23	30	9390	9710	
ST23	40	12517	12639	0.667

Appendix E. CH₄ and CO₂ emission rates

	CH ₄ emission rate from the first compartment (g/cap/day)	CO ₂ emission rate from the first compartment (g/cap/day)	CH ₄ emission rate from the all compartments (g/cap/day)	CO ₂ emission rate from the all compartments (g/cap/day)
ST1-1	11.60	19.26	13.01	22.32
ST1-2	10.62	16.36	11.90	18.96
ST2-1	15.06	17.52	17.58	21.36
ST2-12	15.90	21.16	18.56	25.79
ST3	8.87	27.43	12.34	41.47
ST4	8.76	15.05	9.84	17.49
ST5	16.62	23.24	19.14	27.85
ST6	6.43	8.54	7.53	10.45
ST7	18.79	32.82	21.25	38.44
ST8	12.51	13.89	14.51	16.79
ST9	13.93	26.38	15.34	29.87
ST10	4.42	9.90	5.65	13.50
ST1-1	12.93	23.80	14.50	27.58
ST1-2	9.34	24.09	10.47	27.91
ST1-3	12.64	19.63	14.17	22.75
ST1-4	10.74	21.28	12.05	24.66
ST1-5	9.95	22.20	11.16	25.72
ST2-1	14.99	28.55	17.50	34.80
ST2-2	15.22	25.86	17.77	31.52
ST2-3	15.82	28.69	18.46	34.97
ST2-4	15.90	26.74	18.56	32.59
ST2-5	15.67	26.17	18.29	31.90
ST11	6.61	13.82	8.56	19.17
ST12	24.12	45.74	30.18	60.80
ST13	15.46	32.62	21.11	48.22
ST14	8.21	14.91	9.97	19.11
ST15	26.81	24.91	33.11	32.59
ST16	2.64	4.34	3.41	6.01
ST17	6.79	16.05	9.03	23.00
ST18	46.38	65.97	53.33	78.92
ST19	2.23	3.60	3.35	5.95
ST20	3.95	11.23	4.96	14.97
ST21	5.78	18.83	7.52	26.25
ST22	5.29	14.68	7.06	21.13
ST23	10.29	28.89	12.37	36.56

Appendix F. Concentrations of CH₄, CO₂, CO, N₂O, and NH₃ accumulated in the floating chamber at t = 60 min (summer survey)

	CH ₄ (ppm)	CO ₂ (ppm)	CO (ppm)	N ₂ O (ppm)	NH ₃ (ppm)
ST1*	14,661	7,105	0	0.705	<0.5
ST2*	24,479	12,305	1	0.589	<0.5
ST3	11,151	12,315	0	1.015	1.87
ST4	6,537	4,577	0	0.527	<0.5
ST5	15,561	7,640	0	0.862	<0.5
ST6	9,276	4,816	0	0.496	0.53
ST7	14,043	8,870	1	0.445	<0.5
ST8	20,865	9,630	1	0.523	<0.5
ST9	14,506	9,521	0	<0.1	<0.5
ST10	14,085	12,031	0	0.437	<0.5

Note: *: the average of 2 times sampling;

Appendix G. Concentrations of CH₄, CO₂, CO, N₂O, and NH₃ accumulated in the floating chamber at t = 40 min (winter survey)

	CH ₄ (ppm)	CO ₂ (ppm)	CO (ppm)	N ₂ O (ppm)	NH ₃ (ppm)
ST1-1	10,376	7,149	1	0.221	0.32
ST1-2	9,426	7,847	4	0.511	<0.5
ST1-3	10,537	8,475	1	0.421	<0.5
ST1-4	10,723	8,627	1	0.448	<0.5
ST1-5	11,795	7,743	1	0.338	<0.5
ST2-1	14,824	11,372	1	0.657	0.25
ST2-2	15,161	9,981	1	0.661	<0.5
ST2-3	15,770	11,081	1	0.775	<0.5
ST2-4	16,941	10,524	5	0.661	<0.5
ST2-5	15,628	10,482	3	0.939	<0.5
ST11	7,083	4,482	1	1.067	1.07
ST12	22,571	15,678	1	0.505	<0.5
ST13	11,243	8,413	1	0.156	<0.5
ST14	9,955	7,287	0	0.754	<0.5
ST15	11,846	4,357	1	0.268	0.55
ST16	4,199	2,866	3	0.216	<0.5
ST17	7,514	6,628	0	0.556	0.67
ST18	16,317	9,240	3	0.428	0.85
ST19	5,566	3,355	1	0.642	<0.5
ST20	3,433	3,928	0	0.758	<0.5
ST21	6,618	5,244	3	0.879	0.88
ST22	9,420	11,417	1	0.387	<0.5
ST23	8,517	6,639	1	0.667	<0.5