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Impact of GHG mitigation measures in sanitation service chains: a focus on septic tanks and sewers

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ABSTRACT

Sanitation service chains (SSC) often consist of a complex mix of different components, frequently involving the coexistence of non-sewered sanitation (e.g., septic tanks) and sewered sanitation. Poorly-maintained components within these chains can lead to substantial, yet potentially avoidable greenhouse gas (GHG) emissions. In this study, we developed a model for estimating the impact of GHG mitigation measures along SSCs that feature overlapping and poorly maintained non-sewered and sewered sanitation, taking the interdependencies of the GHG emissions of these components into account. To this end, we employed mass balance, empirical emission equations, and a carbon footprint estimation model to estimate GHG emissions by component at baseline and under four mitigation scenarios using an example SSC in Hanoi. The results showed that the SSC is predominantly methane-emitting, with poorly-maintained septic tanks and sewers being the primary contributors to the GHG emissions. Annual septic tank emptying was also identified as an effective strategy for reducing GHG emissions and it accounted for a 31–38% decline in total emissions relative to baseline emission level. Scenario comparison further showed that removing septic tanks and upgrading sewers, even though associated with a slight increase in N_2O emissions from the wastewater treatment plant, offer the greatest long-term mitigation potential, yielding 15–24% lower emissions than

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annual emptying septic tanks with sewer upgrades. Additionally, if septic tanks are not removed, they will remain the primary source of GHG emissions even after upgraded sewer and centralized treatment is established. However, in cases where septic tank removal poses social challenges, frequent emptying remained a robust and immediately applicable mitigation option. Overall, this study provides a framework for identifying and quantifying major GHG emission reduction strategies for complex SSCs. Additionally, the results obtained indicated that managing septic tanks and sewers are important climate action strategies for ensuring sustainable city-wide inclusive sanitation.

KEYWORDS: septic tanks, non-sewered sanitation (NSS), GHG mitigation, sanitation service chains, city-wide inclusive sanitation (CWIS)

1. Introduction

The sanitation sector constitutes an important source of greenhouse gas (GHG) emissions globally (Ddiba et al., 2024). In urban areas in particular, sanitation service chains (SSCs) include a wide range of technologies that can be categorized under four functional components, namely, (i) containment (e.g., pit latrines and septic tanks), (ii) emptying and transportation (e.g., vacuum trucks and sewers), (iii) treatment (e.g., wastewater or fecal sludge treatment plants), and (iv) end-use and disposal (e.g., fertilizer production, landfilling, and discharge into the environment) components (Harada et al., 2015). The technologies associated with these different SSC components vary by city, especially in low- and middle-income countries (LMIC) (Harada et al., 2015; Medland et al., 2016; Hyun et al., 2019), where SSCs rarely consist of a single type of technology, but often constitute a combination of both non-sewered and sewered sanitation. Additionally, in these countries, these different sanitation types are often operated within the same SSC, either in parallel (side-by-side) or in an overlapping or interconnected manner. A typical example of such an interconnection is the partial treatment of domestic wastewater in poorly-maintained septic tanks followed by the subsequent decomposition of the resulting effluent in poorly-maintained sewers, and finally, transportation to a centralized wastewater treatment plant (WWTP) for further treatment.

Each SSC component can be a source of GHG emissions, particularly when the SSC is poorly maintained. For example, with respect to containment components, septic tanks with long emptying intervals, tend to emit more CH_4 than those with shorter emptying intervals (Moonkawin et al., 2023). Similarly, for emptying and transportation components, poorly maintained gravity sewers could become major sources of CH_4 emissions owing to the presence of stagnant wastewater (Chaosakul et al., 2014; IPCC, 2006). Further, during a period of high flow, sewers can emit N_2O (Short et al., 2014), and reportedly, CH_4 and N_2O have global warming potentials (GWPs) that are 28 and 273 times higher than that of CO_2 over a 100-year timescale (IPCC, 2023). Furthermore, wastewater treatment plants (WWTPs) and fecal sludge treatment plants (FSTPs) are sources of CH_4, N_2O, and CO_2, even when properly operated, owing to their associated biochemical reactions and energy-intensive nature (Cakir and Stenstrom, 2005; Doorn et al., 1997; Frijns, 2012; Law et al., 2012; Mamais et al., 2015).

The interconnection between SSC components can considerably complicate the assessment of mitigation strategies. Shortening septic tank emptying interval can reduce CH_4 emissions, but

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lead to higher GHG emissions as a result of the increased frequency of transportation by vacuum trucks and the higher operational demands on FSTPs to handle larger volumes of emptied fecal sludge. Therefore, when designing mitigation measures, it is necessary to take the impact of emptying and transportation using vacuum trucks and treatment at FSTPs into account. Shortening septic tank emptying interval can also affect the quality of septic tank effluents, thereby influencing emissions from subsequent components, such as sewers and WWTPs. This implies that mitigating GHG emissions from individual SCC components can lead to changes in GHG emissions from downstream components, and hence, alter overall emissions. While most previous studies have focused on quantifying GHG emissions from individual SSC components (Chaosakul et al., 2014; Huynh et al., 2021; Short et al., 2014), the first study aimed at estimating city-wide GHG emissions, taking all SSC components into account was recently conducted in Kampala, Uganda, and this study by Johnson et al. (2022) serves as a baseline for quantifying GHG emissions for the entire SSCs. However, a predictive framework for evaluating potential mitigation scenarios across interconnected SSC components is still lacking.

To bridge this knowledge gap, a model that connects all SSC components for GHG emission estimation, taking into account the interdependencies of the individual SSC components was developed in this study. This model allowed the prediction of GHG emissions from individual SSC components as well as the entire SSC and highlighted how changes in upstream components directly affect downstream emissions, thereby aiding the development of effective countermeasures. We applied this approach to the Truc Bach sewerage and drainage area in Hanoi, Vietnam, a typical complex SSC comprising poorly maintained and overlapping sewered and non-sewered sanitation. First, we estimated the current state of GHG emissions in this SSC. Thereafter, we estimated GHG emissions under four potential mitigation scenarios considering the following GHG emission mitigation measures: frequent emptying of septic tanks, removal of septic tanks, and/or improving sewer conditions. These mitigation measures were selected not only to identify the most effective mitigation strategy for the selected area, but also to provide reference information applicable to mitigate GHG emissions in areas where the overlapping and interconnected use of non-sewered sanitation, especially septic tanks, and sewered sanitation is widely employed.

2. Materials and methods

2.1 Study area

The study area was selected based on the following criteria: (i) a SSC comprising all the above mentioned SSC components; (ii) the SSC is representative of SSCs in LMIC, in terms of management and component conditions; and (iii) data including septic tank GHG emissions, wastewater characteristics (e.g., blackwater and graywater, fecal sludge, WWTP influent), WWTP configuration, and the proportion of wastewater collected and transferred from each component of the SSC (Supplementary Information Table S1-1) are available and accessible. The sewerage and drainage area that fulfilled these criteria was the Truc Bach drainage area in urban Hanoi, Vietnam (Fig. S1-1).

In Hanoi, 88% of households rely on septic tanks (Brandes et al., 2016), with the average emptying interval being 10.2 years (Pham, 2014), and typically, these septic tanks receive only blackwater and consist of two or three compartments (Huynh et al., 2021). Effluent from these septic tanks and graywater from households are often discharged directly into combined gravity sewers or open drains (The World Bank, 2013).

The Truc Bach sewerage and drainage area has a population of 15,700 individuals (Brandes et al., 2016) and covers 0.55 km^2 (Hanoi Sewerage and Drainage Company Limited, 2021). Further, it has one WWTP, the Truc Bach WWTP, with a treatment capacity of 2,500 m^3/d, which allows the treatment of wastewater from Truc Bach and nearby areas. It also has one FSTP, the Cau Dzien FSTP (i.e., Hanoi URENCO 4), with a design capacity of 300 m^3/d. All the fecal sludge treated at this FSTP originates from public toilets (Brandes et al., 2016), while fecal sludge from household septic tanks is emptied using vacuum trucks and directly discharged into the environment without treatment (Nguyen et al., 2011).

2.2 Data analysis

2.2.1 System boundary and input data

We defined the system boundary for GHG emissions along the selected SSC in our study area as shown in Fig. 1. Thus, we included emissions from: (i) containment (i.e., septic tanks), (ii) emptying and transportation (i.e., vacuum trucks and sewers), and (iii) treatment (i.e., WWTP and FSTP) components. We focused on emissions from engineered infrastructure. Therefore, end-use and disposal-related emissions, including those from the sludge and wastewater discharged into the environment, were considered to be outside the system boundary. However, as a large fraction of wastewater and fecal sludge might be discharged without treatment in

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many cities in LMIC, we performed uncertainty analysis to explore the potential impact of the adopted system boundary as described in Section 2.2.9.

Further, we focused only on wastewater generated from households, while stormwater and wastewater from other types of facilities (e.g., restaurants, hotels, and public toilets) were not included in the dataset.

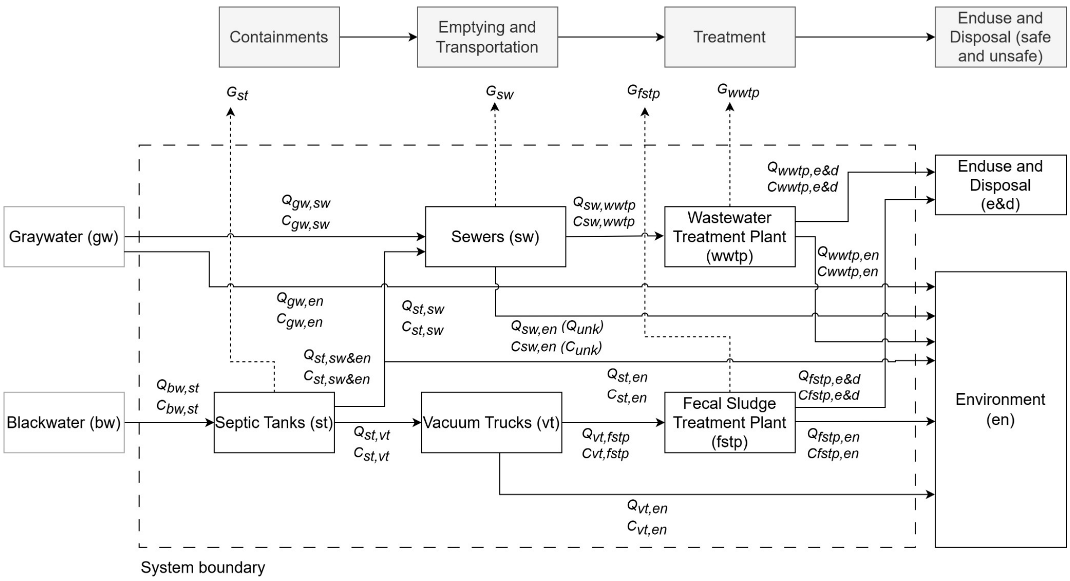

Fig. 1. Schematic representation of flow rates (Q) and chemical oxygen demand (COD) concentrations (C) in the sanitation service chain (SSC), including the system boundary. $Q_{i,j}$ denotes the flow rate from component i to j; $C_{i,j}$ denotes the change in COD concentration from component i to j; and G_i denotes GHG emissions from component i.

Wastewater flow rate (Q) and COD load (L) were calculated for each component using the mass balance approach (Eq. (1) and (2)). The descriptions and equations used to calculate all the parameters required to estimate Q and L are listed in Table S1-2. Q and L estimates were determined using the measured and reported parameters listed in Table S1-1 considering the system boundary.

$$\sum Q_{in,i} - \sum Q_{out,i} = 0 \quad (1)$$

$$\sum L_{in,i} - \sum L_{out,i} = 0 \quad (2)$$

where *Q* represents wastewater flow rate (m^3/d) and *L* represents the COD load (kg COD/d) obtained by multiplying *Q* (m^3/d) by the COD concentration (*C*) (g/m^3).

To ensure the mass of COD was conserved for each SSC component, the total degraded COD load was quantified taking into account its conversion into gaseous end-products, i.e., CH_4 and biogenic CO_2. In this study, we did not perform complete nitrogen balance. However, N_2O emissions were estimated using methods suitable for the different SSC components. Specifically, for the WWTP, total nitrogen concentration was input for a process-based model, while for the sewers, for which data on wastewater nitrogen content is unavailable, a per-capita N_2O emission factor was applied (see details in Section 2.2.4 and 2.2.6).

Given the absence of data on the quality and quantity of wastewater discharged directly from sewers into the environment, including leakage data, during mass balance calculations for sewers, we subtracted the flow rates and COD loads entering the sewers from those transferred to the WWTP. The value thus obtained was referred to as the unknown flow rate (Q_{unk}). Thereafter, unknown concentrations (C_{unk}) were calculated based on the obtained Q_{unk}. Hence, the unknown COD load, representing the remaining COD loads after subtracting the COD load of wastewater from sewers transferred to the WWTP ($L_{sw,wwtp}$), was determined as L_{unk} = $Q_{unk} \times C_{unk}$ as shown in Eq. (3). Further details in this regard are provided in Section S2.

$$L_{unk} = L_{st,sw} + L_{gw,sw} - L_{sw,wwtp} \quad (3)$$

Additionally, following the guidelines of the Intergovernmental Panel on Climate Change (IPCC), we assumed that in sewers, 50% of COD decomposes via biological processes (Δ_{sw}), resulting in the generation of CH_4 (IPCC, 2006, 2019). Then, we used Sankey diagrams to separately present the percentages of Q and L along the SSC and thus, provide an overview of the current state of wastewater and COD mass streams (SankeyMATIC, 2014). A comprehensive summary of the equations, key parameters, and assumptions for each SSC component is provided in Table S1-3.

2.2.2 GHG emission estimation

GHG emissions from the SSC, including CH_4, N_2O, and CO_2, were categorized under three emission scopes as follows: Scope 1, direct emissions from the decomposition processes of wastewater, e.g., CH_4 and N_2O emissions from biological processes; Scope 2, indirect emissions from electricity use; and Scope 3, indirect emissions associated with consumables and other activities, e.g., fuel consumption and chemical manufacturing. This categorization was performed in accordance with the GHG protocol corporate standard (WRI and WBCSD, 2004). Additionally, we focused on operational emissions. Thus, embodied carbon emissions from infrastructure construction, another Scope 3 category, were excluded. Even though Scopes 2 and 3 emissions are reported as operational emissions (Johnson et al., 2022), in this study, they were considered separately. Thus, we were able to perform a detailed analysis of distinct mitigation pathways and specifically distinguish between emissions related to electricity consumption and those related to fuel consumption during transportation. CO_2 emissions from the decomposition of organic compounds were excluded from the estimation given that they are considered entirely biogenic and would eventually cycle back into the atmosphere (Cheng et al., 2022; IPCC, 2006). The emission types, categorized by scope and according to GHG type (CH_4, N_2O, or CO_2) are listed in Table S1-4.

2.2.3 GHG emissions from septic tanks

To estimate emissions from septic tanks, we used the equation proposed by Moonkawin et al. (2023) for CH_4 emissions from septic tanks with long sludge emptying intervals.

$$EF_{CH4-st1} = mT_{st} + b \quad (4)$$

where $EF_{CH4\text{-}st1}$ represents the emission factor of CH_4 for the 1st compartment of the septic tank (g CH_4/(cap·d)), T_{st} represents the septic tank emptying interval (year), *b* represents the vertical intercept (3.83), and *m* represents slope (0.622).

Due to the inaccessibility of the 2nd and 3rd compartments, we estimated the GHG emission based on two approximations: (i) CH_4 production rates in the 2nd and 3rd compartments are the same as that in the 1st compartment (i.e., maximum septic tank emissions) and (ii) the 2nd and 3rd compartments cause no additional emissions (i.e., minimum septic tank emissions). All results related to GHG emissions from septic tanks were presented as minimum–maximum values. Further, given that N_2O production in septic tanks in Hanoi can be considered negligible

(Huynh et al., 2021), only CH_4 emission was considered. Further details regarding this estimation are provided in Section S3.

2.2.4 GHG emissions from sewers

Given the unavailability of direct measurement data for GHG emissions from sewers in the study area, we used the methane correction factor (MCF) recommended by the IPCC to estimate CH_4 emissions from sewers with stagnant wastewater in warm climates (IPCC, 2019), as shown in Eq. (5).

$$E_{CH4-sw} = C_{sw-in} \times B_0 \times MCF_{sw} \times GWP_{CH4} \times 365 \times 10^{-3} \quad (5)$$

where E_{CH4-sw} represents CH_4 emissions from sewers (tonCO_2e/year); C_{sw-in} represents the COD load entering sewers (kg COD/d), and GWP_{CH4} represents the GWP of CH_4.

The estimation included COD loads entering the sewers, MCF, and the IPCC's theoretical CH_4-producing capacity (B_0). Specifically, MCF refers to the fraction of COD used for CH_4 production and B_0 represents CH_4 production per unit COD (kg CH_4/kg COD). Default MCF (MCF_{sw}: 0.5) and B_0 (0.25 kg CH_4/kg COD) values for sewers were used in this regard. This approach, using IPCC's default MCF of 0.5 to capture the overall anaerobic decomposition of incoming COD in sewers, enabled the estimation of upper-bound or worst-case emissions. Thus, this upper-bound emission reflects the extreme conditions of the sewers (i.e., poorly maintained and stagnant sewers under warm climate). Further, the estimate thus obtained represented the upper-bound GHG emissions given that IPCC's default MCF does not account for the pre-treatment of blackwater in an upstream septic tank, in which readily biodegradable organic matter is removed. Therefore, a lower-bound case reflecting partial degradation was also assessed and discussed using an MCF of 0.2, consistent with Johnson et al. (2022). Details regarding the impact of this assumption are presented in Section 3.4.4, which discusses uncertainties related to sewer emission estimation.

N_2O emissions were estimated using the gravity sewer-based emission factor for N_2O derived by Short et al. (2014) as shown in Eq. (6).

$$E_{N2O-sw} = EF_{N2O-sw} \times N_{pop} \times GWP_{N2O} \times 10^{-6} \quad (6)$$

where $E_{N2O\text{-}sw}$ represents N_2O emission for sewers (ton CO_2e/year); $EF_{N2O\text{-}sw}$ represents the N_2O emission factor for gravity sewers (g N_2O/(cap·year)), and GWP_{N2O} represents the GWP of N_2O.

2.2.5 GHG emissions from vacuum trucks

GHG emissions from fecal sludge transportation using vacuum trucks were estimated based on emissions related to fuel consumption by the diesel vacuum trucks used to transport fecal sludge from the center of the Truc Bach drainage area to the FSTP or to disposal sites in the case of direct discharge without treatment. This trip was considered a round trip, and to estimate the associated emissions, the emission factors of CO_2, CH_4, and N_2O, and the total number of trips required to empty all the septic tanks within a given emptying interval were taken into account. The equations used in this regard are provided in Section S4.

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2.2.6 GHG emissions from WWTPs

Wastewater treatment processes

To estimate GHG emissions from the WWTP, where wastewater from the Truc Bach sewerage and drainage area is treated, we input the flow rate, calculated via mass balance, to the configuration of the Truc Bach WWTP, wherein COD, nitrogen, and phosphorus removal is driven by an anaerobic–anoxic–oxic (A2O) process (Fig. S5-1). The effluent of the WWTP is discharged into the Truc Bach Lake, while the generated sludge is disposed of at a landfill located 41 km from the sewerage and drainage area. The GHG emissions associated with the transportation of sludge were estimated based on the same estimation approach as was applied for vacuum trucks. However, the dewatered sludge was assumed to be handled by a 2-ton truck. The emission factors employed are listed in Tables S1-2.

Model simulation

We employed the *Mantis3lib* carbon footprint estimation model to estimate GHG emissions from the WWTP. The WWTP was simulated considering steady state conditions with constant inflow using GPS-X 8.5 software (HATCH) (Hydromantis, 2022). The model input data included the flow rate of the influent reaching the WWTP ($Q_{sw,wwtp}$) obtained via mass balance, measured influent characteristics, such as COD and total nitrogen concentrations as reported by Watanabe et al. (2018), and the WWTP's configuration and equipment (Tables S5-1 and S5-2). Scope 1 emissions were estimated based on a plant-wide simulation using carbon, nitrogen, and phosphorus removal and integrating anaerobic digestion processes (i.e., ASM2d (Henze et al., 2015) and UCTADM1 (Sötemann et al., 2005)), a four-step N_2O production model (Hiatt and Grady, 2008), and N_2O production by autotrophic bacteria (Mampaey et al., 2013; Ni et al., 2012). Scope 2 emissions were estimated based on electricity use according to regional electricity-related emissions in Vietnam, and Scope 3 emissions were estimated based on the chemical consumption at the WWTP. The equations and parameters used for Scopes 2 and 3 emissions are presented in Section S5.3.

2.2.7 GHG emissions from FSTP

The different processes associated with the Cau Dzien FSTP, with a design capacity is 300 m^3/d (URENCO Hanoi and CENIC Co, 2023) are outlined in Fig. S6-1. Given that fecal sludge from household septic tanks is currently not transported to this FSTP (URENCO Hanoi and CENIC Co, 2023), GHG emissions from this FSTP were not included in the baseline scenario. However, Hanoi city plans to upgrade the FSTP to receive fecal sludge from households and employ sludge dewatering and anoxic-oxic activated sludge technologies (URENCO Hanoi and CENIC Co, 2023). Further details on the future upgraded FSTP, including the estimations of the associated GHG emissions are provided under Scenario A* (Section 2.2.8).

After estimating the GHG emissions associated with all the SSC components, the carbon mass balance of each component was verified using field data. The COD to total organic carbon (TOC) ratio of the influent of the septic tanks was applied to convert the COD into TOC for carbon balance. For septic tanks, mass balance was performed under two conditions: (i) the maximum GHG emission condition and (ii) the minimum GHG emission condition. The carbon mass balance results for each component are presented in Section S7.

2.2.8 Scenario development

First, we established a baseline scenario for GHG emissions along the current SSC and thereafter, explored four different mitigation scenarios for reducing GHG emissions based on SSC improvements (Table 1). Details regarding the different scenarios are provided in Table 1 and Table S8-1. Any point not mentioned was not subject to change and thus remained the same as in the baseline scenario.

Table 1. Potential GHG emission mitigation measures for different scenarios.

No.	Scenario	Potential mitigation measures
1	Baseline (current state)	-
2	Scenario A	Emptying septic tanks once a year
3	Scenario B	Removing or bypassing septic tanks
4	Scenario A*	Emptying septic tanks once a year; Sewer upgrades to ensure 100% conveyance and aerobic conditions; Treating all wastewater that is transported to the WWTP; No direct discharge; Treatment of all the fecal sludge that is transported to the FSTP
5	Scenario B*	Removing or bypassing septic tanks; Sewer upgrades to ensure 100% conveyance and aerobic conditions; Treating all wastewater at the WWTP; No direct discharge

Mitigation scenarios focusing on septic tanks

Scenario A

In Hanoi, it is recommended to empty septic tanks every 1–3 years, depending on the size of the septic tank (Nguyen, 2017). This emptying interval is within the globally recommended interval range of 1–5 years (HM Government, 2015; USEPA, 2002). Therefore, we changed the average emptying interval from 10.2 years at baseline to 1 year (i.e., emptying once a year) under Scenario A to assess the GHG emission reduction potential of frequent septic tank emptying. This change in emptying frequency not only affected the emission factor of the septic tanks (EF_{st}), but also affected the COD of the septic tank effluent ($C_{st\text{-}eff}$) as well as COD of the fecal sludge ($C_{st\text{-}fs}$) according to the empirical equations for septic tank performance and GHG emissions provided in Section S8.2 (Moonkawin et al., 2023). Accordingly, we calculated changes in COD loads and GHG emissions from individual components using the same methods as the baseline. Similar to the baseline scenario, some of the fecal sludge collected during septic tank emptying was not treated at the FSTP, but was directly discharged into the environment.

Scenario B

We hypothesized that removing or bypassing septic tanks can significantly reduce overall GHG emissions along the SSC. Thus, emissions from septic tanks as well as those from associated components, e.g., those related to fecal sludge transportation using vacuum trucks and treatment at FSTP, were considered to be zero. Under this scenario, blackwater is discharged directly into sewers. Thus, the COD of the wastewater transferred from sewers to the WWTP ($C_{sw\text{-}wwtp}$) and from the sewers to the environment ($C_{sw\text{-}en}$) were estimated. Thereafter, the GHG emissions for each component were re-estimated.

Mitigation scenarios focusing on septic tanks and sewers

*Scenario A**

This scenario builds on Scenario A by further modifying sewer conditions and fecal sludge treatment capacity to ensure that 100% of septic tank effluents and graywater are collected and transported to the WWTP, and 100% of emptied fecal sludge is transported to and treated at the future upgraded FSTP. These modifications resulted in the following changes to the inputs: (i) as the sewer was assumed to be clean and wastewater flows fast, CH_4 and N_2O emissions from sewers were assumed to be negligible according to IPCC guidelines (IPCC, 2019), (ii) all fecal sludge was treated at the future upgraded FSTP, which employs sludge dewatering and aerobic wastewater treatment; thus, emissions from the FSTP were estimated based on IPCC guidelines for aerobic treatment processes (IPCC, 2019), and (iii) dewatered sludge is transported to a landfill using a 2-ton truck. As a result, the processes associated with the upgraded plant (Fig. S6-2) were integrated into the GHG emission estimation model for the FSTP and using CH_4 and N_2O emission factors for aerobic treatment, in accordance with IPCC guidelines. Details regarding the estimation are presented in Section S6.2.

*Scenario B**

A fully sewered SSC with 100% sewer coverage was developed, assuming no leakages and the removal of all septic tanks. Further, to estimate the influent characteristics of the wastewater reaching the WWTP, we assumed that flow in the sewers is fast and that the sewers are clean. Thus, changes in wastewater characteristics within the sewers until they reached the WWTP were negligible. Hence, CH_4 and N_2O emissions from sewers were considered negligible, following IPCC guidelines (IPCC, 2019).

Scenarios A* and B*, which further extend the mitigation measures of Scenarios A and B, aimed to accomplish 100% wastewater and fecal sludge collection and treatment. Achieving these performance criteria would require substantial infrastructural changes, including the rehabilitation of sewers, targeted replacement of existing infrastructure, and proper maintenance of sewers. These two advanced scenarios enabled the exploration of GHG emission and reduction potential when sewer connections and conditions are improved and all the wastewater generated in the sewerage and drainage area is treated properly before discharge into the environment. Conversely, in Scenarios A and B, a portion of the wastewater and emptied sludge was discharged into the environment without proper treatment. This untreated discharge was outside the system boundary; hence, its associated emissions were not considered. Therefore, the results obtained under scenario A* could only be compared with that obtained under Scenario B*, and vice versa. Comparison with other scenarios (i.e., baseline and Scenarios A and B) was not applicable.

2.2.9 Sensitivity and uncertainty analyses

To evaluate the robustness of the model-based conclusions, sensitivity analysis alongside three types of uncertainty analyses were performed as detailed below.

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Sensitivity analysis

A one-at-a-time sensitivity analysis was performed to identify model parameters with the most pronounced effect on total GHG emissions within the defined system boundary for the baseline scenario. Specifically, key parameters were varied by ±10% and ±25% from their baseline values, and the associated GHG emissions were calculated as shown in Table S10-1.

Uncertainty analysis

Uncertainty related to parameter settings

To quantify the overall uncertainty associated with baseline GHG emission estimates, we employed bounding cases. Specifically, plausible high and low-bound values were established for the most sensitive parameters identified via the sensitivity analysis. The plausible low and high values of sensitive parameters were based on IPCC guidelines (IPCC, 2019) and reported literature data (Table S10-2). Thereafter, uncertainties were explored by calculating a low-emission case (i.e., all parameters at their lower bound) and a high-emission case (i.e., all parameters at their upper bound) to obtain a final plausible range of the estimated emissions under the baseline scenario.

Uncertainty related to system boundary settings

To assess the potential importance of emissions outside our demarcated system boundary, we estimated potential emissions from the direct discharge of untreated COD from sewers and vacuum trucks into the environment. A best-case condition assumed 0.4% of this COD is decomposed, while a worst-case condition assumed 27% decomposition, reflecting a range of potential anaerobic conditions in the receiving aquatic environments in accordance with IPCC guidelines (IPCC, 2019) for both cases.

Uncertainty related to the septic tank emission equation

A key assumption in this study was the application of the linear emission model (Eq. (4)) to the 1-year emptying interval considered under Scenarios A and A*. The empirical data used for the development of this model were from septic tanks with long emptying intervals (Moonkawin et al., 2023). Relevant studies have shown that methanogenic fermentation in septic systems only becomes effective after 2–3 years of operation (Bounds, 1995; Philip et al., 1993). To test the robustness of our model against this specific assumption, we selected Scenarios A to model a conservative case. In this test, the CH_4 emission factor for a 1-year interval was assumed to be only 50% of the value predicted based on Eq. (4), representing a system with sub-optimal methanogenesis. The results thus obtained were further compared with those obtained using IPCC's approach for estimating CH_4 emissions for septic tanks using a default MCF of 0.5.

Uncertainty related to the sewer emission estimation

As applying the IPCC's default MCF to the total incoming COD does not account for the partial COD degradation ($f_{degraded}$) within the sewer. Therefore, to estimate lower-bound case, we estimated the baseline GHG emission using a fraction of the degradable COD. Following the study of Johnson et al., (2022), we assumed an $f_{degraded}$ of 40%, and multiplying this fraction by IPCC's default MCF of 0.5 yielded an MCF of 0.2 for the lower-bound case.

3. Results and discussion

3.1 Wastewater flow along the SSC

The distribution of household wastewaters (blackwater, graywater, and sludge) along the SSC is shown in Fig. S9-1. Blackwater and graywater constituted 17% and 83%, respectively, of the wastewater generated in the investigated SSC, and only 18% of the total generated wastewater was treated properly at the WWTP, while 82% was discharged into the environment after passing through septic tanks and/or sewers. This percentage of appropriately treated wastewater seems realistic considering wastewater management in LMIC, as it is similar to the values reported in previous studies conducted in other parts of Asia, e.g., Hue, Vietnam (23%) (Watanabe et al., 2021), Thailand (24–27%) (Boontanon and Buathong, 2013; UN Habitat and WHO, 2021), India (27%), Bangladesh (16%), and Iran (22%) (UN Habitat and WHO, 2021). Additionally, of all the wastewaters generated in Hanoi, 21% was not treated at any level before discharge into the environment.

Owing to the absence of data on leakage, infiltration, exfiltration, and sewer connections, we referred to the net flow rate of these flows as unknown wastewater, of which 52% was estimated to have leaked out from sewers into the environment without treatment. This high loss may be attributed to the effects of exfiltration (Watanabe et al., 2021) or to the fact that sewers are still being constructed to drain wastewater and not to transport it to the WWTP.

Additionally, given that the average emptying interval of septic tanks in Hanoi is 10.2 years (Pham, 2014), the fecal sludge collected by vacuum trucks was equivalent to 0.1% of the total generated wastewater, and this fecal sludge was not transported to the FSTP but directly discharged into the environment.

3.2 COD mass flow along the SSC

The COD flowing through each SSC component, expressed as a percentage of the total COD load generated from blackwater and graywater, is presented in Fig. 2. From this figure, it is evident that graywater constituted the main COD source (67%), whereas blackwater comprised 33% of the total generated COD in the sewerage and drainage area. After passing through septic tanks, only one-third of the generated COD passed through the sewers, while the remainder was decomposed in septic tanks, transported with fecal sludge, and directly discharged into the environment without secondary treatment. Further, only 7% of the total COD was transported to and treated at the WWTP. This low percentage of treated COD could be attributed to: (i) the low proportion of wastewater transported to the WWTP (Watanabe, 2018), (ii) the low COD concentration of wastewater after passing through sewers affected by infiltration, and (iii) a high level of COD degradation in poorly maintained sewers (IPCC, 2019; Watanabe, 2018). According to IPCC guidelines, the MCF for poorly maintained and stagnant sewers is 0.5, which indicates that up to 50% of the organic matter that decomposes in a sewer can be converted to CH_4 (IPCC, 2019). Therefore, in the upper-bound or worst case, unknown COD, i.e. COD discharged from sewers into the environment, was estimated to be approximately 24% of the total COD. This substantial portion of unknown COD could potentially cause water pollution and additional GHG emissions following environmental processes.

These findings highlight the severe challenges associated with wastewater management, particularly with respect to the effective transportation and treatment of wastewater and emptied fecal sludge. Furthermore, the high proportion of untreated wastewater suggests that there is a need to improve SSCs by enhancing sewer connections and conditions, monitoring leakage, and ensuring effective fecal sludge management to prevent water pollution and untraceable GHG emissions.

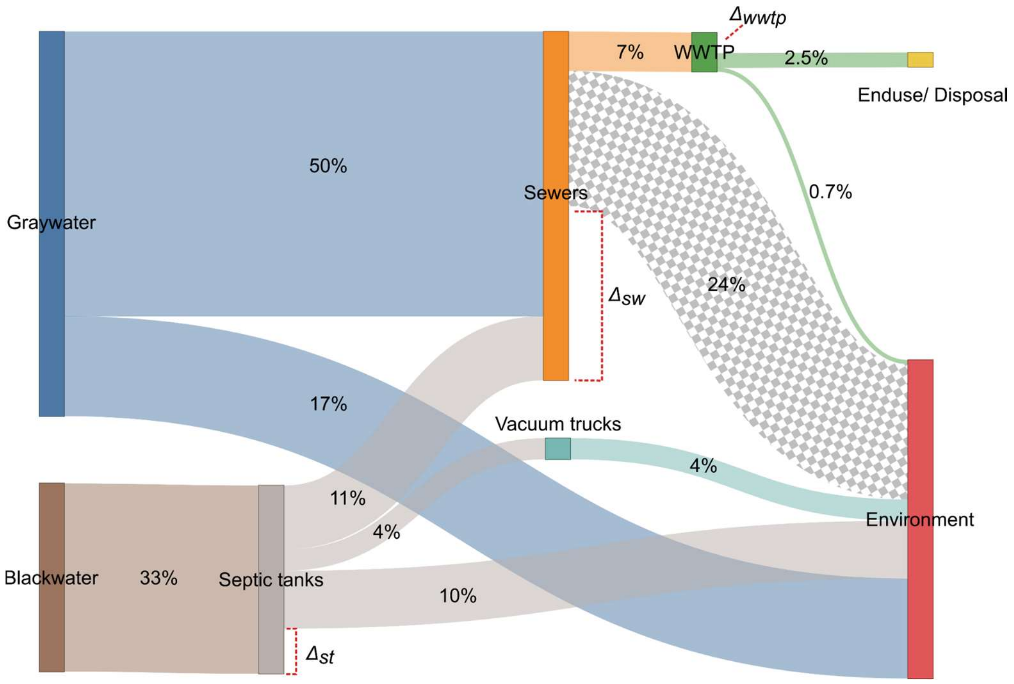

Fig. 2. COD mass flow in Hanoi, Vietnam. The percentage flow is expressed in relation to the total COD generated from blackwater and graywater in the SSC. Δ represents the COD that is decomposed in each component.

3.3 Estimation of GHG emissions along the SSC

3.3.1 Baseline

GHG emission estimation

At baseline, the estimated GHG emissions for the entire SSC varied in the range of 3,698–5,147 ton CO_2e/year (minimum–maximum GHG emissions, respectively) based on the assumptions regarding emissions from the 2nd and 3rd compartments of the septic tank as described in Section 2.2.3. It was also evident that the primary contributor to GHG emissions

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was septic tanks (44–60%), followed by sewers (23–32%), WWTP (17–24%), and vacuum trucks (0.06–0.1%) (Fig. 3).

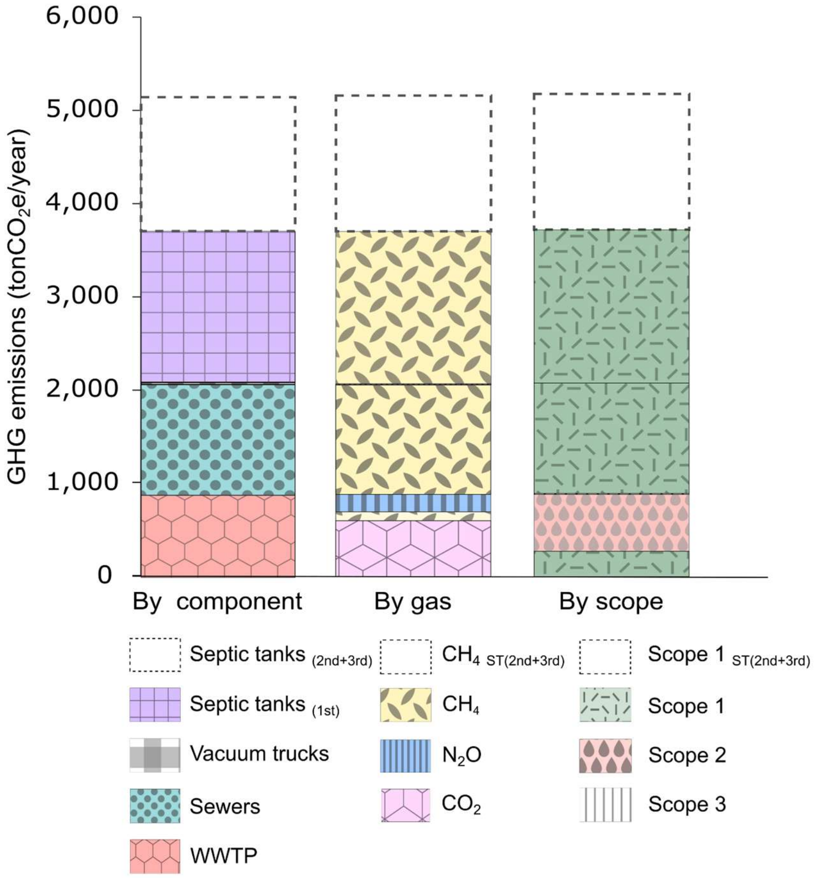

Fig. 3. Baseline GHG emissions along the SSC categorized by component, GHG type, and scope of emission.

Categorization based on GHG type showed that CH_4 accounted for 78–85% of the total GHG emissions, with 56–71% of the total CH_4 emissions originating from septic tanks, while 27–40% originated from sewers. The contribution of CO_2 was 12–16%, whereas that of N_2O was only 4–5%. Furthermore, both CO_2 and N_2O primarily originated from the WWTP. A similar finding has been reported for GHG emissions in Kampala, with CH_4 being the predominant GHG type (81%), followed by CO_2 (14%) and N_2O (6%) (Johnson et al., 2022). Additionally, the analysis of GHG emissions based on each of the three emission scopes showed dominance for Scope 1 emissions (i.e., emissions from the decomposition processes of wastewater) relative to Scopes 2 (i.e., emissions from electricity use) and 3 emissions (i.e., emissions associated with consumables). Specifically, Scopes 1, 2, and 3 emissions accounted for 83–88%, 12–17%, and 0.08–0.1% of the total emissions. Scope 1 emissions primarily originated from septic tanks (53–68%), sewers (26–38%), and WWTP (6–9%). Conversely, Scope 2 emissions only originated from the WWTP, while Scope 3 emissions mainly originated from transportation (97%). Details in this regard are provided in Table S9-1.

Comparison of GHG emissions and key mitigation strategies

Considering the current state of GHG emissions in this SSC, total GHG emissions per capita varied in the range of 236–328 kg CO_2e/(cap·year), similar to the value reported for Kampala, Uganda, i.e., 316 kg CO_2e/(cap·year), which does not include emissions into the environment as well as those related to end-use and disposal (Johnson et al., 2022). The total sanitation-related GHG emissions obtained in this study were 5–10-fold higher than those reported for fully sewered sanitation with WWTPs in previous studies. For example, the values obtained for China and Greece were 37–58 (Tian et al., 2022) and 61 kg CO_2e/(cap·year) (Mamais et al., 2015), respectively. This difference could be attributed to CH_4 emissions from anaerobic processes in septic tanks and to poorly maintained gravity sewers. It has been shown that septic

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tanks with long emptying intervals emit large amounts of GHGs owing to a high level of organic matter accumulation under anaerobic conditions (Huynh et al., 2021). Additionally, inadequately maintained or poorly designed gravity sewers constitute a potential source of CH_4 owing to wastewater stagnation, which promotes anaerobic conditions (Chaosakul et al., 2014; IPCC, 2019; Koottatep et al., 2014). While the GHG emissions associated with individual SSC components have been studied, our estimation facilitates the comparison of emissions across various components, GHG types, and scopes. Notably, our results identified septic tanks as the primary contributors to GHG emissions along SSCs, followed by gravity sewers. Long septic tank emptying intervals as well as sewers with inadequate gravity are common in LMIC. Therefore, septic tanks and gravity sewers could be major emission sources along urban SSCs in areas with similar settings. Hence, mitigation efforts should focus on effective management of septic tank and sewer given their substantial contributions to the total GHG emissions, which is not limited to LMICs.

3.3.2 Mitigation scenarios focusing on septic tanks

Scenario A

Under Scenario A, reductions in CH_4 emissions from septic tanks were estimated by shortening septic tank emptying interval from 10.2 years to 1 year. Thus, the re-estimated COD concentration in fecal sludge in the first compartment of the septic tanks with a 1-year emptying interval was 2,860 g/m^3, approximately six-fold lower than the baseline value (16,397 g/m^3). This lower fecal sludge COD concentration could be attributed to a lower level of organic matter accumulation in the septic tanks, owing to more frequent emptying.

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The GHG emissions from the different SSC components under this scenario are shown in Fig. 4. From this figure, it is evident that the total GHG emissions varied in the range 2,570–3,204 ton CO_2e/year, representing a 31–38% decrease from the baseline emissions. Septic tanks and sewers remained the major contributors to overall GHG emissions (28–42% and 33–41%, respectively). Therefore, with only the change in the septic tank emptying interval, GHG emissions originating from the septic tank decreased by 56% relative to the baseline value. Emissions from vacuum trucks increased by 920%, but still constituted a very small proportion of the total emissions (1.1–1.3%) despite the 10-fold increase in emptying frequency. Therefore, shortening septic tank emptying interval could be a straightforward firsthand measure for reducing overall GHG emissions given that its implementation does not require any changes in existing built components. This reasoning highlights a crucial and globally relevant point that more frequent septic tank emptying represents the most impactful and readily available strategy for mitigating GHG emissions from non-sewered sanitation using anaerobic processes.

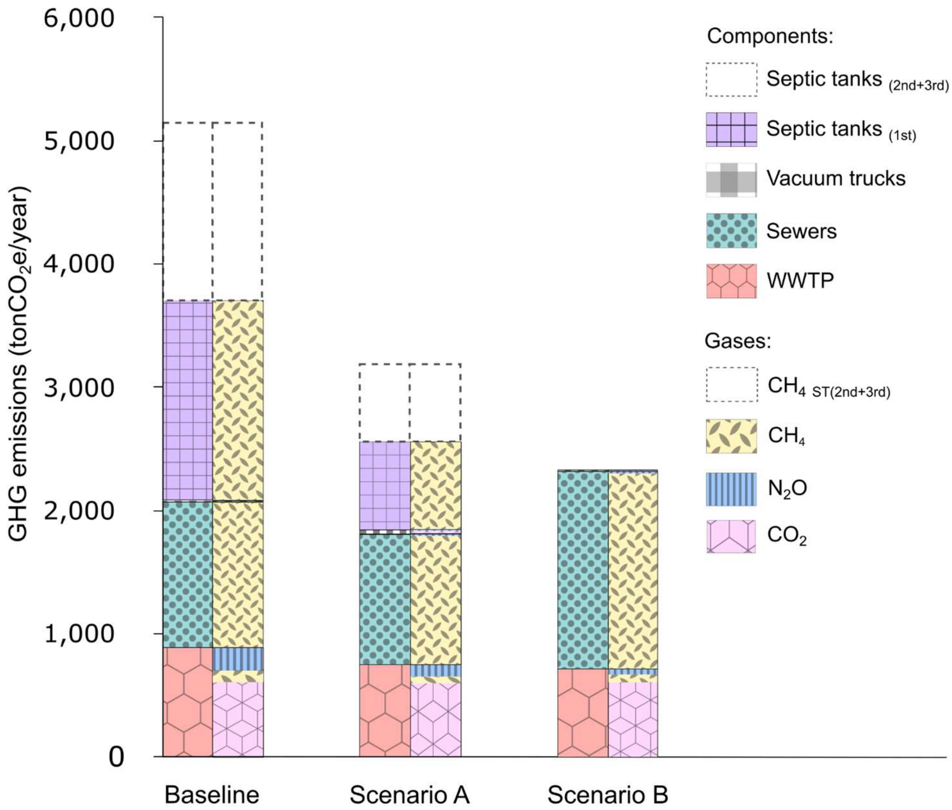

Fig. 4. Comparison of GHG emissions along the SSC between baseline and two mitigation scenarios (Scenarios A and B). The GHG emissions under each scenario are shown according to the SSC component (left bar) and GHG type (right bar), with the GHGs further categorized according to each component.

CH_4 was identified as the dominant GHG, accounting for 71–77% of total emissions, as was observed under the baseline scenario, followed by CO_2 at 20–25%, and N_2O at 3–4%. The emitted CH_4 primarily originated from sewers (43–58%) and septic tanks (39–55%). In terms of emission scope, Scope 1 emissions accounted for 75–80% of the overall emissions, while

Scopes 2 and 3 emissions accounted for 19–24% and 5%, respectively (Further data are presented in Table S9-2). Additionally, septic tanks and sewers remained the primary contributors to GHG emissions along the SSC even after shortening septic tank emptying interval.

Scenario B

Under Scenario B, septic tanks were assumed to be either removed or bypassed; thus, all blackwater was directly discharged into sewers. Accordingly, GHG emissions from septic tanks as well as those associated with transportation by vacuum trucks and treatment at the FSTP were not considered. The estimated GHG emission under Scenario B was 2,319 ton CO_2e/year, representing a 37–55% decline from the baseline value (Fig. 4). The main contributors to this emission were sewers (68%) and WWTP (31%). CH_4 emission was also predominant (72%) under this scenario, whereas CO_2 and N_2O emissions were 26% and 2%, respectively. Similar to Scenario A, Scope 1 emissions accounted for the largest proportion (73%) of GHG emissions, followed by Scope 2 emissions (26%), whereas Scope 3 emissions were relatively small (0.05%). Additional data in this regard are presented in Table S9-3.

Comparing GHG emissions between Scenarios A and B showed that the impact of removing septic tanks under Scenario B was 10–28% higher than that of frequent septic tank emptying under Scenario A. By removing or bypassing septic tanks and allowing wastewater to be directly discharged into sewers, a substantial reduction in emissions could be achieved owing to the elimination of septic tank-related emissions. However, a large amount of CH_4 was still emitted from the sewer given that the sewer conditions were not sufficiently improved or maintained to prevent wastewater stagnation, indicating that mitigation measures should focus on reducing GHG emissions from sewers.

3.3.3 Mitigation scenarios focusing on septic tanks and sewers

Scenario A*

Under Scenario A*, all emptied fecal sludge was transported and treated at the FSTP, and all septic tank effluents and graywater were collected via improved sewers and treated at the WWTP. The estimated total GHG emissions varied in the range 5,008–5,642 ton CO_2e/year (Fig. 5), and the main contributors were WWTP (74–83%) and septic tanks (14–24%), while contributions from vacuum trucks and FSTP were minimal at 0.6–0.7% and 1.8–2.0%, respectively. It is also worth noting that the major gas emitted under Scenario A* was different from those observed at baseline and under Scenarios A and B. Specifically, under Scenario A*, the main GHG emitted was N_2O (57–64%), followed by CO_2 (19–22%) and CH_4 (14–24%), and in terms of emission scope, Scope 1 emissions showed predominance (78–80%), whereas Scope 2 and 3 emissions accounted for 18–20% and only 2–3% of the total GHG emissions, respectively. Additional data in this regard is presented in Table S9-4.

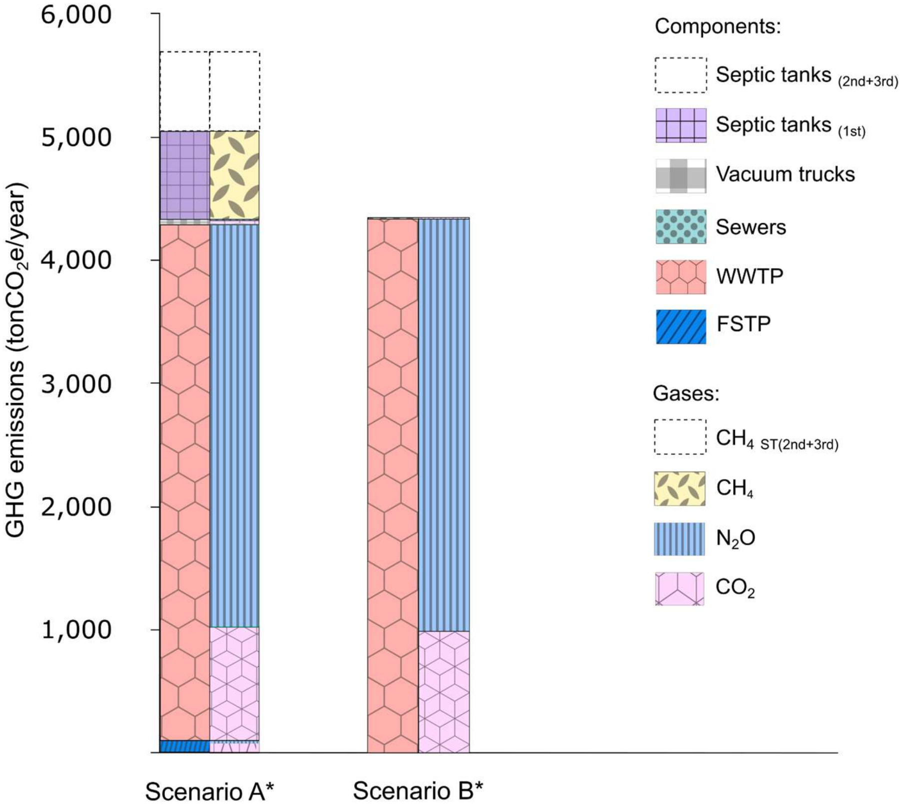

Fig. 5. Comparison of GHG emissions between two mitigation scenarios: Scenario A* and Scenario B*. GHG emissions under each scenario are shown by component (left bar) and GHG type (right bar), with the GHGs further categorized by type and component.

Scenario B*

As shown in Fig. 5, under Scenario B*, characterized as a purely centralized system, the majority of GHG emissions originated from the WWTP (4,278 ton CO_2e/year), and N_2O was the predominant contributor to the GHG emissions (77%), whereas the contributions of CO_2

and CH_4 were 23% and 0.01%, respectively. Further, Scope 1 emissions accounted for 77% of the total emissions, followed by Scope 2 emission at 23%, and Scope 3 emissions at 0.3%. Additionally, N_2O from Scope 1, originating from WWTP bioreactors, was the primary contributor to the total GHG emissions. A similar finding was reported by Gruber et al., 2020 for three Swiss municipal WWTPs. Additionally, GHG emissions from WWTPs varied depending on the operating conditions. Therefore, altering plant operating conditions may be an effective strategy for reducing GHG emissions (Santín et al., 2017; Tong et al., 2024). Further data are shown in Tables S9-5.

A comparison of Scenarios A* and B* showed slightly higher GHG emissions at the WWTP under Scenario B* due to the increase in N_2O emissions. However, total GHG emissions were 15–24% lower under Scenario B* than under Scenario A* due to the elimination of septic tank-related emissions. This observation indicated that to maximize GHG emission reduction, removing or bypassing septic tanks is necessary. Such a measure has also been recommended for an urban community sewer network in China, where septic tanks are in use (Yang et al., 2025). Even though septic tanks in the SSC are important contributors to total GHG emissions, removing or bypassing them poses a substantial challenge in the targeted sewerage and drainage area of this study as they are often located under houses, implying that their removal requires extensive construction work.

A similar pattern was observed under the baseline and initial mitigation scenarios, i.e., Scenarios A and B (Fig. 3 and 4), under which the emissions were dominated by anaerobic components, including infrequently emptied septic tanks and poorly maintained sewers.

Consequently, the emission profile was dominated by CH_4. Conversely, as the system shifted toward a sewered sanitation with improved sewers (Fig. 5), the WWTP as an aerobic/anoxic process became the dominant emission source. Hence, the shift in the gas emission profile to N_2O and indirect CO_2 becoming the major contributors to the GHG emissions. This consistent link between the functioning of SSC components and their GHG emission characteristics explains the similarity of the effects of the different mitigation scenarios.

3.4 Model sensitivity and uncertainty

3.4.1 Sensitivity and uncertainty of parameter settings

The one-at-a-time sensitivity analysis of the baseline scenario indicated that total baseline GHG emissions were most sensitive to septic tank emptying interval and the MCF of sewers (Table S10-1). Further, uncertainty analysis using these sensitive parameters provided a plausible range for the estimated GHG emission under the baseline scenario. As shown in Table S10-2, the estimated emission decreased by 31%, from 3,698 CO_2e/year at the baseline to 2,558 ton CO_2e/year at the lower bound case and increased by 64% from 5,147 CO_2e/year at the baseline to 8,453 ton CO_2e/year at the upper bound case. These findings indicated that the operational conditions of the septic tanks and sewers are the primary drivers of overall model uncertainty. Furthermore, analysis showed a shift in the relative importance of the primary emission sources. In the lower bound case, representing better management for both septic tanks and sewers, the contribution of emissions from septic tanks decreased to 28–42%, comparable to that from sewers (26–33%), suggesting the need for more accurate measurements of emissions from both sources to ensure the efficient prioritization of mitigation investments.

3.4.2 System boundary-related uncertainty

In this study, untreated discharges into the environment represented a major source of uncertainty given that they constituted a substantial portion of the total amount of COD. Our analysis of system boundary-related uncertainty showed that emissions from untreated COD discharged into the environment could increase total GHG emissions by 9–577 ton CO_2e/year (Table S10-3). While the lower value of this range seemed small (0.2–2.3% of the baseline total), the upper value was comparable to baseline emissions from electricity used at the WWTP (11–16%), suggesting the considerable impact of discharged wastewater outside the system boundary. Therefore, emissions from such discharges need to be considered in future studies. At the same time, this finding highlights a potential benefit of improving wastewater collection to mitigate such diffused environmental emissions.

The total untreated COD load discharged directly into the environment decreased from 302 ton COD/year at baseline to 272 ton COD/year under both Scenarios A and B (Table S10-4). However, compared with the total COD load entering the SSC (549 ton COD/year), the untreated COD load to the environment remained substantial. While these GHG emission mitigation scenarios provided partial improvements, only comprehensive upgrades across the entire SSC (i.e., Scenarios A* and B*), which ensure that all the wastewater in the system boundary is treated, offer the possibility to effectively minimize local water pollution and associated untraceable GHG emissions from the environment.

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3.4.3 Uncertainty related to the septic tank emission equation

To determine the uncertainty associated with the septic tank emission equation (Eq. (4)) for short emptying intervals, we estimated emissions considering a conservative case wherein the CH_4 emission factor for a 1-year interval (Scenario A) was assumed to be only 50% of the value predicted by Eq. (4). Thus, GHG emissions from septic tanks using this assumption varied in the range 357–674 ton CO_2e/year, comparable to the results obtained using the default MCF (632 ton CO_2e/year) proposed by IPPC (Table S10-6). Further, under this assumption, the total GHG emission was 2,213–2,530 ton CO_2e/year, representing a 32–51% decrease from the baseline emission amount (Table S10-5). These findings highlight two key points. First, regardless of the septic tank emission equation uncertainty, frequent annual emptying remains an effective mitigation strategy, confirming the robustness of our model as well as its applicability to similar SSC in other cities. Second, the relative contribution of sewers and the WWTP increased to 42–48% and 30–34%, respectively. Therefore, these two emission sources together accounted for the vast majority of the remaining emissions. This finding also indicated that as mitigation efforts successfully addressed one major source, other components emerge as the next dominant priorities, highlighting the value of an SSC-wide framework that can anticipate these shifts and guide a holistic, long-term mitigation strategy.

3.4.4 Uncertainty related to the sewer emission estimation

To assess the impact of our assumption regarding sewer emissions, we compared the results obtained using the IPCC's default MCF of 0.5 with those obtained using the lower-bound MCF of 0.2 reported by Johnson et al. (2022) (Table S10-7). Applying this lower MCF, the GHG emissions from sewers at the baseline decreased from 1,177 ton CO_2e/year to 475 ton CO_2e/year. Thus, the total baseline GHG emissions decreased from 3,698–5,147 ton CO_2e/year to 2,996–4,444 ton CO_2e/year only when our assumption regarding the estimation of sewer emissions was altered. This observation indicated that emissions from sewers constitute a major source of uncertainty depending on the emission factor used and underscores the need for direct measurements to ensure a more accurate estimation of emissions from such an infrastructure.

3.5 Key implications

The core contribution of this study is the identification of septic tank management within complex urban sanitation systems as a major and globally relevant GHG mitigation strategy. Our analysis also showed that shifting from poorly maintained systems to more effectively managed systems or septic tank removal can substantially reduce GHG emissions. However, scenario comparison showed that the most effective and practical mitigation pathway is not one-size-fit-all solution, but one that is highly dependent on local urban settings, existing infrastructure, and socio-economic conditions. Therefore, a full-scale feasibility assessment of GHG emissions from SSC components in any specific city would require a detailed local analysis that was beyond the scope of this work.

Further, in many dense established cities, particularly those in LMIC, like Hanoi, the immediate and complete removal of septic tanks (Scenario B*) is associated with major challenges, including physical difficulties as the septic tanks are located under houses, the high financial burden on homeowners, and the lack of regulatory frameworks to obligate such changes on private properties. Therefore, considering these limitations, feasible solutions are crucial. Our findings indicated that frequent emptying (Scenario A) is an important and non-disruptive mitigation strategy that overcomes these limitations. However, its real-world application may still be associated with several challenges given that drastically increasing septic tank emptying frequency will require additional trucks and a larger fecal sludge treatment capacity. Further, real-world application would necessitate regulatory and financial frameworks to ensure feasibility. Alternatively, promoting decentralized technologies for CH_4 capture and utilization for septic tanks is another plausible strategy for directly mitigating emissions at the source, where tank removal is not feasible.

In contrast, these challenges are less pronounced in other contexts. For example, in newly developing peri-urban areas or regions where septic tanks are located in accessible outdoor spaces for monitoring such as the United States (Diaz-Valbuena et al., 2011), Ireland (Mahon et al., 2022), and Europe (Mester et al., 2023), the technical and financial feasibility of decommissioning septic tanks during planned sewer expansion could be higher. Thus, a direct transition that bypasses or removes septic tanks entirely would represent a more realistic and highly effective GHG mitigation strategy from the outset. Additionally, for areas without any sewer expansion, replacing septic tanks with GHG emission mitigating-type non-sewered technologies could also be a plausible option.

3.6 Limitations and outlooks

First, the model relies on literature-based and default IPCC emission factors. While our uncertainty analysis confirmed the robustness of the model with respect to our major findings,

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the most sensitive parameters were the MCF for sewers and septic tank emptying interval. While septic tank emptying intervals can be determined by the society and not represent a technical challenge for the model, improved emission estimation from sewers that adequately capture context-specific conditions would contribute to more accurate model estimations. Further, our estimation did not rely on an established equation for emissions from septic tanks with short emptying interval. Therefore, deeper insight into septic tank emissions and a more generalized estimation method will enable more accurate model emission estimation, especially for the mitigation scenarios.

Second, the selected system boundary deliberately excluded potential emissions from wastewater and sludge that are directly discharged into the environment, making it impossible to directly compare scenarios with different untreated discharge loads. This limitation is associated with the large volume of unknown wastewater and sludge flow from poorly managed sewer networks. A better understanding of these pathways is important, not only for an accurate estimation of water balance, but also because the pathway of this untreated wastewater determines its GHG emission profile. For instance, wastewater infiltrating into anaerobic soil would primarily produce CH_4, whereas discharge into aerobic surface waters could lead to different emission profiles. Therefore, characterizing these pathways is crucial for a complete and accurate GHG emission inventory.

Finally, this study focused on operational emissions, while embodied GHG emissions associated with infrastructure changes were excluded. Therefore, a complete life-cycle assessment is necessary to account for the upfront GHG emissions associated with construction and rehabilitation as proposed under Scenarios B and B*. Such considerations will provide a more holistic view of the most sustainable pathway for mitigating GHG emissions from SSC components.

4. Conclusions

In this study, we developed a model based on a mass balance approach, empirical emission equations, and a carbon footprint estimation for the estimation of GHG emissions from interconnected SSC components. Further, to test the impacts of different mitigation scenarios, we used a representative SSC in Hanoi that features overlapping and poorly maintained non-sewered and sewered sanitation. The major findings were as follows.

- At baseline, the SSC that comprises infrequently emptied septic tanks and poorly maintained sewers were methane-dominated, with septic tanks being the largest contributors to emissions.
- Annual emptying of septic tank represents a highly effective, non-disruptive mitigation strategy that can reduce total baseline GHG emissions by 31–38%.
- Scenario comparison showed that removing septic tanks alongside sewer upgrades provides long-term mitigation potential, leading to 15–24% GHG reduction compared to the scenario of annual septic tank emptying with sewer upgrades.
- If septic tanks are not removed, they will remain a major source of GHG emissions even after upgraded sewers and centralized treatment are established.

- The best strategy for GHG emission for SSCs is context-specific. For example, if removing privately owned septic tanks poses considerable social challenges, frequent emptying with effective fecal sludge management could serve as a practical mitigation measure.

Overall, to achieve and sustain city-wide inclusive sanitation, it is important to take into account the vital role of non-sewered sanitation components for long-term infrastructure transformations and the development of mitigation measures. Additionally, the climate impact of these anaerobic non-sewered sanitation systems, which are present not only in LMIC, but also in high-income countries, cannot be ignored. Therefore, the development and deployment of effective strategies for mitigating GHG emissions along SSCs, e.g., improving management, adopting new technologies, or implementing context-appropriate policies, is critical. Even though our model had several limitations, it exhibited robustness and presents as a suitable framework for estimating the impacts of GHG mitigation measures along SSCs, and can contribute to the establishment of climate-friendly urban sanitation services.

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Author contributions

JM: Conceptualization, Data Collection, Methodology, Writing – original draft, Writing – review & editing, Data analysis and Interpretation, Visualization; MYS: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Data Analysis and Interpretation, Visualization; VAN, ANP: Data collection, Writing – review & editing; SF, SE: Writing – review & editing, Supervision; HY: Software analysis, Writing – review & editing; HH: Conceptualization, Writing – original draft, Methodology, Funding acquisition, Data Interpretation, Writing – review & editing, Supervision. All authors have read and approved the final version of the manuscript.

Declaration of competing interest

The authors declare no competing financial interest.

Data availability

The datasets generated in this study, including the final GHG emission estimates and mass balance outputs for all scenarios, and all input parameters used for the analysis are cited accordingly within the manuscript.

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