Methods for measuring greenhouse gas emissions from sanitation and wastewater management systems

A review of method features, past applications and facilitating factors for researchers, practitioners and other stakeholders

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SEI Stockholm Environment Institute

Contents

Table of Abbreviations

ABR	Anaerobic baffled reactor
CEAS	Cavity enhanced absorption spectroscopy
CHP	Combined heat and power
CRDS	Cavity ring-down spectroscopy
ECD	Electron capture detector
FID	Flame ionization detector
IPCC	Intergovernmental Panel on Climate Change
TCD	Thermal conductivity detectors
UAV	Unmanned aerial vehicle

Summary

Sanitation and wastewater management systems, while essential for public health and environmental sustainability, are significant yet often overlooked contributors to global greenhouse gas emissions. The accurate accounting of these emissions in national greenhouse gas inventories is impeded by a lack of comprehensive empirical data, attributable to limited methodological adaptation and awareness in the context of diverse sanitation technologies and geographical settings.

To address these gaps, this report presents an analysis of the seven categories of enclosure-based and open methods described by Bastviken et al. (2022), and discusses their applicability across different sanitation and wastewater management technologies and geographical contexts. The report's findings, based on a scoping literature review and interviews with a selection of experts, highlight key methodological gaps and opportunities for innovation. The findings reveal the predominant use of enclosure-based methods, such as static and flow-through flux chambers, which, despite their widespread adoption, are constrained by scale limitations and potential for measurement disturbances. In contrast, emerging methodologies like optical methods and remote sensing offer new avenues for broad-scale, high-resolution emissions monitoring but are currently limited by their high cost and technical demands.

The report advocates for a holistic approach to greenhouse gas measurement in the sanitation and wastewater sector, emphasizing the need for adaptable methodologies that can be tailored to the varied conditions of sanitation systems worldwide. It calls for enhanced collaboration among researchers, policymakers and practitioners to foster methodological advancements and standardization, thereby enabling more effective and widespread empirical data collection. Furthermore, the report underscores the critical importance of increased funding and capacity-building efforts to democratize access to advanced measurement techniques.

With more efforts in the development, dissemination and use of these various methods for measuring emissions in sanitation and wastewater management systems, more countries can ideally be enabled to utilize Tier 3 methods where possible as per the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories, while also generating data for improved emission factors for Tier 2 and Tier 1 methods. This can therefore build a more robust empirical basis for climate action in the sanitation and wastewater management sector.

1. Introduction

The sanitation sector plays a crucial role in greenhouse gas emissions, contributing over half a billion tonnes of CO_2 equivalents annually. This is approximately equivalent to 1.3% of global greenhouse gas emissions. However, the true scale of these emissions might be even larger, considering that emissions from sanitation systems have historically been underestimated in national and subnational emissions inventories due to limited empirical data on the quantity of emissions from various sanitation technologies across the entire sanitation chain (Lambiasi et al., 2024).

This is especially the case in low- and middle-income countries, where rapidly growing urban areas have heterogeneous sanitation infrastructure configurations, with both sewer-based and non-sewered sanitation systems. Sanitation systems that do not rely on sewers, including technologies such as pit latrines, composting toilets and septic tanks, are often not adequately covered in emissions inventories (Manga & Muoghalu, 2024).

Greenhouse gas emissions inventories are typically based on methods from the *IPCC Guidelines for National Greenhouse Gas Inventories* (Rypdal et al., 2006), spread across three tiers:

Tier 1 is the most basic level, utilizing global emission factors and default values, suitable for circumstances where country-specific data are limited.

Tier 2 includes more detailed methodologies, employing country-specific emission factors and activity data, thus offering improved accuracy over Tier 1.

Tier 3, the most sophisticated level, involves comprehensive and detailed methodologies, including higher resolution activity data and country-specific emission factors, often incorporating direct measurement and modelling approaches.

Each ascending tier represents a progression in data specificity and methodological complexity, reflecting a trade-off between accuracy and resource requirements. Estimates of greenhouse gas emissions from sanitation systems are often made using Tier 1 and Tier 2 methods, but the emission factors therein have limitations and the assumptions behind them might not be universally applicable (Diaz-Valbuena et al., 2011; Johnson et al., 2022), which contributes to significant uncertainties in results.

Compared to other sectors such as aviation, where emissions can be mitigated through substitution, emissions from sanitation systems cannot be substituted (Climate Resilient Sanitation Coalition & Water Initiative for Net Zero, 2024). Moreover, a growing global population and efforts to achieve universal sanitation coverage (Sustainable

Development Goal 6.2) could imply an increase in greenhouse gas emissions from excreta management.

Available estimates indicate that methane emissions from sanitation systems in sub-Saharan Africa could increase by over 60% (USAID Urban Resilience by Building and Applying New Evidence in Water & Sanitation, and Hygiene (URBAN WASH), 2023). In India, while a 14% increase in access to toilets occurred between 2015 and 2020, at the same time, methane emissions increased fivefold from pit latrines (Cheng et al., 2022). But data are lacking, which highlights the need for a more accurate accounting for sanitation systems in greenhouse gas emissions inventories, so as to inform policy and practice on relevant mitigation options, considering the global urgency to meet the Paris Agreement's 1.5°C target.

Empirical measurements of greenhouse gas emissions are crucial for establishing accurate accounting for sanitation systems in greenhouse gas emissions inventories. Results from empirical measurements can be used directly in emissions inventories that are based on Tier 3 methods, but they are also a basis for developing more robust emission factors for use in Tier 1 and Tier 2 methods.

The emission factors in the IPCC guidelines cover a limited set of sanitation technologies, mostly technologies for wastewater treatment plants. Despite widespread use of various non-sewered technologies, the guidelines only include emission factors for pit latrines and septic tanks (Bartram et al., 2019; Doorn et al., 2006).

Emission factors for sanitation systems in the guidelines are generally based on limited empirical data (Moore et al., 2023; Song et al., 2023), and this contributes to significant uncertainties in emissions inventories. More empirical measurements of greenhouse gas emissions are needed from more types of sanitation technologies and also in a variety of geographical settings.

For more empirical measurements of greenhouse gas emissions to be conducted, a wider awareness and knowledge about the available methods is necessary. A number of reviews have been conducted in the past on methods for empirical measurement of greenhouse gas emissions both broadly and focused on applications to specific sectors or industries (see e.g. Bastviken et al., 2022; Cardador et al., 2022; Denmead, 2008; Hassouna et al., 2023; Poudel et al., 2023). However, no review has focused on assessing the application of various methods to sanitation systems more broadly. Bastviken et al. (2022) conducted a relatively recent review of methods for measuring greenhouse gas fluxes across various sectors, with a focus on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). However, no comprehensive assessment has been made of measurement applications to sanitation systems, including how these applications may vary across geographical contexts. This report seeks to contribute to filling this gap.

We provide an overview of available methods for measuring and quantifying greenhouse gas emissions in the sanitation and wastewater management sector, offering guidance on the application of these methodologies to various technologies across the sanitation service chain in both sewered and non-sewered sanitation. This report arises out of a scoping review, for which the overall research questions that the review sought to address are:

- What methods are available for empirical measurements of greenhouse gas emissions from sanitation and wastewater management systems?
- What are the respective features of these methods and how have the methods been used for quantifying greenhouse gas emissions from across the sanitation and wastewater management chain?
- What factors can facilitate the wider use of these methods for empirical measurements of greenhouse gas emissions from sanitation systems in low- and middle-income countries?

This report is intended for researchers working on climate mitigation in sanitation systems, as well as for sanitation utilities, city or municipal authorities, and national agencies with planning and implementation responsibility for sanitation and climate change mitigation and adaptation. It is also of interest to research councils that aim to fund research in this area of work, as well as climate funds and other investors that are considering investments with dual benefits for Sustainable Development Goal (SDG) 6 (clean water and sanitation) and SDG 13 (climate action).

2. Methods

We conducted a scoping review (James et al., 2016; Munn et al., 2018) of the literature on measuring greenhouse gas emissions from sanitation systems, and interviews with selected professionals working in the sanitation sector on topics of climate change, air pollution and measurement of greenhouse gas emissions.

2.1 Scoping review

The scoping review described in this report was based on the categorization of methods by Bastviken et al. (2022), broadly categorized as enclosure-based and open methods and further divided into seven types (see Table 1), with a focus on their application to sanitation and wastewater management systems. Details about how the methods have been used on sanitation systems are provided in Section 3.

We sought to identify literature that illustrated the application of the above method types to sanitation technologies and systems, using the “functional groups” of the sanitation service chain as conceptualized by Tilley et al. (2014) as our reference model (see Table 2).

Our literature search strategy incorporated three components, all including any relevant synonyms and truncations:

1. Keywords related to greenhouse gases, emissions and their measurement, such as greenhouse gases/fluxes/emissions and measurement/mapping/quantification;

2. Keywords related to specific method categories from Bastviken et al. (2022);

3. Keywords related to sanitation functional groups and associated technologies, as listed in Table 2.

We conducted iterative searches mainly in Web of Science and Google Scholar, replacing or complementing terms with synonyms or specific greenhouse gases such as methane, nitrous oxide, and carbon dioxide as appropriate, in the search strings. Initial screenings of literature were conducted based solely on titles and abstracts, ensuring we captured the most pertinent studies. All identified literature, including the full texts, was then systematically stored within a shared Zotero Library, which was further organized with subcollections dedicated to each functional group of the sanitation chain.

After our literature search and discovery phase, we extracted relevant data from the full texts stored in our Zotero library, using a spreadsheet for this purpose. Extracted data included the bibliographic information from each document as well as the empirical details from the studies described in the document, including the geographical location, the sanitation technologies and the specific greenhouse gases in focus, the types of methods used for measuring greenhouse gas emissions, and how

Table 1. Description of types of methods for measuring greenhouse gas fluxes (based on Bastviken et al., 2022)

Method categories and types		Method description
Enclosure-based methods	Static and flow-through flux chambers	Static flux chambers are sealed containers placed over an area to capture gases released from the surface of wastewater or sludge, for example. The change in gas concentration inside the chamber over time indicates the flux, or rate of gas emission or uptake. Flow-through flux chambers have a continuous flow of air through the chamber, and by measuring the difference in gas concentrations between the incoming and outgoing air, along with the flow rate, the greenhouse gas flux can be calculated.
	Incubation approaches	Samples of sanitation waste, such as sludge or wastewater, are placed in sealed containers under controlled conditions, i.e. ex situ conditions. Over time, the change in gas concentrations within these containers is measured to determine the rate of greenhouse gas production.
	Enclosure-based methods for measuring flux at outlets of well-defined point sources	Emissions are captured directly from a specific source, such as a chimney or pipe. A temporary enclosure, e.g. a sampling bag, can be used to collect the gases. The gas flow rate into the bag and the gas concentration in the bag are then used to calculate the flux.
Open methods	Open methods for measuring flux at outlets of well-defined point sources	Gas concentration and flow rate are measured directly at the outlet without an enclosure, allowing for continuous monitoring of the flux.
	Micrometeorological methods by point measurements in ambient air	Measures gases directly in the air above the target system, without enclosing any part of the surface. Techniques such as eddy covariance, among others, capture the vertical movement of air and the concentrations of greenhouse gases. By analysing the correlation between the air movement and gas concentrations, one can estimate the fluxes of the gases into or out of the atmosphere from the target system.
	Open methods based on column density, tracers or inverse modelling	Column density techniques use instruments to measure the amount of gas between the instrument and a reference point, such as a satellite or ground sensor, creating a "column" of air. By comparing the gas concentration inside this column to background levels, emissions from the target system can be inferred. Tracer techniques track a known quantity of a tracer gas released into the target system. Downwind, the ratio of the tracer gas to the greenhouse gas of interest is measured. This ratio, along with the known release rate of the tracer, is used to calculate the emission rate of the greenhouse gas. Inverse modelling uses mathematical models to backtrack from measured greenhouse gas concentrations in the air to their potential sources, e.g. a specific sanitation technology. By understanding wind patterns and gas dispersion, the model estimates where and how much greenhouse gas is being emitted.
	Open methods based on mass balances	Involves calculating greenhouse gas emissions by assessing the difference between incoming and outgoing gas fluxes from an area. The difference represents the net greenhouse gas emissions. This can involve monitoring greenhouse gas concentrations at strategic points around the area and considering the flow rates of air or water carrying these gases.
	Optical methods with potential to map greenhouse gas concentrations and fluxes	Optical approaches use radiation-based sensors to detect greenhouse gases. Passive optical approaches, for example, rely on natural background radiation to detect gas concentrations. Instruments measure the absorption of sunlight or infrared radiation by greenhouse gases over an area, providing a map of gas concentrations. Active optical approaches emit their own radiation towards the target area and analyse the radiation that bounces back. The interaction of this emitted radiation with greenhouse gases alters its characteristics, enabling the determination of gas concentrations. Combined with wind speed data, these concentrations can help estimate the fluxes of greenhouse gases.

Table 2: Functional groups of the sanitation service chain with examples of technologies in each group

Functional group	Description	Examples of technologies in the functional group
User interface	The way the user accesses the sanitation system, including configuration of the technology removing excreta (with the use of water or not).	Any type of toilet including dry toilets, urine-diverting dry toilets, urinals, pour flush toilet, cistern flush toilets, urine-diverting flush toilet
Collection and storage/treatment	Ways in which the products generated at the User Interface are collected, stored and possibly passively treated, as in the case of on-site technologies.	Urine storage tank/container, single pit, single or double ventilated improved pit, fossa alterna, twin pits for pour flush, dehydration vaults, composting chamber, septic tank, anaerobic baffled reactor (ABR), anaerobic filters and biogas reactors
Conveyance	Describes the ways products are transported between functional groups, such as from the user interface or collection point to storage/treatment.	Jerrycan/tank, human-powered emptying and transport, motorized emptying and transport, simplified sewer, solids-free sewer, conventional gravity sewer, transfer station (underground holding tank)
Centralized and semi-centralized treatment	Treatment technologies used when a larger number of users are being served. It can include pre- and post-treatment of wastewater, brown water and grey water, as well as sludge.	Settler, Imhoff tank, ABR, anaerobic filter, waste stabilization ponds, aerated pond, free-water surface constructed wetland, horizontal subsurface flow constructed wetland, vertical flow constructed wetland, trickling filter, up flow anaerobic sludge blanket reactor, activated sludge, sedimentation/thickening ponds, unplanted drying beds, planted drying beds, co-composting, biogas reactor
Use and/or disposal	Includes the ways that products are reintroduced in the environment, either as reduced-risk waste materials, or as recycled resources, inside or outside the system.	Fill and cover/Arborloo, application of stored urine, application of dehydrated faeces, application of pit humus and compost, application of sludge, irrigation, soak pit, leach field, fishpond, floating plant pond, water disposal/ groundwater recharge, surface disposal and storage, biogas combustion

Sources: The functional groups are based on Tilley et al. (2014), and the table is reproduced from Lambiasi et al. (2024).

the methods were used for gas sampling and/or analysis in the study being described. We also extracted information on the features, costs, pros and cons of the methods, where they were described in any of the studies.

To improve efficiency, ChatGPT was used to extract the relevant information from some of the documents, particularly those with studies regarding the use and/or disposal and the treatment functional groups.

Following data extraction, the project team convened for an internal workshop. In our discussions, we pinpointed and deliberated on the emerging patterns from the literature, resulting in a synthesis of the findings, reported here.

2.2 Interviews

Following the scoping review of literature, we conducted a series of interviews in December 2023 with pertinent stakeholders, to gather more insights on the use of various methods for measuring greenhouse gas emissions in sanitation systems, particularly in low- and middle-income country contexts. We conducted 10 interviews, all in semi-structured format (King et al., 2018).

The interviewees were experts whose work focuses on sanitation and greenhouse gas emissions broadly, in diverse contexts, as shown in the summary in Table 3. The interviewees were selected mainly based on their experience and previous work related to greenhouse gas emissions in sanitation systems. At the time of the interviews, half of the interviewees had direct experience with empirical measurement of greenhouse gases from various sanitation technologies, while the others were knowledgeable about greenhouse gas measurement but had not applied empirical methods themselves. All interviewees provided informed consent in writing prior to the interviews.

The interview questions focused on obtaining the interviewees' perspectives on how they might use the various methods identified in the scoping review. Additionally, we sought to understand the potential advantages and challenges they anticipated with the use of various methods, drawing from their hands-on experience with the conditions in their respective countries of work. After analysing the interview transcripts using thematic content analysis, the findings from the interviews were integrated into the findings from the literature review for an overall synthesis.

Table 3. Profiles of the interviewees and their organizational and country affiliations

Code	Organization type	Country
Interview 1	Water and sanitation utility	Portugal
Interview 2	Research institute	South Africa
Interview 3	University	Mexico
Interview 4	University	Australia
Interview 5	Industry association	UK
Interview 6*	Non-governmental organization	Bangladesh
Interview 7	University	Thailand
Interview 8	Research institute	India
Interview 9	University	Uganda
Interview 10	Consultancy company	India

**Note: Interview 6 was conducted with two respondents, both from the same organization.*

3. Measurement methods and their use in sanitation and wastewater management

An overview of the various categories and methods applied to technologies in the functional groups in the sanitation service chain is provided in Table 4. As described in Table 4, a wide range of methods have been applied to study emissions from technologies at various stages of the sanitation chain, and in a variety of countries ranging from low-income to high-income countries, based on World Bank classifications (World Bank, n.d.). However, methods applied to the treatment stage of the sanitation chain have more variety compared to other stages.

We found no studies in the literature describing measurements of greenhouse gases at the user interface – i.e. the part of a sanitation system with which the typical user interacts, such as the toilet, pedestal or urinals. This likely stems from the assumption that the minimal residence time of excreta at the user interface leads to negligible greenhouse gas emissions, thus not incentivizing measurements in this area (Lambiasi et al., 2024).

Among the various types of methods, enclosure-based methods – especially flux chambers – were used in most empirical studies on greenhouse gas emissions from the other functional groups of the sanitation chain. As noted by Poudel et al. (2023), the type of flux chambers used in most sanitation applications are based on designs that were purposefully built for applications in agriculture, i.e. soil-plant interfaces. For sanitation applications, these chamber designs typically must be adapted to fit liquid-air interfaces, which are common when dealing with wastewater and sludge. For example, flux chambers used for agricultural applications can be placed firmly on soil, but when measuring emissions from a septic tank, the chamber cannot sit on septage and hence the design has to be adapted to include “legs” that penetrate to the bottom of the septic tank and hold the chamber up at the surface of the septage.

We did not find any studies in the literature that used the following techniques to measure emission fluxes from sanitation technologies and systems: open approaches at point sources, micrometeorological methods by point measurements in ambient air, and open methods based on mass balances. This absence might indicate that these approaches are not useful or conducive for applications in sanitation systems, or that there is need for future methodological development or adaptation to suit the specific needs of greenhouse gas measurement in sanitation systems.

Table 4. Overview of which types of methods for quantifying greenhouse gas emissions have been applied to the functional groups of the sanitation service chain, with examples of countries where measurements have been done

Method categories and types		User interface	Collection and storage	Conveyance	Treatment	Use and/or disposal (resource recovery)
Enclosure-based methods	Static and flow-through flux chambers	–	Ethiopia, India, Ireland, Kenya, Nepal, Senegal, Thailand, Uganda, US, Viet Nam	US	Austria, Burkina Faso, China, Denmark, Haiti, Japan, Mexico, Spain, Netherlands, UK, US	Australia, Brazil, Canada, Haiti, Netherlands, UK, US, Zimbabwe
	Methods for outlets of well-defined point sources	–	India	Australia, US	Australia, Canada, Italy, Japan, Netherlands	–
	Incubation approaches	–	Tanzania	China	Japan, Netherlands	Brazil, China, UK, US
Open methods	Open approaches at point sources	–	–	–	–	–
	Micrometeorological methods by point measurements in ambient air	–	–	–	–	–
	Open methods based on column density, tracers or inverse modelling	–	–	–	China, Denmark, Sweden, US	–
	Open methods based on mass balances	–	–	–	–	–
	Optical methods with potential to map greenhouse gas concentrations and fluxes	–	–	Australia, France, Romania, South Korea, Spain	Austria, Denmark, Sweden, UK	Sweden

In Sections 3.1 to 3.5, we describe further how the types of methods have been used across the various stages of the sanitation chain. We also provide some examples of instances where the methods have been applied and the empirical settings.

3.1 User interface

No studies have been identified that focus on measuring greenhouse gas emissions from or applying the methods to sanitation technologies in the user interface functional group. These technologies range from various types of toilets, pedestals, pans and urinals (see Tilley et al., 2014). They mainly serve to hygienically separate excreta from human contact, and then they connect to technologies in other functional groups for management of excreta. Typical usage has minimal residence time for excreta at the user interface; this implies negligible greenhouse gas emissions if any at this stage, which perhaps does not incentivize measuring the emissions from technologies in this functional group.

3.2 Collection and storage

Non-sewered sanitation systems collect and store waste. Relatively few studies in the literature have focused on quantifying greenhouse gas emissions from the sanitation technologies in this functional group.

A recent systematic review by Poudel et al. (2023) found only eight studies with field measurements of greenhouse gas emissions from on-site sanitation systems, all of them focusing on septic tanks and their effluent disposal systems as shown in Table 5. A study by Moonkawin et al. (2023) was published after Poudel et al. (2023), in which the authors also focused on septic tanks and used the same methods as in Huynh et al. (2021), but with a focus on assessing the impact of long emptying intervals on emissions. Other technologies in this functional group, such as urine storage tanks and dehydration vaults (see Tilley et al., 2014), are yet to be the subject of in situ measurement of greenhouse gas emissions.

From the information obtained from interviews, as of December 2023, studies are ongoing to measure greenhouse gas emissions from septic tanks in Thailand and India using static flux chambers and gas analysers respectively; from container-based sanitation in Kenya using flux chambers; and from pit latrines and septic tanks in Nepal, Ethiopia, Senegal and Uganda, using flux chambers under the project "Sanitation and Climate: Assessing Resilience and Emissions (SCARE)" (University of Bristol, 2023).

For septic tanks, enclosure-based methods and particularly flux chambers are the most common methods used for measuring greenhouse gas emissions thus far, with studies conducted in the US, Ireland and Viet Nam. Poudel et al. (2023) described various gas sampling approaches used in eight studies, including modified static, floating and automated chambers, with gas analysis using gas chromatography, spectrometry and infrared gas analysers.

Van Eekert et al. (2019) conducted a study that measured biogas (mainly methane and carbon dioxide) from pit latrine sludge, using incubation approaches. Besides the above, no other studies have been found in the literature with a focus on measuring greenhouse gas emissions from sanitation technologies in this functional group, whether by enclosure-based or open methods.

Table 5. Overview of studies described by Poudel et al. (2023) and Moonkawin et al. (2023) of greenhouse gas measurements from septic tanks

Location	Focus of measurements	Gas sampling approach	Gas analysis approach and tools	Gases	Reference
Ann Arbor, Michigan, US	Septic tanks at 7 sites	Submerged inverted steel bowls	Mass spectrometry and iodometry	CH_4, H_2S	Winneberger (1984)
Cool, California, US	Compartments of septic tanks at 8 sites as well as vents and soil dispersal systems at 2 of the sites	Modified flux chamber, with a small fan for mixing the air	Shimadzu gas chromatograph (Model GC-2014) with a 63Ni ECD, FID, and TCD linked to a Shimadzu autosampler (Model AOC-5000)	CH_4, CO_2, N_2O	Diaz-Valbuena et al. (2011)
New York, US	Roof vents, sand filters and leach fields connected to septic tanks at 9 sites	Modified flux chamber made from cylindrical plastic buckets	Gas chromatograph (Model 6890 N GC/ECD, Agilent Technologies Inc., Santa Clara, CA) using an FID and an ECD for methane and nitrous oxide, and a Portable Photosynthesis System attached to a LI6250 CO_2 analyser (LI-COR, Lincoln, NE)	CH_4, N_2O, CO_2	Truhlar et al. (2016)
Westmeath, Ireland	Soak-away connected to a septic tank at 1 site	Multi-chamber automated soil flux chamber	Automated flux chamber system (LI-8100A Automated Soil Gas Flux System, LI-COR Biosciences, Inc.) with a non-dispersive infrared gas analyser, multiplexer and automated soil gas flux chambers (8100-104, LI-COR Biosciences, Inc.)	CO_2	Somlai-Haase et al. (2017)
Westmeath, Ireland	Soak-away connected to a septic tank at 1 site	Multi-chamber automated soil flux chamber	Automated flux chamber system (LI-8100A Automated Soil Gas Flux System, LI-COR Biosciences, Inc.) with a non-dispersive infrared gas analyser, multiplexer and automated soil gas flux chambers (8100-104, LI-COR Biosciences, Inc.) for carbon dioxide, and an Ultraportable Greenhouse Gas Analyser (model 915-0011, Los Gatos Research) for methane	CO_2, CH_4	Somlai-Haase et al. (2019)
New York, US	Leach fields of septic tank systems at 3 sites	Modified flux chamber made from cylindrical plastic buckets	Gas chromatograph (Model 6890 N GC/ECD, Agilent Technologies Inc., Santa Clara, California, US) using an FID and an ECD for methane and nitrous oxide, and a Portable Photosynthesis System attached to a LI6250 CO_2 analyser (LI-COR, Lincoln, Nebraska, US)	CH_4, N_2O, CO_2	Truhlar et al. (2019)
Hanoi, Viet Nam	First compartment of septic tanks at 10 sites	Floating flux chamber	Gas chromatograph (Shimadzu GC-2014) with a flame ionization detector, thermal conductivity detector, and electron capture detector for methane, carbon dioxide and nitrous oxide respectively, and a portable gas analyser (PG300, HORIBA) for dissolved methane and carbon dioxide concentrations	CO_2, CH_4, N_2O	Huynh et al. (2021), Moonkawin et al. (2023)
Limerick, Ireland	Septic tank chambers, vents and soil treatment units at 2 sites	Integrated and automated soil gas flux measurement systems, plus manual sampling with a 8100-664 Trace Gas Sample Kit (Li-Cor Biosciences, Inc.) for analysis of CH_4 and N_2O	Automated soil gas flux measurement systems for CO_2 (LI-8100A, Li-Cor Biosciences, Inc.) and CH_4 (UGGA 915-0011, Los Gatos Research). Gas chromatograph (Clarus 500, Perkin Elmer) equipped with capillary columns (Elite-Plot Q), a flame ionization detector for CH_4 and an electron capture detector for N_2O	CO_2, CH_4 and N_2O	Knappe et al. (2022)

3.3 Conveyance and transport

The sanitation technologies in the conveyance functional group can broadly be categorized into road or pipe transport. Those relevant for road transport include manual or motorized emptying and transport, and those relevant for pipe transport, simplified sewers and gravity or pressurized sewers (Strande et al., 2023; Tilley et al., 2014).

No studies have been found in the literature with empirical measurement of direct greenhouse gas emissions during road-based transportation of excreta from containments or user interface to treatment facilities. However, work is ongoing on quantifying gaseous emissions during septic tank and pit latrine emptying operations in India, with a focus on gases such as methane, hydrogen sulphide, carbon dioxide and sulphur oxide, although results are yet to be published (Raj et al., 2023).

For sewer pipeline networks, sewers are recognized sources of both methane and nitrous oxide emissions, although more empirical studies have been done for methane than nitrous oxide (Mannina et al., 2018). Empirical studies on greenhouse gas emissions from sewer lines have typically focused on sampling at ventilation points such as manholes, sewer grates and wet wells or using chambers connected to the headspace of sewer pipes (Liu et al., 2015).

Various enclosure-based methods have been applied to measure greenhouse gas emissions from sewer networks, including incubation approaches via lab-scale sewer reactors to measure headspace emissions, e.g. in China (Zhang et al., 2023); point source enclosure approaches to measure dissolved methane in pressurized sewers, e.g. in Australia and the US (Foley et al., 2009; Fries et al., 2018); and flux chambers to measure emissions from manholes, e.g. in the US (Fries et al., 2018). All these examples involved analysing the gas samples in gas chromatography instruments equipped with an electron capture detector (ECD) and a flame ionization detector (FID).

For open methods and their application to sewer networks, we only found studies using active and passive optical measurement approaches in the literature. The examples identified include both manual measurement campaigns and automated measurements, i.e. where sensors are deployed for real-time monitoring, taking measurements automatically and continuously over a long period of time.

Examples of active optical approaches include the installation of infrared sensors for automated real-time monitoring of methane emissions at manholes and pumping stations on a sewer line in Australia (Liu et al., 2014), as well as the use of cavity ring-down spectroscopy (CRDS) instruments, cavity enhanced absorption spectroscopy (CEAS) and off-axis integrated cavity output spectroscopy (OA-ICOS) analysers mounted on motor vehicles for street-level monitoring of emissions along sewer networks in France, South Korea and Romania (Defratyka et al., 2021; Fernandez et al., 2022; Joo et al., 2024). Passive optical approaches have also been used in Spain for continuous monitoring of methane and nitrous oxide emissions from sewer network manholes, wet wells and influent points to wastewater treatment plants, via non-dispersive infrared gas analysers (Eijo-Río et al., 2015).

3.4 Centralized and semi-centralized treatment

Most studies assessing greenhouse gas emissions from sanitation systems tend to focus on wastewater and sludge treatment technologies, particularly in the context of centralized wastewater treatment plants. Enclosure-based methods have been used in several instances for measuring emissions from sanitation technologies in the treatment functional group. This typically involves gas sampling (manual or automated) with flux chambers or other kinds of enclosed containers, and then analysis with gas analysers or gas chromatograph equipment. Table 6 provides an overview of some examples of studies where enclosure-based methods have been used to measure greenhouse gas emissions from various sanitation technologies in different countries. Most of the studies have been conducted using flux chambers (both static and flow-through chambers), but a wide range of sanitation technologies are included, from conventional waste stabilization ponds to advanced membrane bioreactors, hence showing the wide applicability of enclosure-based methods to different types of technologies.

A variety of gas sampling and analysis equipment is described in Table 6 along with the examples of studies where they have been applied. In addition to the studies described in Table 6, information obtained from the interviews also indicated ongoing work to measure emissions at a wastewater treatment plant in Mexico, using flux chambers.

Open methods have also been used in several instances to measure greenhouse gas emissions from wastewater and sludge treatment technologies, as shown in Table 7. Only two of the five types of open methods open methods have been applied to studies in sanitation systems. This may perhaps be due to some open methods being suited for studies of much larger areas (up to several square kilometres).

While examples were identified in the literature with open methods being used to measure greenhouse gas emissions from various technologies, from lagoons to anaerobic digestors and sand filters, these were mostly done using tracer flux measurements, inverse modelling and passive optical approaches. Other open methods based on micrometeorological approaches (e.g. eddy covariance) and mass balances (e.g. boundary layer budgeting approach) seem to be less commonly applied to wastewater and sludge treatment technologies.

Table 6: Examples of studies using enclosure-based methods for measuring greenhouse gas emissions in wastewater and sludge treatment technologies

Method	Sanitation technologies where gases were measured	Gas sampling approach	Gas analysis approach and tools	Gases	Examples of locations of measurements	References
Static chambers	Integrated fixed film-activated sludge system, recirculating textile media filter, fixed activated sludge treatment unit, recirculating trickling filters, waste stabilization ponds, co-composting of solid waste and sewage sludge, sludge treatment reed bed systems, unplanted sludge drying beds, sludge treatment wetlands, aeration tanks, settling tanks	Static chambers typically constructed from materials like cylindrical Plexiglas, polypropylene, polyvinyl chloride, and other plastics, in half-spherical and other shapes. Gas samples typically extracted using syringes at specific time intervals and sometimes stored in glass vials if not going to be analysed immediately	Gas analysis typically done using gas chromatography with flame ionization detectors, electron capture detectors, and thermal conductivity detectors. Others used mobile gas detectors such as GT901 from Shenzhen Keernuo Technology Co., Ltd, Gas Monitor INNOVA1312 from Innova AirTech Instruments, LGR-UGGA-30P Gas Analyser, and real-time cavity ring-down spectroscopy (CRDS) analyser (Picarro G2508)	CH_4, CO_2, N_2O	Rhode Island, US; Ouagadougou, Burkina Faso; Qingdao, China; Dalian, China; Aguascalientes, Mexico; Helsinge, Denmark; Barcelona, Spain; Cap-Haïtien and Port-au-Prince, Haiti; Sendai City, Japan	(Bian et al., 2017; Brannon et al., 2017; Cui et al., 2015; Hernandez-Paniagua et al., 2014; Konate et al., 2013; Larsen et al., 2017; Liang et al., 2021; McNicol et al., 2020; Qi et al., 2019; Ryals et al., 2019; Uggetti et al., 2012a,b)
Flow-through chambers	Primary settling tanks, sludge storage tanks, digester effluent tanks, centrifuges, plug flow reactor, carousel reactor, anaerobic digestion reactors, activated sludge process	Gas collection floating hoods or simar kind of chamber with continuous gas flow, typically connected to gas analysers for continuous gas sampling and analysis	Gas analysis primarily done with infrared gas analysers (e.g., N-Tox®, Servomex 4900, SAXON JUNKALOR NDIR 5000 and 7000) for real-time and continuous measurement of gas concentrations, and gas flow ates measured by anemometers or pitot tubes	CH_4, N_2O	Birmingham, UK; Capelle aan den IJssel, near Rotterdam, Netherlands; biogas plants at 25 wastewater treatment plants in Denmark; four wastewater treatment plants in Austria	(Aboobakar et al., 2013a,b; Daelman et al., 2013; Fredenslund et al., 2023; Tauber et al., 2019)
Incubation approaches	Bar screen, primary settler, selector tank, plug flow reactor, carousel reactor, secondary clarifiers, sludge pumps, gravity thickeners, anaerobic digester, digested sludge storage tanks, belt thickeners, sludge dewatering centrifuges, biological nitrogen removal with nitrification and denitrification processes	Typically involves confining waste streams e.g. sludge, wastewater etc in vessels or lab-scale reactors under controlled conditions. Gases are sampled from the vessels or reactors using syringes	Gas analysis typically done in the lab using gas chromatographs, e.g. Varian 3800 and Shimadzu GC-8A	CH_4, N_2O	Capelle aan den IJssel, Netherlands; Japan	(Daelman et al., 2012; Itokawa et al., 2001)
Point source enclosure approaches	Bar screens, primary settling tank, gravity thickener, selector tank, compost filter, carousel tank, digested sludge storage tanks, gas supply to gas engines, ozone washer, intermittent aeration tank, anoxic tanks, membrane separation unit, coagulation unit, activated carbon unit, chlorine disinfection unit, integrated fixed film-activated sludge, membrane bioreactor, waste stabilization ponds	Sampling typically involves temporarily covering the emission source with a device, such as a gas sampling bag, which captures a defined volume of gas. The rate at which the bag fills provides the gas flow rate as measured by anemometers. Gas flow rate and the concentration in the sampling bag together give the gas flux.	Gas analysis done using gas chromatographs e.g. Varian 38000, Shimadzu GC-8A, Thermo Scientific™ TRACE GC	CH_4, CO_2, N_2O	Capelle aan den IJssel, Netherlands; Tokyo, Japan; Palermo, Italy; Western Australia; Quebec, Canada	(Daelman et al., 2012; Glaz et al., 2016; Itokawa et al., 2001; Mannina et al., 2017)

Table 7. Examples of studies using open methods for measuring greenhouse gas emissions from wastewater and sludge treatment technologies

Method	Sanitation technologies where gases were measured	Measurement approach	Gases	Examples of locations where measurements were done	References
Tracer flux measurements	Composting piles, sequencing batch reactors, activated sludge, moving bed bioreactors, membrane bioreactors, sand filters, BiodeniphoTM process, flocculation and clarification ponds for wastewater treatment, anaerobic digestion, combined heat and power (CHP), flow equalization basin, screens, sedimentation basins, secondary BiodenitroTM configuration treatment, aerated flow equalization pond, decanter centrifuge, thermal drying, and sludge incineration	Typically involved the use of acetylene as a tracer gas, combined with mobile analytical platforms equipped with CRDS gas analysers. Acetylene was released at a known rate, with downwind measurements of the greenhouse gas and acetylene concentrations facilitating the calculation of emission rates by comparing the plume concentrations of the tracer and target gases.	CH_4, N_2O	Guilin, China; Växjö and Källby, Sweden; Holbæk, Lundtofte and Lynetten, Denmark; Avedøre, Denmark	(Chen et al., 2022; Delre et al., 2017; Fredenslund et al., 2023; Yoshida et al., 2014)
Inverse modelling	Wastewater lagoons	Procedure involved measuring the target methane concentration from the lagoons using open path laser spectroscopy (Gasfinder 2.0, Boreal Laser, Inc.), the background methane concentration using a back-flush gas chromatography with FID (Model 55I, Thermo Scientific), and wind and turbulence data using an anemometer (Model 81000, R.M. Young). Emissions quantification was done using an inverse dispersion model (Windtrax 2.0.7.9, Thunder Beach Scientific), based on Monin-Obukhov similarity theory, and a backward Lagrangian stochastic model.	CH_4	Curry County, New Mexico, US	(Todd et al., 2011)
Passive and active optical approaches	Anaerobic digestion reactors, sludge deposits at a wastewater treatment plant, settling tanks, pre-aeration tanks, membrane bioreactors, membrane ultrafiltration tanks, screens and grit removal, activated sludge, sand filters, sludge thickeners, sludge dewatering, CHP	Identification of methane sources and quantifying the emissions was done using non-dispersive infrared cameras (e.g. FLIR Gas Find IR-320) or mid-infrared laser gas sensors and analysers e.g. Aeris MIRA Pico, Teledyne Analytical Instrument GFC-7002E and Fresenius Instrument GA2020.	CH_4, N_2O	Biogas plants at 22 wastewater treatment plants in Denmark; wastewater treatment plantsin Linköping and at Hammarby Sjöstadsverk in Stockholm, Sweden; 4 wastewater treatment plantsin Austria; wastewater treatment plantin Reading, UK	(Baresel et al., 2022; Fredenslund et al., 2023; Gålfalk et al., 2021; Tauber et al., 2019; Winter et al., 2012)

3.5. Use and/or disposal

Greenhouse gases can be released during and after the disposal of waste streams such as sludge or effluent on land or surface waters. Fugitive emissions can also be significant from resource recovery processes, when excreta-derived products such as treated sludge, pellets and effluent are applied to agricultural land or used in the generation of energy (biogas or solid fuels like briquettes) and when treated effluent is used for irrigation or groundwater recharge.

Of course, resource recovery products typically substitute for some other products made from virgin materials whose extraction, processing and distribution results into fossil-fuel greenhouse gas emissions. Therefore, the net emissions from the resource recovery products tend to be negative. However, it is also important to quantify these emissions to gain an understanding of the net emissions from the overall sanitation systems; hence, we include an overview of the methods that have been used for this functional group, as described below.

Flux chambers are the enclosure-based methods that are most often used in the context of measuring greenhouse gas emissions from the disposal of sanitation waste streams or the use of resource recovery products from sanitation and wastewater management systems. Static chambers have been used in a wide variety of instances, including the application of various excreta-derived fertilizers to agricultural land such as urine in the Netherlands (Kool et al., 2006), compost in Canada and Brazil (Badewa et al., 2022; de Urzedo et al., 2013), sewage sludge in Brazil and Canada (de Urzedo et al., 2013; Roman-Perez et al., 2021), and sludge pellets in the UK (Jones et al., 2005), as well as irrigation with wastewater effluent in Zimbabwe (Mapanda et al., 2010). Static chambers have also been used in instances with surface disposal and storage of excreta-derived waste streams such as compost piles in Haiti (McNicol et al., 2020; Ryals et al., 2019) and sewage sludge in Australia (Majumder et al., 2014), as well as for subsurface disposal of septic tank effluent in leach fields and soak pits in the US and Ireland (Diaz-Valbuena et al., 2011; Leverenz et al., 2010; Somlai et al., 2019; Truhlar et al., 2016). All these studies mostly used chambers made of polyvinyl chloride (PVC), with the gas in the chamber being sampled manually before further analysis. Gas analysis was typically done using infrared gas analysers (see e.g. Jones et al., 2005; Kool et al., 2006; Majumder et al., 2014) or gas chromatography instruments with ECD for N_2O analysis, thermal conductivity detectors (TCD) for CO_2 analysis and FID for both CH_4 and CO_2 analysis (see e.g. Badewa et al., 2022; de Urzedo et al., 2013; Majumder et al., 2014; Mapanda et al., 2010).

Compared to static chambers, incubation approaches have been used less frequently, particularly in instances where sewage sludge and its derivative pellets and biochar have been applied to agricultural land in the UK, Brazil and US (Akiyama et al., 2004; Grutzmacher et al., 2018; Paramasivam et al., 2008), as well as in instances where wastewater effluent has been used for irrigation in China (Xue et al., 2012). These studies used incubation vessels made of glass or plastic, with gas sampling done manually. For gas analysis, these studies mainly used gas chromatography instruments with ECD, FID and TCD detectors from manufacturers such as Shimadzu, Hewlett Packard and Agilent.

Optical methods are well suited for instances where measurements of greenhouse gas emissions are done over a large area at the scale of several hectares, which is the case for some instances of resource recovery such as the use of excreta-derived fertilizers on agricultural land. However, their use seems to be rare in the context of measuring emissions from the use of excreta-derived resource recovery products. Nevertheless, instances where optical methods have been used on technologies for the disposal of excreta-derived waste streams include measuring methane emissions from sludge deposits at a wastewater treatment plant in Sweden (Gålfalk et al., 2021). This particular case involved using a drone or unmanned aerial vehicle (UAV) equipped with a lightweight mid-infrared methane sensor for measuring methane concentrations, a visual camera, and a GPS tracker for logging coordinates, speed and altitude; other on-board sensors measured wind speeds, humidity, pressure and temperature, paired with a data logger for all the sensors. All measurements were done on-board the drone during flight, with a viewer and laptop on the ground providing real-time viewing of the data, which were then saved for further analysis.

No examples were identified in the literature describing the use of the other types of open methods for measuring greenhouse gas emissions from use or disposal sanitation technologies. This could be an indication of these methods not having been customized yet for applications to use or disposal sanitation technologies, or it could simply be that technologies in this functional group have not yet received sufficient scholarly attention to warrant measurements using a wider variety of methods.

4. Applied attributes and features of various methods

As described in the results in section 3, at least five categories of methods have been applied to quantifying greenhouse gas emissions from sanitation and wastewater management systems. In Table 8, a comparative overview of the features of these categories of methods is provided, with regards to how they relate to applications for sanitation technologies and systems.

The methods reviewed can cover applications with a range of resolutions, i.e. the level of detail at which various emission sources can be distinguished. These range from enclosure-based methods that can measure emissions at spatial resolutions less than 1 m^2 to optical methods that can cover several square kilometres. In the context of sanitation systems, this variation in available measurement resolution is important because technologies used along the many stages of the sanitation chain have different footprints. A pit latrine could be a few square metres and hence suited for measurements with a flux chamber, while a wastewater treatment plant may cover several hectares, especially if it includes technologies such as waste stabilization ponds or drying beds. Enclosure-based methods tend to have higher resolution but are difficult to use at larger scales. Flux chambers are used in the majority of studies described in this report, but they can underestimate total emission fluxes when it comes to facilities with larger areas, since chambers cannot be installed to cover large areas and hence require some extrapolation (Song et al., 2023). On the other hand, open methods can cover a wider range of resolutions and also perform better at larger scales, but they may be difficult to use to identify specific point sources due to low resolution in some cases.

As pointed out by Gålfalk et al. (2021), we need methods that can cover large areas but at a resolution that allows for identification of the various separate sources of emissions. This is especially relevant for quantifying emissions from on-site sanitation technologies, which are significant emission sources (see e.g. Johnson et al., 2022) yet are typically scattered throughout large urban and rural areas.

Besides incubation approaches, which require controlled conditions that are typically only available in a laboratory environment, most of the other methods can be undertaken with partially or wholly mobile equipment. This is relevant given that some aspects of sanitation systems can be located in areas that are relatively remote. The ability to collect and analyse samples directly without the need for transporting samples long distances can make it much easier to conduct empirical studies. As can be seen in Table 8, several enclosure-based and open methods make this possible. However, it is worth noting that some methods involve the extensive use of energy-consuming equipment, such as fans for mixing gases in flux chamber headspace (see e.g. Poudel et al., 2023) or automated samplers and gas analysers (see e.g. Somlai-Haase et al., 2017). While batteries or similar power backups can typically be used for these kinds of equipment, it can be challenging to use them to conduct extensive measurement campaigns in contexts where empirical work is being done far away from power grid networks. However, battery-powered gas sensors have been used successfully in some instances to enable automated real-time measurements of greenhouse gas emissions, e.g. on sewer lines in Australia (Liu et al., 2014).

As can be seen in Table 8, most of the equipment for conducting empirical measurements is quite expensive. This, in addition to the fact that specialized personnel are needed to plan and conduct the empirical studies, implies that emission measurements have typically been the preserve of universities and research institutions, with little involvement of other actors in the sanitation sector such as water utilities and municipal sanitation departments. The cost of measurement equipment also reflects the fact that some of these measurement techniques, especially among open methods, were developed originally for applications in the oil and gas industry (Wang et al., 2022) due to compliance and safety requirements, and they are now being slowly adapted for applications in other sectors such as sanitation (personal communications, interviewees).

To mitigate the high costs associated with some of the methods, some research teams rely on outsourcing analysis services to private companies or other institutions that already have the necessary equipment. For example, such outsourcing can apply to the use of flux chambers: an academic research team might develop their own flux chambers and do sampling themselves before transporting the samples quickly to a contract lab that has gas chromatography equipment to do the analysis. A variation of this can also be applied to other methods, such as hiring mobile equipment for a measurement campaign and then returning it to the owner institution afterwards.

Table 8 : Overview and comparison of methods for quantifying greenhouse gas emissions in the context of their application to sanitation and wastewater management technologies and systems

	Static and flow-through flux chambers	**Methods for outlets of well-defined point sources**	**Incubation approaches**	**Open methods based on column density, tracers or inverse modelling**	**Optical methods with potential to map greenhouse gas concentrations and fluxes**
Examples of sanitation technologies to which the methods have been applied	Septic tank chambers, roof vents, sand filters and leach fields, pit latrines, container-based sanitation, sewer manholes, integrated fixed film-activated sludge system, recirculating trickling filters, waste stabilization ponds, co-composting of solid waste and sewage sludge, sludge drying beds, sludge treatment wetlands, aeration tanks, settling tanks, sludge storage tanks, digester effluent tanks, centrifuges, plug flow reactor, carousel reactor, anaerobic digestion reactors, application of excreta-derived fertilizers and wastewater irrigation to agricultural land, surface disposal and storage	Pressurized sewers, Bar screens, settling tanks or thickeners, selector tank, compost filter, carousel tank, digested sludge storage tanks, gas supply to gas engines, ozone washer, aeration tanks, anoxic tanks, membrane separation unit, coagulation unit, activated carbon unit, chlorine disinfection unit, activated sludge, membrane bioreactor, waste stabilization ponds	Lab-scale sewer reactors, bar screens, settling tanks, plug flow reactors, carousel reactor, sludge pumps, gravity and belt thickeners, anaerobic digesters, sludge storage tanks, sludge dewatering centrifuges, biological nitrogen removal with nitrification and denitrification processes, application of excreta-derived fertilizers and wastewater irrigation to agricultural land	Composting piles, sequencing batch reactors, membrane bioreactors, sand filters, Biodenipho™ process, anaerobic digestion, CHP, flow equalization ponds or basins, screens, sedimentation basins, Biodenitro™ treatment, decanter centrifuge, thermal drying and sludge incineration, wastewater lagoons	Sewer lines, wet wells, manholes and pumping stations, anaerobic digestion reactors, surface disposal and storage of sludge, settling tanks, membrane bioreactors, screens and grit removal, activated sludge, sand filters, sludge thickeners, CHP.
Resolution and scale of application	Typical spatial resolution of <1 m2. Difficult to use for applications at larger scales as it requires the use of multiple flux chambers.	Typically covers point sources with area of <1 or a few m2.	Small volumes of, for example, wastewater or sludge can be incubated at lab-scale, up to a few hundred litres for pilot scale reactors.	Resolution and scale can range from a few square metres to several hectares	Resolution and scale can range from a few m2 to several km2.
Mobility	Flux chambers are highly mobile. Gas analysis can also be done using portable gas analysers. Lab-scale instruments for gas chromatography are much less mobile.	Mobile equipment can be used in some instances, but mobility is low if analysis is done using lab-scale instruments for gas chromatography	Incubation requires controlled conditions, typically available only in lab conditions and this limits mobility.	Some sensor devices are mobile, e.g. a mobile CRDS gas analyser, while others are not.	Several types of laser-based sensors are mobile and can be mounted on UAVs. Ground-based methods using non-dispersive infrared cameras also favour high mobility.
Energy requirements for field operations	Field measurements can require power sources if using fans for mixing air in the chamber, using autosamplers and/or using gas analysers with automated continuous measurements.	No power is needed for field sampling, except if using anemometers for gas flow rate measurements.	Incubations are typically done in labs where a power source is often available.	Mobile sensor devices are typically battery operated.	A power source is usually needed especially for active optical methods. Can be battery-powered or connected to external electricity source.

	Static and flow-through flux chambers	**Methods for outlets of well-defined point sources**	**Incubation approaches**	**Open methods based on column density, tracers or inverse modelling**	**Optical methods with potential to map greenhouse gas concentrations and fluxes**
Equipment costs (examples)	Custom-made flux chambers can cost anywhere from USD 500 to USD 2000, depending on the materials used and location plus the consumables needed. Gases can be analysed in Gas Chromatographs that can cost in the range of USD 10 000 to USD 50 000. Other gas analysers such as Geotech GA5000 and G200 cost USD 2500–5500.	Gases can be analysed in Gas Chromatographs that cost USD 10 000–50 000. Other gas analysers can also be used which cost USD 2500–5500.		Fourier Transform Infrared Spectroscopy (FTIR) instruments, which can be used to measure gas concentrations in methods based on tracer flux measurement and inverse modelling, can cost in the range of USD 10 000–35 000 when new or USD 2000–25 000 when used.	UAV-mountable gas analysers (e.g. Aeris' MIRA) can cost about USD 10 000–40 000, but there are cheaper ones, e.g. for CO_2, which cost about USD 300. Suitable UAVs (e.g. from the company DJI) cost about USD 10 000–20 000 (Dinh, 2020), with suitable sensor hubs and computer adapters costing about USD 3500. Geotech's GA5000 portable gas analyser measures CH_4, CO_2, O_2, H_2S and CO, and costs about USD 5500. A G200 N2O analyser costs about USD 2500. A hyperspectral camera such as the one used by Gålfalk et al (2022) costs upwards of USD 750 000.
Advantages	Relatively simple methods and are the most known methods for sanitation applications. Relatively low cost, especially if flux chambers are made from locally available materials and low-cost gas analysers are used.	Relatively simple method and can offer precise measurement at specific known emission sources.	Controlled conditions can enable to study the influence of specific factors on greenhouse gas emissions and hence to establish cause-effect linkages.	Can be used to measure emissions at both diffuse and point sources over large areas. They are non-invasive and can allow for automated continuous measurements.	They are non-invasive, can cover large areas, e.g. over an entire wastewater treatment plant, but with high resolution and can detect previously unknown sources of emissions.
Disadvantages	Can lead to underestimation of emissions if used to cover a large area using only a few selected points. Emission hotspots can be missed. They can also be disturbed by under- or over-pressurization of the chamber, hence hindering proper measurements.	Limited to identifiable discrete emission points.	Requires access to suitable lab facilities for the incubation. The results obtained can vary among the incubated replicates, and also do not reflect in situ conditions in the typical sanitation system.	Effective measurements typically require good weather conditions. Tracer flux measurements depend on high availability of consumables i.e. the tracer gas.	Passive optical methods depend on good temperature contrasts in the measurement area, hence relying on good weather conditions. Most equipment is very costly, which limits widespread applications.

5. Ongoing method development and improvements

Driven by global interest in addressing the challenge of climate change, there are several ongoing efforts to further develop and improve existing methods for empirical measurements of greenhouse gas emissions, with some of these efforts being directly for applications in sanitation and wastewater management systems.

To address the need for adaptation of flux chambers from applications in agriculture and solid waste management to sanitation systems, a modified chamber design has been proposed by Reddy et al. (2022), including the repurposing of landfill gas analysers (GeoTech GA5000 and GeoTech G200) to enable simultaneous sampling and analysis in the field without a need for expensive lab-based analysis equipment. Recent work by Bastviken et al. (2020) also highlighted available low-cost gas sensors such as the Figaro NGM2611-E13 (which can cost as low as USD 40), which can be connected to flux chambers for real-time measurement of emissions. Open access protocols for calibration and setting up dataloggers for this flux chamber combined with a low-cost gas sensor (see Bastviken et al., 2020) create the possibility for more cost-effective measurement of greenhouse gas emissions from sanitation systems in a variety of geographical contexts.

The extent of automation that is possible with some methods for measuring greenhouse gas emissions has enabled continuous monitoring of emissions using automated sensors in some contexts in sanitation systems. The sanitation sector, particularly wastewater treatment in utility-sized plants, is highly regulated with regards to discharge standards for effluent. In the past such regulation has driven developments in sensors to track various chemical and physical parameters in wastewater treatment processes. This same experience is being carried over to automated sensors for greenhouse gases. Examples include the development and use of automated sensors for continuous real-time measurements of N_2O at various wastewater treatment plants in Switzerland (Gruber, 2021) and the development of a mobile sensor platform in Canada, which can be used for continuous automated monitoring of emissions from lagoons or in similar contexts (Fu et al., 2017).

At the same time, interest is increasing in the potential of digital technologies for opening up new opportunities for harnessing various kinds of data from sanitation systems – the “smart sanitation economy” (see e.g. Andres et al., 2018; Carnovale, 2024; Rary et al., 2020; TBC & IWA, 2020). While mostly public health related applications have been proposed so far, the emergence of low-cost sensors for measuring greenhouse gas emissions (see Bastviken et al., 2020) could extend the applications of “smart sanitation” approaches to automated continuous monitoring of greenhouse gas emissions.

There are also developments in methods based on remote sensing, some of which are already highlighted in Table 7. The methodological developments in this area include ground-based approaches, e.g. the use of hyperspectral mid-infrared cameras for applications at wastewater treatment plants, and aerial-based approaches where sensors are mounted on drones, airplanes or satellites (Gålfalk et al., 2021). These kinds of methods enable faster measurements of emissions over much larger areas. A key challenge, however, is that in some cases, the resolution of some of the sensors used may not be high enough to distinguish between greenhouse gas emissions originating from sanitation technologies versus those from other sources, especially in urban areas with multiple emission sources. A breakthrough in this area would be the development of a method based on remote sensing whereby emissions on a city-scale or neighbourhood scale can be measured while distinguishing the emissions from dispersed sanitation technologies and systems across the area. This technique could find wide applications in urban areas where on-site sanitation systems are predominant, such as in Kampala and Kigali. However, the relatively high costs of equipment for methods based on remote sensing remain a barrier for wider applications of these methods.

6. Challenges and opportunities for empirical methods in low- and middle-income countries

Empirical studies of greenhouse gas emissions from sanitation using the various methods discussed above are spread across a variety of countries, as shown in Table 4. The use of flux chambers is reported across countries representing all four income groups as classified by the World Bank (World Bank, n.d.). On the other hand, the use of open methods is concentrated in high-income countries, with the exception of China, which is in the upper middle-income group. Other methods, such as those based on optical mapping of greenhouse gas concentrations and fluxes or column density tracers, are primarily reported in higher-income countries such as Australia, South Korea, France and Spain. This trend may reflect the greater availability of resources for research and development in these countries, allowing for the exploration of novel and potentially more precise greenhouse gas measurement techniques.

Our interviews with stakeholders delved deeper into some of the factors behind this spread of methods, to understand what is needed to facilitate more empirical measurements of greenhouse gas emissions from sanitation systems in low- and middle-income countries. The issues that emerged from the interviews were costs, standardization of approaches, demand and knowledge exchange, discussed in the following sections.

6.1 Costs

A recurrent theme in both the literature and interviews we conducted was the high costs associated with conducting empirical measurements of greenhouse gas emissions, especially in sanitation settings. As can be seen from the information in Table 8, the costs of equipment for sampling and analysing greenhouse gas emissions can range from thousands to several hundreds of thousands of US dollars. As such, empirical measurements of greenhouse gas emissions from sanitation systems have tended to be the domain of research teams at universities with significant research budgets, particularly in high-income countries, as the data in Table 4 shows. These high costs therefore create hurdles for more widespread empirical measurements from sanitation systems in low- and middle-income countries where limited budgets may not permit investing in expensive equipment.

Besides the equipment costs, other costs related empirical work include laboratory consumables for sampling and analysis procedures, battery packs for using mobile equipment, and transport costs for ferrying equipment and samples between fieldwork locations and laboratories where analysis is sometimes done. These costs can be relatively lower than equipment costs, but they are not insignificant.

An additional concern raised during the interviews is the cost of hiring and maintaining qualified personnel to operate, maintain and calibrate measurement equipment, especially considering the sensitive nature of the devices. In general, conducting empirical measurements of greenhouse gas emissions requires highly qualified people with skills from fields like chemistry, atmospheric sciences, environmental sciences and engineering, among others. The need to have adequate access to qualified personnel therefore also can be a hurdle in some resource-limited contexts if there is no external funding, especially if the demand for empirical data on greenhouse gas emissions is not significant enough to underwrite the large budgets required to cover all these cost-related aspects.

6.2 Standardization of approaches

The absence of standardized approaches when measuring emissions from on-site sanitation technologies emerged as a key concern from the literature and the interviews. This is partly due to the lack of standards on methodological approaches and equipment such as flux chambers, but also due to limited standardization in the form and construction of some sanitation technologies.

As described above, most of the methods for measuring greenhouse gas emissions were originally developed for applications in other fields and later adopted for applications in the sanitation sector. But because no clear standard exists for setting up equipment for measuring emissions from sanitation technologies, each research team often makes their own adaptations to equipment, and this can somewhat limit comparability of results from different empirical studies.

This lack of comparability is further exacerbated by the variability in the design of some sanitation technologies and user behaviour. For example, pit latrine depth can vary, and pit latrines can be lined or unlined; user practices can influence how quickly the pit fills up and the water content in the pit. Each setting can require different adaptations to flux chambers during installation. While adaptations to measuring equipment can be necessary in such contexts, they also imply that more expertise can be needed to ensure high accuracy in the results as well as potential comparability with results from other studies.

6.3 Demand for empirical data and its utility in policy processes

Interest appears to be growing in data on greenhouse gas emissions from sanitation systems, among a breadth of stakeholders that seem to be more aware of the significant contribution that the sanitation sector makes to emissions (Lambiasi et al., 2024). These stakeholders include academics, government entities, development finance institutions, sanitation utility companies, non-governmental organizations and philanthropic organizations. The interest in data on emissions from sanitation systems is largely driven by three factors: the need to fulfil reporting obligations at various governance levels; the need to determine low-emissions options for sanitation technologies and systems; and interest in obtaining climate finance for sanitation-related projects.

While greenhouse gas emissions are typically not part of the discharge standards to which water and sanitation utilities must adhere, some countries increasingly require utilities to report their emissions as part of input to national and regional emissions inventories (Alix et al., 2022; IWA, 2023). These reporting requirements therefore drive the interest in data on greenhouse gas emissions from utilities and government entities. Ongoing efforts around the globe to mitigate climate change have also incentivized academics, non-governmental organizations and other implementing organizations working in the sanitation sector to try to identify ways in which greenhouse gas emissions from sanitation systems can be reduced, which in turn has raised interest in data on the greenhouse gas footprint of various sanitation technologies (Lutkin et al., 2022; Ye et al., 2022).

The potential of obtaining climate finance, e.g. via carbon credits, has also incentivized sanitation utilities, government entities and other implementing organizations in the sanitation sector to gather data on greenhouse gas emission from sanitation systems and related mitigation avenues (Alix et al., 2022; CBSA, 2023). Data on emissions are, of course, also of interest to finance institutions and philanthropic organizations that are managing climate finance portfolios.

However, the interest is not universally shared by those in the sanitation sector. Some see the interest in greenhouse gas emissions data as potentially detracting from more impactful sanitation interventions in low- and middle-income countries. To date, these countries have made low contributions to global greenhouse gas emissions, and thus, some countries argue that the priority should be on adapting their sanitation systems to the impacts of climate change. This perspective emphasizes that a narrow focus on greenhouse gas mitigation could lead to sanitation options that are misaligned with the broader needs of climate adaptation, which is crucial for enhancing resilience in vulnerable regions.

The tensions between these perspectives exists across the sanitation sector, although based on the interviews, some initiatives address both emissions and resilience aspects of sanitation systems. Therefore, it is crucial to better understand the actual demand for empirical data on emissions and how this data can be used in policymaking. Clarifying the policy applications of emissions data could ensure that the development of measurement methods is appropriately paced and targeted. This approach will help balance the dual goals of reducing emissions and adapting sanitation systems to climate impacts, ultimately supporting more comprehensive and effective climate action in the sanitation sector.

6.4 Knowledge exchange and collaboration across the sector

To advance empirical measurement of greenhouse gas emissions from sanitation systems in low- and middle-income countries, the information from the scientific literature review and our interviews emphasized the importance of collaboration and knowledge sharing among researchers who are engaged in these kinds of studies. Collaborative approaches could prevent duplication of efforts, enabling researchers to build on previous work, especially considering the existing gaps in empirical data from sanitation systems in these geographical contexts. Given the high costs of measurement equipment, more collaboration across institutions could also enable the sharing of equipment where possible, to optimize the available resources. An example of this was highlighted during the interviews, where one research team doing studies in Uganda shared equipment with another team that then conducted measurements in Kenya.

Exchange of knowledge on methods among stakeholders can also enable subsequent studies to address methodological gaps identified in previous studies, instead of replicating the same gaps. This is especially important given the need for adaptations of measurement equipment in some contexts. Ongoing efforts already share more widely adaptations on flux chamber design for on-site sanitation systems (see e.g. Reddy et al., 2022).

Collaborations need to be strengthened across sectors, i.e. academia on one hand and various kinds of sanitation practitioners on the other. Some practitioners are interested in data on greenhouse gas emissions, for example, due to regulatory compliance or climate finance incentives, but they do not have interest or capacity for doing empirical measurements. These kinds of situations can be a foundation for mutually beneficial collaborations between academics and practitioners, especially considering that getting robust empirical data often requires measurement campaigns over a long period of time. Similar situations include automated real-time measurements in wastewater or faecal sludge treatment facilities, where researchers and practitioners can work together.

7. Conclusions and recommendations

Our findings highlight that several methods have been used to quantify emissions from technologies at various stages of the sanitation service chain. The variety of methods reviewed, from enclosure-based to advanced optical techniques, reveals a spectrum of applicability, cost and technical complexity. Static and flow-through flux chambers, despite their widespread use, are limited by scale and potential disturbance effects. Conversely, novel optical methods and remote sensing offer expansive coverage and high-resolution insights but are hindered by high costs and specialized expertise requirements. Enclosure-based methods are predominant in a wide variety of countries, with applications in both sewered and non-sewered sanitation contexts. However, open methods are so far mostly used only in high-income countries, with applications focused on wastewater treatment plants and sewers.

Given our findings, we advocate for a multifaceted approach to greenhouse gas measurement in sanitation, emphasizing the importance of methodological adaptability to diverse sanitation technologies and contexts. We also underscore the necessity of collaboration and knowledge exchange among stakeholders to catalyse methodological advancements and standardization, thereby facilitating broader and more efficient empirical data collection.

The need to collect empirical data more widely on greenhouse gas emissions from sanitation systems is not merely an academic exercise, but a critical step towards achieving global climate targets. The more empirical data we have, the more accurate our emissions inventories can become and the more effective the mitigation strategies based on those inventories will become.

It is therefore crucial that policymakers, researchers and practitioners collaborate more closely in conducting empirical work on quantifying emissions and in the dissemination of data. This collective action is essential not just for advancing methodological innovation, but also for adapting and optimizing existing, cost-effective methods that are suitable for diverse sanitation technologies and contexts.

Given the broad consensus on the importance of quantifying emissions, it is vital to focus investments on developing and refining affordable and scalable measurement techniques that can be readily implemented in low- and middle-income countries, which have the most crucial data gaps regarding greenhouse gas emissions from sanitation systems. Prioritizing substantial funding for these adaptable and accessible methods will enhance the capability of these countries to gather accurate emissions data globally.

Concurrently, a concerted push towards capacity development is imperative, to increase awareness of the multifaceted measurement methods and enhance the proficiency of stakeholders across nations in employing these techniques. Ultimately, the goal is to take advantage of more precise emissions data to inform the design, financing and implementation of sustainable, resilient and low-emissions sanitation infrastructure, thereby contributing to the broader objectives of environmental protection and public health improvement.

As such, the findings in this report call for

- **advancing methodological innovation and standardization**. Investing in the development and refinement of affordable and scalable measurement techniques is crucial for enabling more accurate and comprehensive greenhouse gas emissions monitoring in sanitation systems worldwide. Methodological advancements should focus on making technologies adaptable to various sanitation technologies and geographical settings, particularly in low- and middle-income countries. However, emphasis should also be placed on attaining a certain level of standardization to ensure consistency and comparability of data across different regions and contexts.

- **capacity development and collaboration**. Investing in capacity-building initiatives is essential to increase awareness of the available measurement techniques and their applications, and hence empow er local stakeholders, including researchers, policymakers and sanitation practitioners, with the knowledge and skills required to use various greenhouse gas measurement methods. Capacity development efforts should also focus on fostering a deeper understanding of the implications of greenhouse gas emissions data for policymaking and climate action. Additionally, providing access to resources and tools necessary for empirical measurements will enable stakeholders in resource-limited settings to conduct accurate and effective greenhouse gas emissions monitoring. This can be done through collaborative arrangements, as pointed out in our findings. Creating collaborative networks and partnerships can aid in sharing knowledge and resources, facilitate coordinated research efforts, enhance the dissemination of findings, and support the implementation of standardized methodologies.

Through making concerted efforts in methodological innovation, standardization, capacity development and collaboration, we can significantly enhance the accuracy, reliability and comprehensiveness of greenhouse gas emissions measurements in sanitation systems. Emphasizing these areas will address current data gaps and improve the comparability of results across different contexts and technologies. Such advancements are crucial for informing evidence-based policy and investment decisions, ultimately building a more robust empirical basis for climate action in the sanitation and wastewater management sector.

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