MANAGING THE CLIMATE IMPACT OF HUMAN WASTE

A study to understand the impact of methane emissions from fecal sludge and potential abatement approaches

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Cover photo: Anaerobic biogas digester in Africa, 2019. Image courtesy of Maji Solutions, a company that designs treatment projects in West Africa.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

ABD	Anaerobic Biogas Digester
ABR	Anaerobic Baffled Reactor
ASP	Activated Sludge Process
BOD	Biological Oxygen Demand
BSF	Black Soldier Fly
C:N	Carbon to Nitrogen
CDD	Consortium for DEWATS Dissemination Society
CBS	Container-based Sanitation
CH_4	Methane
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
COD	Chemical Oxygen Demand
CPI	Climate Policy Initiative
CW	Constructed Wetland
DHS	Demographic and Health Surveys
EAWAG	Swiss Federal Institute of Aquatic Science and Technology
FS	Fecal Sludge
FSM	Fecal Sludge Management
FSTP	Fecal Sludge Treatment Plant
GHG	Greenhouse Gas
GWP	Global Warming Potential
GWT	Groundwater Table
IPCC	Intergovernmental Panel on Climate Change
JMP	Joint Monitoring Programme
$kgCO_2e/year$	Annual per Capita Methane Emissions
KII	Key Informant Interview
LMIC	Low- and Middle-Income Country

MCF	Methane Correction Factor
Mt	Metric Ton
OP	Omni Processor
SDG	Sustainable Development Goal
SFD	Shit Flow Diagram
SSA	Sub-Saharan Africa
T	Ton
tCO_2e	Tons of Carbon Dioxide Equivalent
TS	Total Solids
UASB	Upflow Anaerobic Sludge Blanket
UDDT	Urine-Diverting Dry Toilet
UNICEF	United Nations Children's Fund
URBAN WASH	Urban Resilience by Building and Applying New Evidence in WASH
USAID	United States Agency for International Development
UV	Ultraviolet
VSSF	Vertical Sub-Surface Flow
WASH	Water, Sanitation, and Hygiene
WHO	World Health Organization
WRM	Water Resources Management
WWTP	Wastewater Treatment Plant

PREFACE

Urban Resilience by Building and Applying New Evidence in WASH (URBAN WASH) is a centrally funded activity of the United States Agency for International Development (USAID) Bureau for Resilience and Food Security. It is a global five-year (2021–2026) research and learning program implemented by Tetra Tech in collaboration with Aquaya Institute, FSG, Iris Group, SEGURA Consulting LLC, the Stockholm Environment Institute, and WaterAid. It is led by a team of experienced researchers and urban water, sanitation, and hygiene (WASH) experts and is supported by an external Advisory Board composed of WASH and urban resilience innovators and thought leaders.

The goal of the program is to promote impactful, sustainable, equitable, and climate-resilient WASH and water resources management (WRM) policy and programming in urban and peri-urban areas by strengthening evidence-based decision making among partners and host governments at the local, regional, state, and national levels. To achieve this objective, URBAN WASH will perform tasks and complete deliverables under the following three interrelated components:

1. Component 1: Establish and support strategic engagement and partnerships to ensure local application and broader relevance of research and use of evidence.
2. Component 2: Generate high-quality evidence through implementation research to increase the sector's understanding in three main areas:
    a. Enabling environment (i.e., viable urban WASH and WRM policies and regulations and institutional arrangements) for improved drinking water quality and city-wide sanitation *(Focus Area 1)*;
    b. Approaches for sustainable small-scale and informal service provision *(Focus Area 2)*; and
    c. Sustainable approaches to improve source water protection and diversification for resilient water supplies *(Focus Area 3)*.
3. Component 3: Provide on-demand technical assistance to USAID missions and technical bureaus to support urban WASH and WRM programming, including research, evaluations, and assessments.

An overarching aim across the components is to support climate-resilient, low-emissions WASH programming. As methane emissions from sanitation are a known contributor to climate change, URBAN WASH is working to understand the landscape of existing knowledge about methane emissions and abatement approaches for urban sanitation in low- and middle-income countries.

EXECUTIVE SUMMARY

Today, methane emissions are the second largest driver of global warming, accounting for roughly 20 percent of global anthropogenic greenhouse gas emissions (United States Environmental Protection Agency 2022b). Methane emissions from the sanitation sector have been estimated to contribute between 7 percent and 10 percent to global anthropogenic methane emissions (McKinsey and Company 2021). However, these estimates focus on wastewater from sewered sanitation systems and do not account for the emissions from non-sewered sanitation systems, typical in many low- and middle-income country (LMIC) contexts. The technologies typically used in these non-sewered sanitation systems allow waste to decompose under anaerobic conditions, thereby contributing to anthropogenic methane emissions. Abatement of emissions from such sanitation systems can therefore play a part in the climate action plan to curb methane emissions.

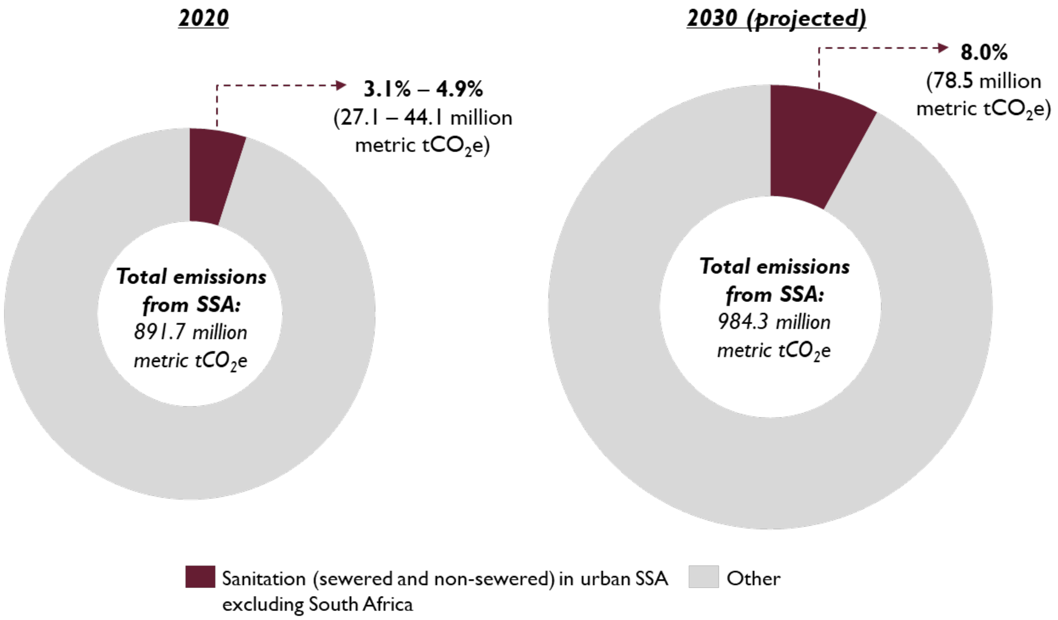
However, there is limited evidence on approaches that can abate methane emissions from sanitation in urban LMIC contexts, where technical and financial resources to implement solutions may be limited. The study involved two phases of research to address these knowledge gaps:

- Phase 1 aimed to quantify and understand the current sources and drivers of methane emissions from sanitation systems in LMIC contexts by developing an emissions model in sub-Saharan Africa (SSA)—excluding South Africa as a sample urban LMIC context.
- Phase 2 aimed to identify promising interventions (including technologies, service models, and behavior changes) for adoption in urban LMIC contexts and relevant evidence gaps.

SCALE OF THE PROBLEM

The contribution of sanitation to methane emissions in urban LMIC contexts **is significant and likely to increase over time.** This study estimated that sanitation systems (both sewered and non-sewered) in urban SSA (excluding South Africa) contributed 3.1 percent to 4.9 percent to the region's total reported annual anthropogenic methane emissions in 2020. This is comparable to sectors like rice cultivation and coal mining, which are usually given more emphasis in discussions around methane abatement (McKinsey and Company 2021). This percentage is projected to grow to 8.0 percent of the projected total annual methane emissions in 2030 (refer to Figure ES 1).

Figure ES 1. Estimated emissions from sanitation in urban SSA as a proportion of total annual anthropogenic methane emissions



SOURCES AND DRIVERS OF EMISSIONS

Current emissions are due to the high prevalence of non-sewered containment facilities (~93.3 percent in urban SSA) that often remain unemptied and promote the anaerobic decomposition of the waste. The high level of anaerobic decomposition is driven by the use of wet containment technologies (i.e., those that use water for flushing and cleansing), sharing of facilities by many users, and the absence of a pit lining in areas with high groundwater table levels.

The projected growth in emissions by 2030 is due to two trends. First, **urban population growth** (projected to grow by 53.1 percent for SSA [World Bank n.d.]) will increase the total amount of human waste that sanitation systems will need to process. Second, **achievement of Sustainable Development Goal 6.2 targets** of 100 percent coverage of improved, individual containment facilities and 100 percent treatment coverage will increase emissions if done so achieved through anaerobic containment and treatment technologies that are currently prevalent in urban SSA.

THE WAY FORWARD TO ABATE METHANE

Given the overall urgency of the climate crisis, action is needed today to start curbing methane emissions from sanitation systems in LMICs. Interventions are especially needed for the containment and treatment stages of non-sewered sanitation systems, as the expansion of sewered sanitation systems is unlikely due to limited financial capacity and/or capabilities of most cities in LMICs.

Our study highlights that there are no interventions across containment and treatment stages of non-sewered sanitation systems that are appropriate to scale in all contexts. But there are interventions that a) are applicable in certain LMIC contexts, b) are promising but need more research evidence from LMIC contexts and c) have technological gaps which need further research and development.

Keeping these three categories of interventions in mind, this study proposes four categories of investments, with promising interventions under each, to start developing methane-abating sanitation systems in urban LMIC contexts (refer to Figure ES 2):

1. Implement the interventions that show **high abatement potential** and **appear promising for specific LMIC contexts**:

- **For dry containment facilities, individual toilet usage** in areas with low groundwater table levels, **lining of pits** in areas with high groundwater table levels, and **container-based sanitation** in dense, informal settlements where households are willing to use non-permanent solutions.
- **For fecal sludge treatment, unplanted drying beds** for solid-liquid separation of fecal sludge with high total solids content and low treatment volume, **mechanical pressing** for solid-liquid separation where technical expertise and continuous supply of chemical polymers and mechanical parts are available, **co-composting** for pathogen reduction where additional waste streams are available, and **flaring** of methane from existing anaerobic digesters.
- **For wastewater treatment, clarifiers** for primary treatment where energy is readily available, and **activated sludge processes** or **aerobic digesters** for secondary treatment in contexts where energy and technical expertise are available or **constructed wetlands** for secondary treatment contexts with low strength wastewater.

2. Experiment and generate evidence for interventions that **appear promising** but warrant **further research for scaled implementation in LMICs:**

- **For containment facilities,** smaller cities have implemented **scheduled emptying** services successfully, but there is a need for implementation evidence from larger cities; the precise degree of this type of service's impact on emissions needs to be understood better.
- **For fecal sludge treatment,** LMICs have implemented **aerobic technologies** for biological decomposition, **black soldier fly larvae** for pathogen reduction, and **in-house use of biogas** (instead of release into the atmosphere) from anaerobic digesters in limited contexts, and more evidence on their feasibility and viability is needed.
- **For wastewater treatment,** there has been successful implementation of **flaring or in-house use of methane captured** from anaerobic treatment of wastewater in developed contexts, but there is a need for evidence on their adaptation for the low-resource settings of LMICs.

3. Innovate to develop interventions that address gaps in the identified abatement approaches:

- **Reducing emissions from wet containment facilities** (e.g., by controlling the water content entering the substructure); and
- **Capturing methane** for **outbound use** from anaerobic decomposition at **treatment plants**.

4. Create a favorable **enabling environment** to increase awareness of the climate impact of sanitation systems and incentivize the adoption of more climate-friendly technologies, service models, and behaviors.

Figure ES 2. Summary of actions needed for methane abatement in sanitation

Implement

Adopt for specific context:

- Water content control in **dry containment** facilities through **individual usage**, **lining of pits**, and **container-based sanitation**
- **Solid-liquid separation** through **unplanted drying beds** or **mechanical pressing, pathogen reduction** and **reuse** through **co-composting** for **fecal sludge treatment**
- **Flaring** of **methane captured** from anaerobic **fecal sludge treatment**
- **Primary wastewater treatment** through **clarifiers** and **secondary treatment** through **aerobic digesters, activated sludge processes,** or **constructed wetlands**

Experiment

Address evidence gaps through implementation research for:

- Reduction of decomposition time (especially for **wet containment** facilities) through **scheduled emptying**
- **Biological decomposition** through **aerobic technologies, pathogen reduction** and **reuse** at fecal sludge treatment facilities through **black soldier fly larvae**
- **In-house use** of methane captured from anaerobic **fecal sludge treatment**
- **Flaring** or **in-house use** of **methane captured** from anaerobic **wastewater treatment**

Innovate

Address technical gaps through research and development on interventions for:

- **Emissions reduction** in substructure of **wet containment** facilities
- **Capturing methane** for **outbound use** from anaerobic decomposition at **treatment plants**

Enabling environment

Short term

- **Advocacy and dissemination** for increasing awareness and promoting promising solutions
- **Decision support tools** and measurement of **emission factors**
- Landscape of **climate financing** opportunities

Medium term

- **Guidelines and policies** for adopting promising solutions
- **Monitoring and tracking emissions** to understand impact of interventions and inform refinements
- **Financing mechanisms** for addressing viability challenges

1.0 CONTEXT AND PURPOSE OF THE STUDY

The global response to the climate crisis largely hinges on limiting global warming to the 1.5°C threshold set in the 2015 Paris Agreement.[1] Staying within this threshold requires immediate, deep, and sustained reductions in greenhouse gas (GHG) emissions across sectors.

Today, methane emissions are the second largest driver of global warming, accounting for roughly 20 percent of global anthropogenic (i.e., human-influenced) GHG emissions (United States Environmental Protection Agency 2022b). Methane also has an outsized impact on the climate. While it is more than 25 times as potent as carbon dioxide (CO_2) at trapping heat in the atmosphere (United States Environmental Protection Agency 2022a), it also dissipates much quicker than CO_2, with an average lifetime of around a decade (compared to centuries for CO_2) (*Nature* 2021). Hence, even if CO_2 emissions were reduced drastically today, its impact on the climate would only be felt much later in the century. However, reducing methane emissions today would have an impact on warming in the nearer term. Methane abatement can, therefore, add some much-needed buffer to the small remaining carbon budget—the maximum amount of CO_2 that can be emitted while still having a chance to limit warming to 1.5°C or 2.0°C (United Nations Environment Programme, 2021).

Climate action to curb methane emissions can extend to the sanitation sector. This is because sanitation systems can contribute to anthropogenic methane emissions if the biological decomposition of human feces is facilitated by anaerobic technologies. Literature on methane emissions in sanitation focuses on wastewater from sewered sanitation systems, which are estimated to contribute 7.0 percent–10.0 percent of global anthropogenic methane emissions (McKinsey and Company 2021). However, methane emissions from non-sewered sanitation systems, typical of many low- and middle-income country (LMIC) contexts, are not well quantified (Shaw, Kennedy, and Dorea 2021) and may be significantly underestimated. There is also limited evidence on the approaches that can abate methane in sanitation, especially for LMIC contexts, where technical and financial resources to implement interventions may be limited.

This study aimed to address these gaps by developing quantitative estimates of methane emissions in urban LMIC contexts, understanding the sources and drivers of these emissions, and identifying promising approaches and interventions (including technologies, service models, and behavior changes) for adoption in urban LMIC contexts and relevant evidence gaps warranting further investigation. Based on the findings, this report aims to guide future research and interventions to abate methane in LMIC sanitation systems and contribute to the global response to the climate crisis.

The report is organized into the following sections:

- **Methodology** used for defining sanitation systems, estimating methane emissions, and identifying abatement approaches and interventions;
- **Scale of the problem**, based on estimates of current and future methane emissions;
- **Sources and drivers of emissions**;
- **Abatement approaches** to reduce containment and treatment emissions;
- **Assessment of interventions**, (i.e., the technologies, service models, and behavior changes, for various abatement approaches); and

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[1] The Paris Agreement is a legally binding international treaty on climate change, adopted by 196 parties at the United Nations Council of Parties (COP) 21 in Paris on December 12, 2015. Its goal is to limit global warming to well below 2.0°C, preferably to 1.5°C, compared to pre-industrial levels.

- **The way forward**, which proposes a series of immediate- and medium-term actions to develop methane-abating sanitation systems in urban LMIC contexts.

2.0 METHODOLOGY

The study started by defining "sanitation systems" and the various components under them. The study then conducted two-phased research to quantify the impact of methane emissions from sanitation systems in urban LMIC contexts and identify promising abatement approaches and interventions.

2.1 DEFINING SANITATION SYSTEMS IN LMICS

Key definitions of sanitation systems in LMICs were developed based on the following:

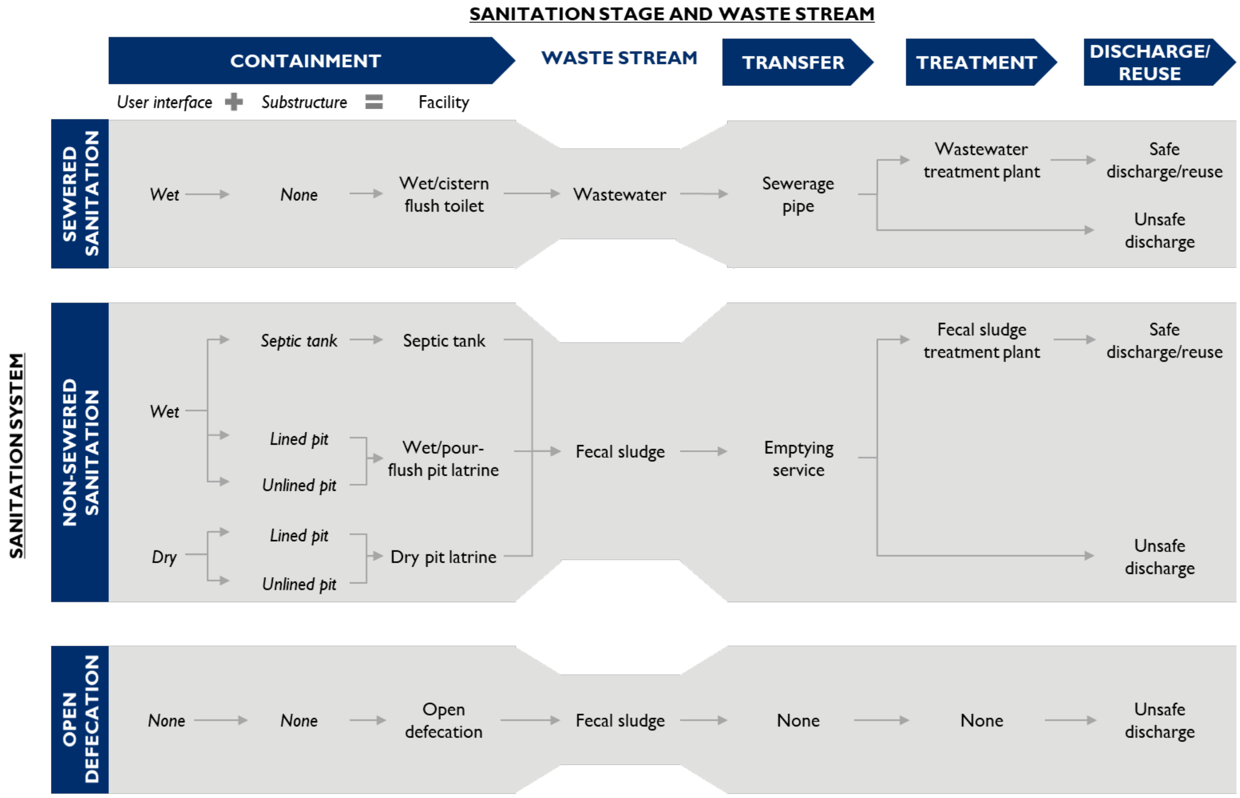
- **Scanning and adapting definitions from sanitation compendia and datasets,** such as the "Compendium of Sanitation Systems and Technologies" by the Swiss Federal Institute of Aquatic Science and Technology (EAWAG) (Tilley et al. 2014) and World Health Organization (WHO) and United Nations Children's Fund (UNICEF) Joint Monitoring Programme's (JMP) sanitation ladder (WHO UNICEF JMP n.d.); and
- **Validating definitions with sanitation sector experts**.

The study defined **sanitation systems** as the series of technologies and services used for the management of human waste. Different sanitation systems generate different waste streams that move through various stages. The study aimed to understand methane emissions from two sanitation systems—sewered and non-sewered systems—and from open defecation:

- **Sewered sanitation** systems refer to those where the waste collected at the defecation site is connected to the disposal site through a sewerage network.
- **Non-sewered sanitation** systems refer to those where the waste collected at the defecation site is stored at (or near) the defecation site and then transported to the disposal site by emptying service providers.
- **Open defecation** refers to the practice of defecating in the open, such as in fields, bushes, forests, ditches, streets, canals, or other open spaces.

Figure 1 visualizes these systems, resulting waste streams, and the stages of managing sanitation waste.

Figure 1. Sanitation systems, waste streams, and stages considered by the study



Both sewered and non-sewered sanitation systems include four discrete stages for the management of human waste:

- **Containment** refers to the combination of technologies used for the collection and storage of human waste near the defecation site in facilities used by individual or multiple households, including:
  - **User interface**, which the user comes in contact with during defecation; it can include toilets, pans, or urinals to collect the waste, and wet or dry flushing and cleansing mechanisms; and
  - **Substructure**, which is used to store the waste collected by the user interface; it can include pits or tanks and can be lined (with materials like cement or bricks) or unlined.
- **Transfer** refers to the technologies or services used to transport the waste from the containment site to the disposal site.
- **Treatment** refers to the series of technologies, typically at a treatment facility or plant located away from the containment facility, used for converting the waste to non-hazardous compounds safe for discharge into the environment.
- **Discharge** refers to the methods by which waste is ultimately returned to the environment, either post-treatment, which avoids environmental contamination and public health risks, or unsafely without prior treatment. Treated human waste can also be used to generate **reuse** products, which can be solid (e.g., compost), liquid (e.g., treated water), or gas (e.g., biogas), instead of discharging it post-treatment.

Sewered sanitation systems use wet user interface technologies, typically a cistern flush toilet, to collect the waste and have no substructure technology as the waste is instantly transferred via sewerage pipes.

The resulting waste stream is wastewater, which includes sanitation waste (excreta, urine, flush, and other cleansing material) and non-sanitation waste (e.g., bath and kitchen drain water) flowing into the same sewerage pipe network. It can either be treated at a wastewater treatment facility using various technologies to treat the wastewater before safe discharge or reuse, or discharged unsafely into the environment.

Non-sewered sanitation systems can use wet (typically pour-flush toilets) or dry user interface technologies to collect the waste, and their adoption is often linked to contextual norms for the use of water for anal cleansing. Facilities with both wet and dry user interface technologies can have lined or unlined pits as the substructure technology, while those with wet user interface technologies can also have a septic tank. The presence of a lining can determine the amount of water entering the substructure, depending on whether it lies above or below the level of the groundwater table. The resulting waste stream from non-sewered containment facilities is fecal sludge, which primarily includes sanitation waste (excreta, urine, flush, and cleansing water). Fecal sludge can have varying characteristics, such as total solids (TS)[2], biological oxygen demand (BOD)[3], and organic strength[4], based on the containment usage, technology, and emptying frequency (Strande et al. 2018). Literature can use different terminologies for the waste from non-sewered containment facilities (e.g., septage from septic tanks, pit humus from dry twin pit latrines).

Non-sewered containment facilities like pit latrines and septic tanks require periodic emptying services to transfer the fecal sludge to the disposal site when the substructure fills up. Fecal sludge can be treated at a fecal sludge treatment facility using various technologies to treat it before safe discharge or reuse, or unsafely discharged in the open. If non-sewered containment facilities are left unemptied over a period of time, biological decomposition of the accumulated waste occurs.

Open defecation does not include containment, transfer, or treatment of the waste but only unsafe discharge of waste into the environment without any treatment, which can lead to environmental contamination and public health hazards.

2.2 QUANTIFYING EMISSIONS AND IDENTIFYING ABATEMENT INTERVENTIONS

After defining sanitation systems, the study conducted research in two phases:

- Phase 1 aimed to quantify and understand the current sources and drivers of methane emissions from sanitation systems in urban LMIC contexts.
- Phase 2 aimed to identify promising approaches and interventions (including technologies, service models, and behavior changes) for adoption in urban LMIC contexts and relevant evidence gaps warranting further investigation based on key informant interviews (KIIs) and a targeted literature scan.

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[2] TS is the parameter used to measure the consistency of fecal sludge, which is quantified as a percentage by measuring material remaining after 24 hours of drying at 103–105°C.

[3] BOD is the amount of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic conditions at a specified temperature. The BOD value serves as a proxy for the amount of organic content in waste.

[4] Organic strength is the amount of dissolved or suspended carbon-based (i.e., organic) compounds in fecal sludge or wastewater that can be oxidized biologically and determine the BOD of the waste to be treated.

Select experts also validated the key assumptions and findings for each phase, given the nascent nature of inquiry on the topic and the limited literature available.

2.2.1 PHASE 1: IDENTIFYING SOURCES AND DRIVERS OF ANTHROPOGENIC METHANE EMISSIONS

The study team conducted a rapid literature review in the first phase of the study, covering around 14 documents sourced from search engines through a series of search strings such as:

- "Methane emissions" and "sanitation,"
- "Methane emissions" and "pit latrines,"
- "Methane emissions" and "non-sewered sanitation,"
- "Methane emissions" and "wastewater,"
- "Climate change" and "sanitation,"
- "Greenhouse gases" and "sanitation," and
- "Greenhouse gases" and "non-sewered sanitation systems."

The rapid literature review provided limited information on methane emissions and their drivers from non-sewered sanitation systems typical of urban LMIC contexts. To address this gap, the team developed an Excel model to quantify methane emissions using a four-step process. See below for an overview of the four steps and Appendix A for a detailed methodology.

Step 1: Selecting the sample geography and year

The study selected urban areas in sub-Saharan Africa (SSA), excluding South Africa, as the sample geography for the following reasons:

- Urban regions are likely to be the primary source of methane emissions in the future for two reasons—urban regions will constitute a significant share of the total population (~68.0 percent of the global population in 2050 compared to ~55.0 percent in 2018 [United Nations Department of Economic and Social Affairs 2018]), and will likely see an increase in the prevalence of treatment plants to treat the generated human waste—both of which can increase methane emissions.
- SSA is a priority region for water, sanitation, and hygiene (WASH) funders due to the currently low coverage of safely managed sanitation (~21.0 percent [WHO UNICEF JMP n.d.]). Additionally, a prior study done in Kampala, Uganda (Johnson et al. 2022) provided critical context-specific data, such as technology configurations in treatment plants, which is unavailable for other urban LMIC contexts.
- South Africa was excluded from the modeling exercise as its prevalence of sewered systems is significantly higher than the rest of urban SSA, which would skew the estimations for an LMIC. For example, ~80.0 percent of the population of South Africa is connected to sewered sanitation systems (National Department of Health [NDoH], Statistics South Africa [Stats SA], South African Medical Research Council [SAMRC], and ICF International [ICF] 2019) compared to only ~6.0 percent for the rest of SSA (Demographic and Health Surveys [DHS] n.d.). All subsequent mentions of "urban SSA" in the main sections of the report refer to urban SSA excluding South Africa.
- The learnings from analyzing urban SSA can be extrapolated to other LMIC contexts to a degree since the trends used in the model to project future methane emissions (i.e., urban population growth and push to achieve Sustainable Development Goals [SDGs]), apply across urban LMICs.

The study chose 2020 as the reference year for two reasons:

- The most recent population estimates that could be sourced at the time of the study for urban regions in SSA countries were for 2020.
- The most recent data available for global methane emissions at the time of the study was for 2020 (McKinsey and Company 2021).

Step 2: Developing the model logic

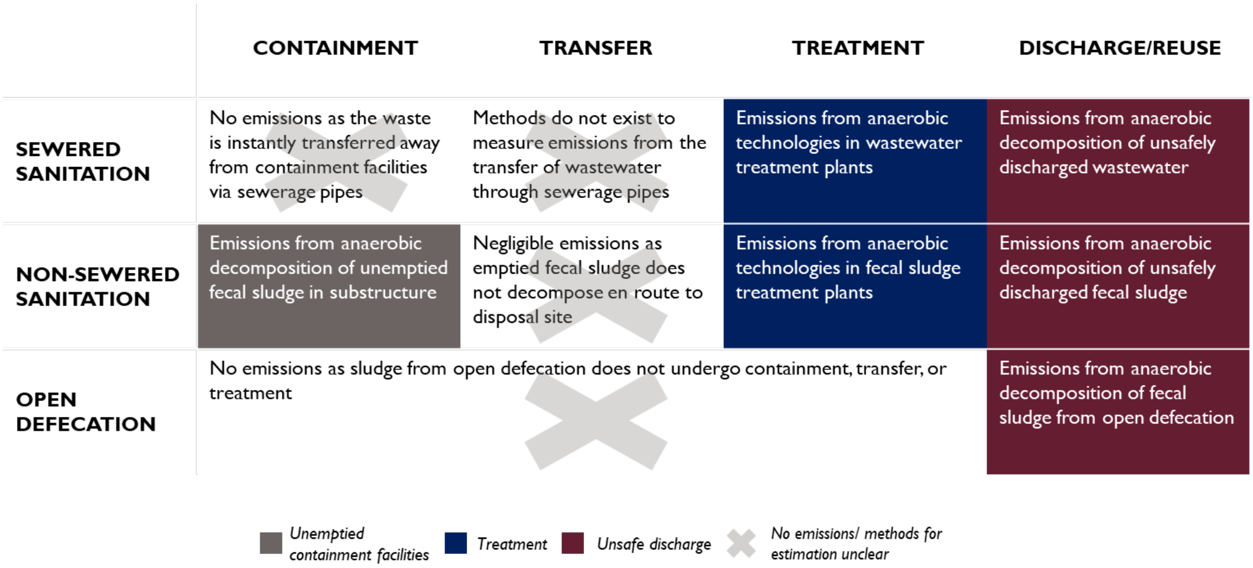
The model quantified methane emissions from three sources across the various sanitation systems (refer to Figure 2):

- Unemptied containment facilities of non-sewered sanitation systems;
- Treatment of wastewater (from sewered sanitation systems) and emptied fecal sludge (from non-sewered sanitation systems); and
- Unsafe discharge of wastewater (from sewered sanitation systems) and emptied fecal sludge (from non-sewered sanitation systems) and from open defecation.

It excluded methane emissions from containment for sewered systems, transfer for both sewered and non-sewered systems, and from all stages except discharge for open defecation.

Figure 2 provides a rationale for selecting these sources of methane emissions from sanitation systems.

Figure 2. Sources of methane emissions from sanitation systems as quantified by the study



	CONTAINMENT	TRANSFER	TREATMENT	DISCHARGE/REUSE
SEWERED SANITATION	No emissions as the waste is instantly transferred away from containment facilities via sewerage pipes	Methods do not exist to measure emissions from the transfer of wastewater through sewerage pipes	Emissions from anaerobic technologies in wastewater treatment plants	Emissions from anaerobic decomposition of unsafely discharged wastewater
NON-SEWERED SANITATION	Emissions from anaerobic decomposition of unemptied fecal sludge in substructure	Negligible emissions as emptied fecal sludge does not decompose en route to disposal site	Emissions from anaerobic technologies in fecal sludge treatment plants	Emissions from anaerobic decomposition of unsafely discharged fecal sludge
OPEN DEFECATION	No emissions as sludge from open defecation does not undergo containment, transfer, or treatment			Emissions from anaerobic decomposition of fecal sludge from open defecation

To calculate methane emissions from the three sources, the study referred primarily to methods from a recent study conducted in Kampala, Uganda (Johnson et al. 2022) and complemented them with those recommended by the Intergovernmental Panel on Climate Change (IPCC) (Bartram et al. 2019). The study in Kampala, Uganda, is one of the few studies that quantified methane emissions from multiple sanitation systems and their stages in LMICs. This study went beyond the methodology from the IPCC (Bartram et al. 2019) to provide equations specifically developed for non-sewered sanitation systems and treatment processes common in LMIC contexts.

The team developed two values for methane emissions—an optimistic case to provide a lower end and a pessimistic case to develop a higher end of total emissions—to deal with uncertainties in the values required for some variables.

Step 3: Gathering model inputs

Two types of input data were sourced for calculating methane emissions from sanitation systems:

- **Population data:** The study sourced data on the split of sanitation systems across the population of urban SSA primarily from the latest DHS datasets of 24 SSA countries (DHS n.d.).
- **Emissions data:** The study sourced methane emissions data from IPCC (Bartram et al. 2019), the study in Kampala (Johnson et al. 2022), and assumptions the team developed, which sector experts verified .

Step 4: Defining future scenarios

The study projected methane emissions from sanitation in 2030 to understand the expected trend of methane emissions from sanitation systems as a proportion of total anthropogenic methane emissions in the region. This allowed the team to compare the key drivers of methane emissions between 2020 and 2030 and understand where interventions are required. The team projected emissions using the pessimistic 2020 case as the baseline to allow for planning for the worst-case scenario.

The 2030 emissions were modeled based on two trends (a population-level trend and a sanitation sector-level trend) that are applicable to most urban LMIC contexts:

- Increased urban population growth in LMIC contexts (United Nations Department of Economic and Social Affairs 2018; World Bank n.d.).
- Achievement of SDG 6.2 for sanitation and hygiene,[5] which, although unlikely to be achieved by 2030 given the current progress, represents the directional push in the sector.

2.2.2 PHASE 2: IDENTIFYING PROMISING ABATEMENT INTERVENTIONS

The second phase of the study identified potential abatement approaches to address the drivers of emissions from sanitation systems derived from the previous phase and assessed interventions (technologies, service models, and behavior changes) implementing these approaches for their adoption in urban LMIC contexts.

The study identified a long list of interventions across different sanitation systems and stages using sanitation compendiums, such as:

- The Compendium of Sanitation Systems and Technologies by EAWAG (Tilley et al. 2014);
- The Collection of Contemporary Toilet Designs by Water, Engineering, and Development Centre (WEDC) (EOOS and WEDC 2014); and
- Facilities mentioned by IPCC across different reports (Bartram et al. 2019; Takahiko et al. 2014).

The study then conducted KIIs with 22 experts (refer to Table 1 for a summary of experts) and a targeted literature scan of about 230 documents to assess interventions on the following parameters:

- Abatement potential relative to prevalent technologies, service models, and behaviors;

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[5] SDG 6.2 states, "by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations."

- Implementation maturity (i.e., the observed prevalence in LMICs);
- Operational feasibility for households (e.g., ease-of-use and maintenance) and implementers (e.g., land and energy requirements) of treatment plants; and
- Financial viability, in terms of affordability for households and level of investment and reuse potential (cited as a consideration) for implementers of treatment plants.

KIIs and a targeted scan of the literature were required since there was limited literature consolidating the required information for different technologies or services. For the KIIs, experts were identified through existing networks, authorship, or mention in relevant papers and subsequent referrals.

Table 1. Key informant interviews conducted

Type of Expert	Geography of Focus				Number of Experts
	Sub-Saharan Africa	Latin America	Asia	Global	
Implementers of treatment plants	4	3	4	2	**13**
Academicians	-	-	-	7	**7**
Climate finance experts	-	-	-	2	**2**
Total	4	3	4	11	**22**

The study identified literature through compendiums, bibliographies, keyword searches related to methane abatement, and relevant technologies on search engines like Google, the Sustainable Sanitation and Water Management toolbox, ResearchGate, ScienceDirect, and inputs from experts.

The study also validated several aspects of the report, given the nascent nature of inquiry on the topic and the limited literature available:

- One implementer of treatment plants and one academician, both with extensive experience in the sanitation sector, reviewed drafts of the report.
- Two academics with extensive research experience in the climate and sanitation sectors validated methane correction factors (MCFs) used for various containment facilities and treatment technologies.
- Four implementers operating in Asia and SSA validated emerging findings on abatement approaches and interventions for treatment.

The analysis of abatement approaches/interventions excluded certain aspects that are outside the scope of the study:

- The study primarily focused on methane emissions and not emissions of other GHGs (such as CO_2 and nitrous dioxide) when analyzing interventions. The Kampala study highlighted that methane remains the primary contributor of emissions even when accounting for these other gases (measured in $kgCO_2e$, based on their global warming potential [GWP][6]). However, the study mentions the emissions of other GHGs for select interventions, where they are relevant.
- The decomposition process of human waste (and hence the GHGs released) is sensitive to environmental conditions (e.g., temperature) and proper functioning of treatment plants. The analysis does not integrate environmental conditions and assumes well-functioning treatment

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[6] Measure of how much energy the emissions of 1 ton of methane will absorb over a given period of time, relative to the emissions of 1 ton of CO_2. The GWP of methane is 25, meaning a discharge of a ton of methane is equivalent to emitting 25 tons of CO_2 (United States Environmental Protection Agency 2022a).

plants, given limited information on these factors (and their impact on methane emissions) in literature.

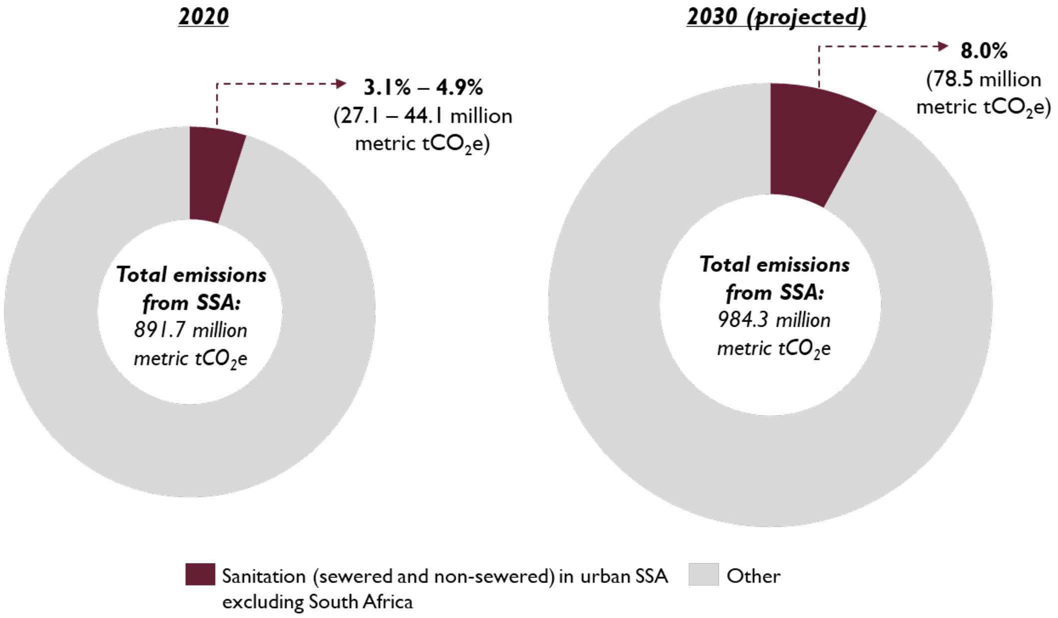
- Only interventions that indicated medium to high abatement potential were subsequently assessed for their implementation maturity, operational feasibility, or financial viability.

3.0 SCALE OF THE PROBLEM

The modeling exercise in Phase I reveals that methane emissions from sanitation in urban LMIC contexts can be considerable and are likely to grow in the future (refer to Figure 3).

Sanitation emissions in urban SSA in 2020 are estimated to be in the range of 27.1 to 44.1 million metric tons (t) carbon dioxide equivalent (CO_2e).[7] For perspective, this emissions estimate represents 3.1 percent to 4.9 percent of the total reported annual anthropogenic methane emissions in SSA in 2020. This is comparable to sectors like rice cultivation and coal mining, which are usually given more emphasis in discussions around methane abatement (McKinsey and Company 2021).[8]

Figure 3. Estimated emissions from sanitation in urban SSA as a proportion of total annual anthropogenic methane emissions in SSA



Notes:

- *The approach for estimating "Sanitation (sewered and non-sewered) emissions in urban SSA excluding South Africa" is given in Appendix A.*
- *The approach for estimating total annual anthropogenic methane emissions in SSA is given in Appendix B.*
- *The size of the donut charts (reflecting the total emissions from SSA) in 2020 and 2030 is approximately to scale.*

Other literature also suggests that methane emissions from sanitation systems in LMIC contexts can be considerable. The study in Kampala, Uganda (Johnson et al. 2022) quantified that methane emissions from sanitation systems might be as high as 38.6 percent[9] of the total annual GHG emissions in the city. Another study that compared methane emissions from pit latrines (a non-sewered containment facility)

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[7] The range represents the optimistic and pessimistic cases for emissions from sanitation in urban SSA, developed to account for uncertainties in the values of few variables required for calculating emissions. Details are provided in Appendix A.

[8] Major contributing sectors as a proportion of total emissions include biomass and biofuel burning (25.2 percent), enteric fermentation and manure (22.4 percent), and oil and gas (16.8 percent) based on analysis of (McKinsey and Company 2021) and the study's model.

[9] The per capita emissions from sanitation from this study (0.10 tCO_2e per year) and the study in Kampala (0.08 tCO_2e per year) are broadly similar, so the difference in the contribution of methane emissions from sanitation in Kampala can be attributed to the denominator (i.e., the total GHG emissions in the city).

in around 20 LMIC contexts estimated that they can contribute 1.0–25.0 percent of the national annual methane emissions (Reid et al. 2014).

Future methane emissions are likely to increase, both in absolute and relative terms to overall methane emissions in SSA, if urban population growth and the general push toward achieving SDG 6.2 targets continue. The model estimates that future emissions in the pessimistic scenario can increase by 77.9 percent to as high as 78.5 million metric tCO_2e (from 44.1 million metric tCO_2e in 2020) if the urban population grows at its historical rate and SDG targets are met. This is projected to increase the contribution of sanitation systems (sewered and non-sewered) to methane emissions in urban SSA by 61.2 percent, to represent 8.0 percent (from 4.9 percent in 2020) of SSA's total projected anthropogenic methane emissions in 2030. This finding is consistent with another study that highlighted meeting SDG targets will increase GHG emissions (Shaw, Kennedy, and Dorea 2021).

The insights from this analysis highlight both the need and urgency to understand the drivers of methane emissions in LMIC contexts and identify abatement approaches and interventions. Despite the non-trivial scale of methane emissions from sanitation systems in LMIC contexts (with predominantly non-sewered sanitation systems), literature on methane abatement does not quantify or discuss drivers of methane emissions (Johnson et al. 2022; Reid et al. 2014). The situation is likely to get worse unless current guidance in the sector evolves to consider the climate impact of its proposed targets explicitly.

4.0 SOURCES AND DRIVERS OF EMISSIONS

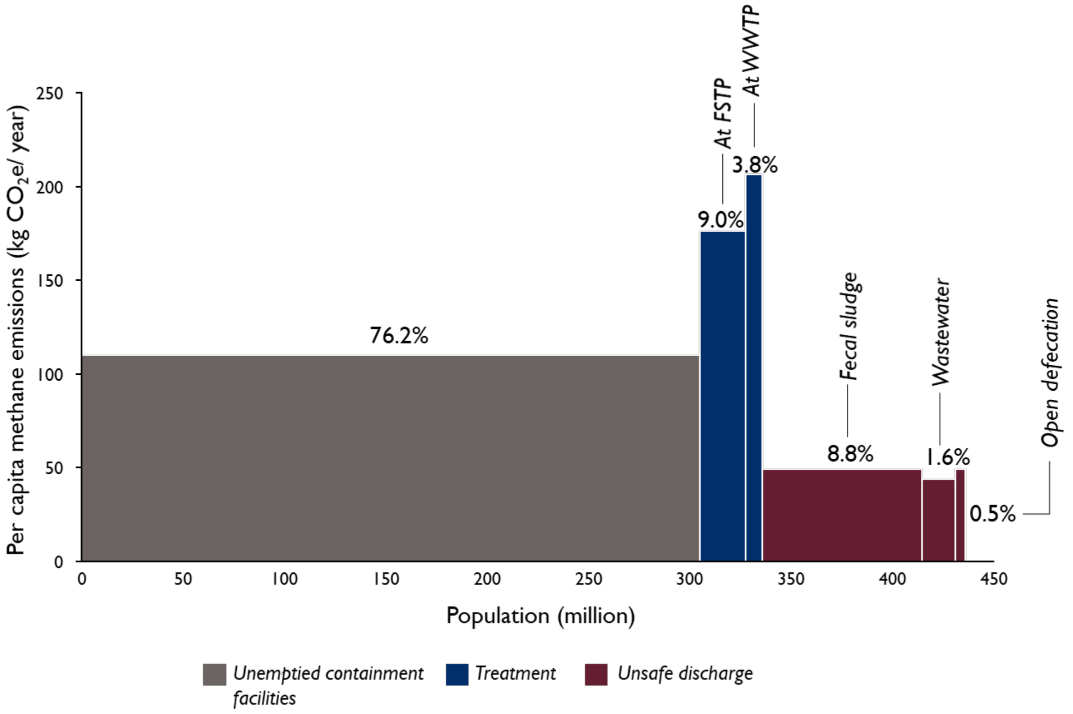
The study estimated sources and drivers of current and future methane emissions in urban SSA through the modeling exercise and then identified where abatement interventions are most required.

The analysis reveals that current emissions from sanitation systems are primarily driven by the anaerobic decomposition of fecal sludge in unemptied, non-sewered containment facilities. The growth in projected future emissions is driven by two trends (a population-level trend and a sanitation sector-level trend) that are applicable to most LMIC contexts—urban population growth and the push toward achievement of the sanitation and hygiene goals set under SDG 6.2 without considering the climate impact of technologies. These drivers are detailed below.

4.1 KEY DRIVERS OF CURRENT EMISSIONS

Non-sewered containment facilities that are unemptied contribute a majority (76.2 percent) of the estimated annual total anthropogenic methane emissions from sanitation systems (refer to Figure 4), according to the model.

Figure 4. Annual per capita methane emissions (kgCO$_2$e/year) and population split (million) in urban SSA by source of emissions (2020)



Acronyms: FSTP: fecal sludge treatment plant; WWTP: wastewater treatment plant

Notes:

- *Percentage values denote the contribution of each source to the total methane emissions. The height of the bars denotes the per capita emissions from each source, while the width denotes the population by the source of emissions. The area under the bar represents the total emissions from each source.*
- *The value of per capita emissions for unemptied containment facilities is the weighted average (based on population) of per capita emissions from each containment facility. Refer to Appendix C for the split of emissions by containment facility.*

- *The sum of the contribution of individual sources may not add up to 100 percent due to rounding.*

The high contribution of unemptied, non-sewered containment facilities is mainly due to two characteristics of these facilities in urban SSA.

First, non-sewered containment facilities that remain unemptied are widely prevalent in urban SSA (indicated by the width of the gray bar in Figure 4). Most (~93.3 percent) of the urban population has non-sewered sanitation systems, given the low coverage of sewerage networks (~5.6 percent) across the region[10]. Moreover, non-sewered containment facilities in urban SSA are either not emptied at all or emptied infrequently. For this study, the model assumes that approximately 25.0 percent of non-sewered containment facilities are emptied in a given year in urban SSA, based on a review of multiple literature sources:

- Studies of 15 cities (predominantly capital or large) in five SSA countries provide a high estimate of 30.4 percent to 58.0 percent for the proportion of households with non-sewered containment facilities that empty them in a year (refer to Table 2).
- In contrast, a dataset aggregating sanitation information of 32 cities (including a few smaller towns such as Bure in Ethiopia, Bignona in Senegal, and Kasungu in Malawi) in over 10 SSA countries estimated that only 40.0 percent of the population with non-sewered containment facilities had ever emptied them (SFD Promotion Initiative n.d.). This suggests that the proportion of the population emptying in a year would be much lower than 40.0 percent and the estimates of 30.4 percent to 58.0 percent from the other studies.
- To balance the different estimates and the fact that emptying frequency is likely to be very low in peri-urban areas or small towns (due to the availability of space to build new substructures and lack of emptying services) not included in the above studies, this study assumed 25.0 percent (for the purpose of modeling) to be the proportion of households in urban SSA emptying their facilities in a given year. This estimate was also validated by experts.

Table 2. Proportion of population emptying their containment facilities in a given year

City, Country	**Estimated proportion of population emptying in a given year** (source)
Ouagadougou, Bobo Dioulasso, and Fada N'Gourma, Burkina Faso	**45.7%** (Chowdhry and Kone 2012)
Addis Ababa, Dire Dawa, and Hosaena, Ethiopia	**45.9%** (Chowdhry and Kone 2012)
Nairobi, Kisumu, and Mombasa, Kenya	**54.1%** (Chowdhry and Kone 2012)
Abuja, Ibadan, and Yenagoa, Nigeria	**47.9%** (Chowdhry and Kone 2012)
Dakar, Touba, and Thies, Senegal	**58.0%** (Chowdhry and Kone,2012)
Abuja, Nigeria *(for pit latrines and septic tanks)*	**30.4%–45.3%** (Sridhar et al. 2011)

Notes:

- *The source data provided the proportion of the population emptying their facilities at various intervals (emptying twice a year, once every two years, etc.).*
- *To estimate the proportion of the population emptying in a given year, the study did the following:*
  - *For households with emptying intervals of more than a year, the study assumed that they were emptying their containment facilities over equal intervals. For example, if 20 percent emptied their facilities every two years, the team assumed that 10 percent emptied them each year.*
  - *The study added these estimates (for all emptying intervals of more than a year) to the proportion of households emptying at least once a year.*

Second, the majority of these non-sewered containment facilities promote a high degree of anaerobic decomposition of fecal sludge, which leads to the emission of methane (indicated by the height of the

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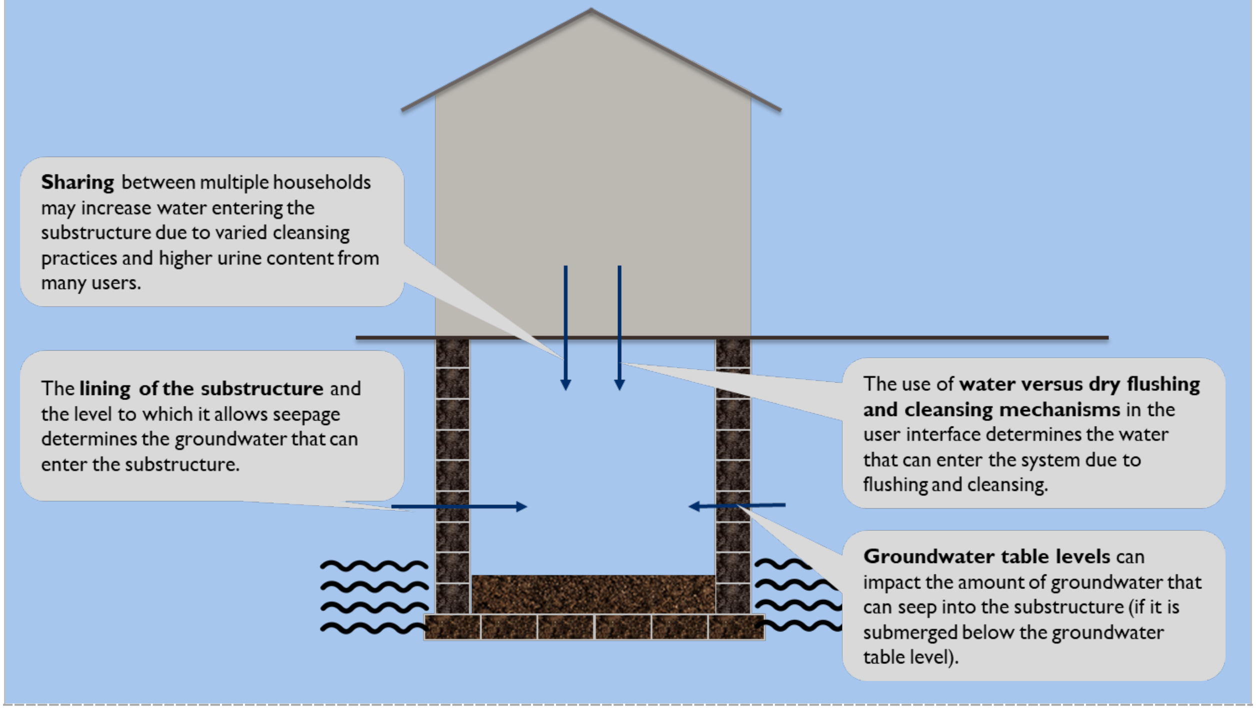
[10] The remaining 1.10 percent of the population practices open defecation.

gray bar in Figure 4). The degree of anaerobic decomposition can be measured by the MCF of a containment facility[11]—the higher the MCF, the more anaerobic it is and the greater the emissions. The study highlighted that the MCF of a containment facility is determined by the interface and substructure technologies used, the number of users, and the groundwater table levels relative to the substructure depth (see Box 1 for details).

Box 1. Understanding anaerobic conditions in containment facilities

The degree of anaerobic decomposition is primarily a function of the water content in the substructure of the containment facility. The user interface and substructure technologies used, the number of users, and groundwater table levels can impact the water entering/exiting the substructure (refer to Figure 5).

Figure 5. Factors impacting water content in the substructure



A majority of the urban SSA population with unemptied, non-sewered containment facilities has containment facilities with relatively high MCFs due to a combination of the factors described in Box 1. Figure 6 maps the population split and possible MCFs across various unemptied, non-sewered containment facilities. The study derived these MCFs from three sources (in order of preference): direct values stated by IPCC (Bartram et al. 2019), values used for modeling sanitation emissions in a recent study from Kampala (Johnson et al. 2022), and values that were based on assumptions developed by the study team and validated by experts. While many of these MCFs need further validation through empirical research, the values used in the study still provide a directional view of the key drivers of emissions.

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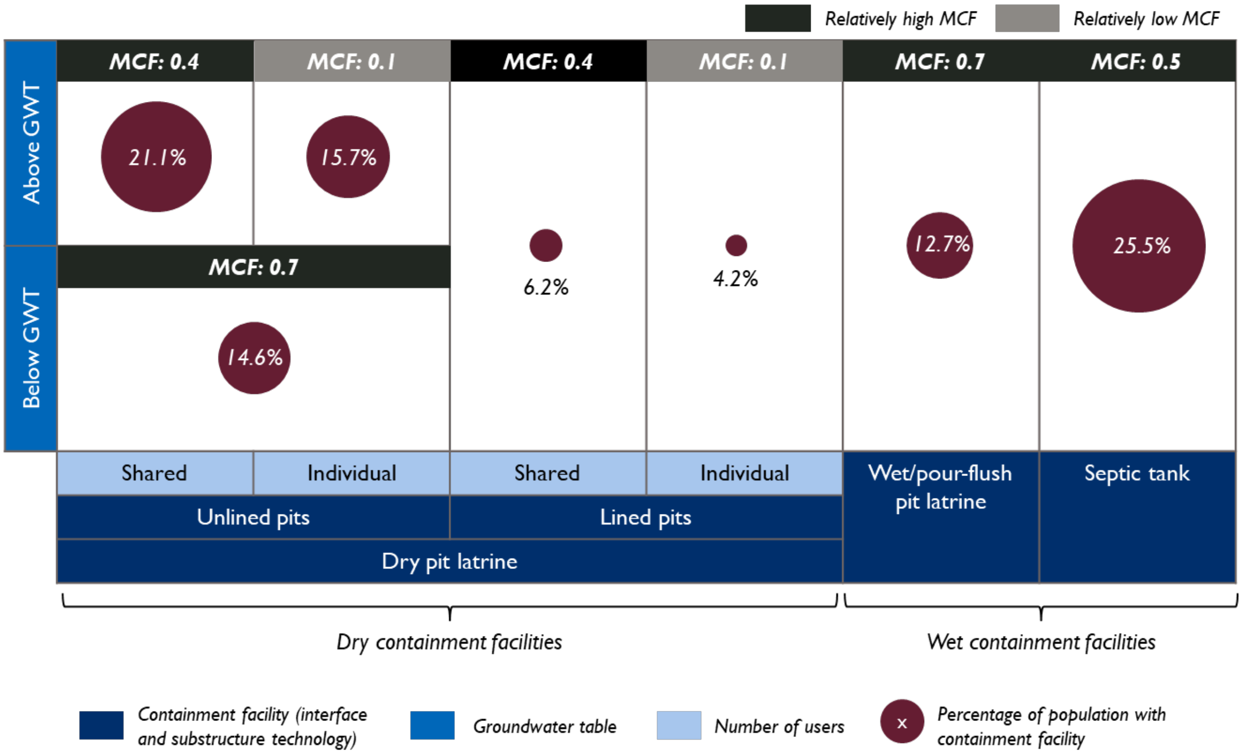
[11] MCF (methane correction factor is a value between 0 and 1 denoting the degree to which the system is anaerobic (Bartram et al. 2019). Zero denotes full aerobic decomposition of the organic matter, and 1 denotes full anaerobic decomposition.

Figure 6. MCFs and population split across unemptied, non-sewered containment facilities in urban SSA (2020)



Acronyms: GWT: groundwater table; MCF: methane correction factor

Notes:

- *Bubbles indicate the proportion of the population with unemptied, non-sewered containment facilities, using each type of facility. The sizes of the bubbles are to scale.*
- *Dry containment facilities were classified as "below" and "above" GWT, based on a visual analysis of the GWT map of SSA (MacDonald et al. 2012) and assumptions. Refer to Table 3 in Appendix A for the detailed approach.*

Over a third (38.2 percent) of the population with unemptied, non-sewered containment facilities in urban SSA use wet containment facilities, including pour-flush pit latrines and septic tanks. The research suggests that pour-flush pit latrines can be highly anaerobic (MCF 0.7), as there is no provision for the poured water to escape the pit. Even if the latrine has an unlined pit that allows seepage, the continued use of water for flushing or cleansing leads to the retention of water within the pit and in the surrounding soil. Septic tanks may be less anaerobic (MCF 0.5) than pour-flush pit latrines, as the technology separates effluents (liquid content) from the fecal sludge and allows the floating liquid to seep out through a pipe at the top of the tank. However, their MCF is likely to be higher than most dry pit latrines.

The rest of the urban SSA's population with unemptied, non-sewered containment facilities uses dry containment facilities, including lined or unlined dry pit latrines. The research suggests that the majority of these facilities can have MCFs of at least 0.4. Almost 15 percent of this population (14.6) have dry pit latrines with unlined pits below the groundwater table, which can have a very high MCF of 0.7, as water from the groundwater table seeps into the pits. Moreover, 27.3 percent of the population uses shared dry facilities. Shared dry facilities can have higher MCFs than individual facilities because of more water content entering the substructure from multiple users and the pit filling faster. The latter reduces surface aeration, which literature suggests can also lead to anaerobic conditions (Nwaneri et al. 2008).

The study notes that the MCFs of shared and individual dry facilities (0.4 and 0.1, respectively) are based on existing literature and may need to be validated further, since some experts mentioned that shared toilets may be emptied more frequently, reducing anaerobic conditions in the pit as explained in Section 6.1.2.

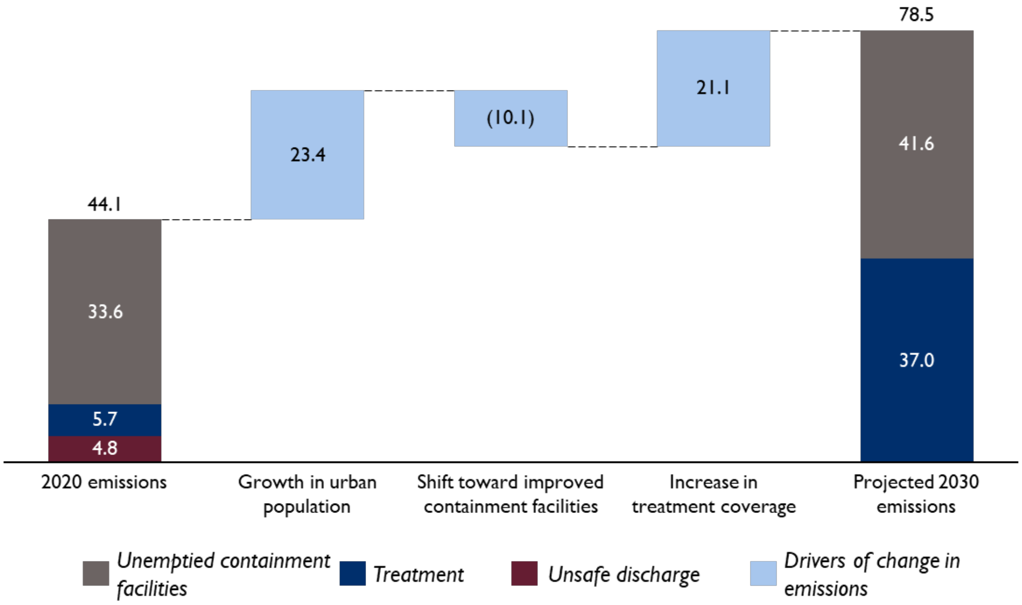
Only around 20 percent of the urban SSA's population has containment facilities with relatively low MCFs (0.1 as per the research). This section of the population uses individual dry pit latrines with pits that are either below the groundwater table but have a lining preventing water from entering them or are above the groundwater table (and hence, do not have water entering them).

In comparison to methane emissions from unemptied, non-sewered containment facilities, emissions from treatment and unsafe discharge are lower—12.8 percent and 11 percent (sum of dark blue and dark red bars in Figure 4) of total emissions, respectively—and their relevance is discussed in the next section.

4.2 KEY DRIVERS OF FUTURE EMISSIONS

The study modeled two trends that are applicable to most LMIC contexts: urban population growth and a push toward the achievement of SDG 6.2 targets. The two trends lead to an overall increase in projected 2030 methane emissions (refer to Figure 7).

Figure 7. Projected changes in the source of methane emissions from 2020 to 2030 by drivers of change (million metric tCO₂e/year)



Notes:

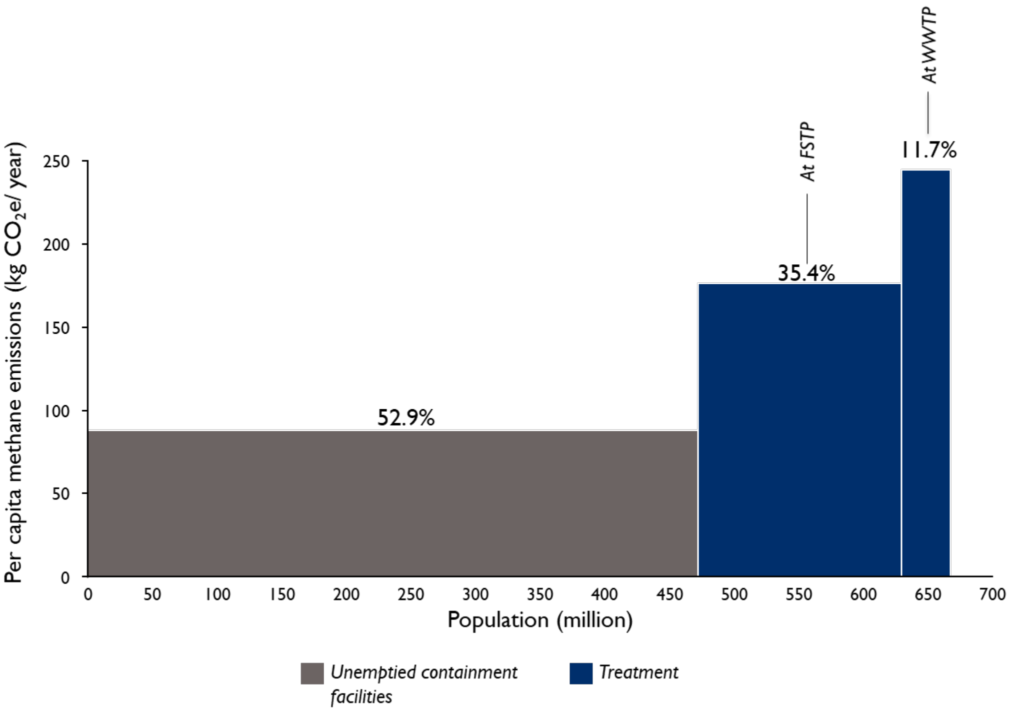
- *The first bar ("growth in urban population") denotes the impact of the projected growth of urban population (by 2030) on 2020 emissions.*
- *The second bar ("shift toward improved containment facilities") denotes the impact of an end to open defecation and usage of only improved containment facilities for the projected 2030 population of urban SSA, assuming no change in emptying and treatment coverage from 2020.*
- *The third bar ("increase in treatment coverage") denotes the impact of an end to the unsafe discharge of wastewater and emptied fecal sludge for the 2030 urban SSA population with only improved facilities, assuming no change in emptying coverage from 2020.*
- *Numbers within the chart may not add up to the totals due to rounding.*

Urban population growth will increase emissions due to an increase in the amount of human waste generated (first light blue bar in Figure 7). A push toward the achievement of SDG 6.2 will also increase emissions if existing, mainly anaerobic, sanitation technologies are scaled up without considering their climate impact. Technologies specified under the target for containment (100 percent coverage of improved, individual containment facilities) can still be relatively anaerobic under certain conditions (e.g., high groundwater table levels) and hence, only marginally improve emissions (second light blue bar in Figure 7). Technologies are not specified under the target to achieve 100 percent treatment coverage, potentially leading to a significant increase in emissions if prevalent anaerobic treatment technologies continue to be adopted (third light blue bar in Figure 7).

If a scenario in which both trends are realized in 2030 (i.e., urban populations grow as projected and SDG 6.2 is achieved), both unemptied containment facilities and treatment plants will contribute broadly equally to total methane emissions (refer to Figure 8).

This is not a comprehensive analysis of how the future may evolve (for example, the actual progress toward SDG 6.2 may be different). However, even this limited analysis points to a need for strong and concerted actions to address the impact of human waste on climate change.

Figure 8. Projected annual per capita methane emissions (kgCO₂e/year) and population split (million) by source of emissions (2030)



Notes:

- *Percentage values denote the contribution of each source to the total methane emissions. The height of the bars denotes the per capita emissions from each source, while the width denotes the population by the source of emissions. The area under the bar represents the total methane emissions from each source.*
- *Appendix A provides a detailed list of variables and values modified to model 2030 emissions.*

4.2.1 URBAN POPULATION GROWTH

The urban population in SSA will grow by 53.1 percent if historical trends (between 2010 and 2020) continue (World Bank n.d.). This will increase the amount of sanitation waste generated, leading to a proportionate increase in overall methane emissions.

4.2.2 ACHIEVEMENT OF SDG 6.2 CONTAINMENT TARGETS

Achievement of SDG 6.2 containment targets will reduce emissions because:

- A shift from shared to individual dry containment facilities can reduce MCFs because fewer users will lead to less water entering the substructure and slower filling of the substructure.
- A shift to improved dry containment facilities will reduce MCFs because a proportion of the population shifting to improved facilities will construct lined pits,[12] which prevent water from entering the substructure if it is below the level of the groundwater table.

The shift from open defecation (MCF 0.11–0.20) to improved, individual containment facilities for achieving the SDG 6.2 treatment targets can increase the per capita emissions in LMICs. IPCC guidelines and interviewed experts highlight that the MCF of most containment facilities is higher than that of open defecation. However, the impact of this shift on projected emissions will be much lower than the shifts stated above since the urban population practicing open defecation was negligible (~1.1 percent) in the modeled 2020 scenario.

4.2.3 ACHIEVEMENT OF SDG 6.2 TREATMENT TARGETS

Achievement of SDG 6.2 treatment targets will increase emissions if anaerobic technologies are scaled up to replace unsafe discharge.

Literature indicates that treatment plants using anaerobic technologies are common in LMIC contexts. For example, between 55 and 100 percent of the WWTPs in SSA countries (Senegal, Algeria, Burkina Faso, and Ghana) use anaerobic (MCF 0.80 as per the research) and facultative waste stabilization ponds (MCF 0.20) (Müllegger, Langergraber, and Lechner 2013).[13]

Interviews with implementers of treatment plants indicate that anaerobic technologies with high MCFs are often selected because they meet several of their criteria. For example, WWTPs with waste stabilization ponds and FSTPs with anaerobic technologies are preferred because they:

- Can efficiently remove BOD of the input waste;
- Require low capital investment for machinery, relying on nature-based processes instead;
- Require low involvement of professionals for operations, as anaerobic decomposition occurs naturally; and
- Require limited energy input to power operations (Tilley et al. 2014), relying on labor input for loading or unloading waste.

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[12] The study assumed 25.0 percent of individuals shifting to improved dry pit latrines (from unimproved dry pit latrines) will install lined pits.

[13] Waste stabilization ponds (or lagoons) are large, fabricated water bodies used individually or linked in a series for treating wastewater in centralized treatment plants (Emersan n.d.).

Continued adoption of such anaerobic plants with high MCFs to replace unsafe discharge (with low MCFs of 0.11–0.20) for achieving the SDG 6.2 treatment targets will increase overall emissions in LMICs. Unsafe discharge of fecal sludge or wastewater leads to relatively more aerobic decomposition—in land, as open areas allow more aeration of the waste and in water due to dissolved oxygen in water bodies.[14]

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[14] Decomposition of waste in water bodies may be aerobic or anaerobic depending on the depth and flow of the water body. The model uses the MCF value given by IPCC for unsafe discharge into water bodies, validated and edited by a sector expert.

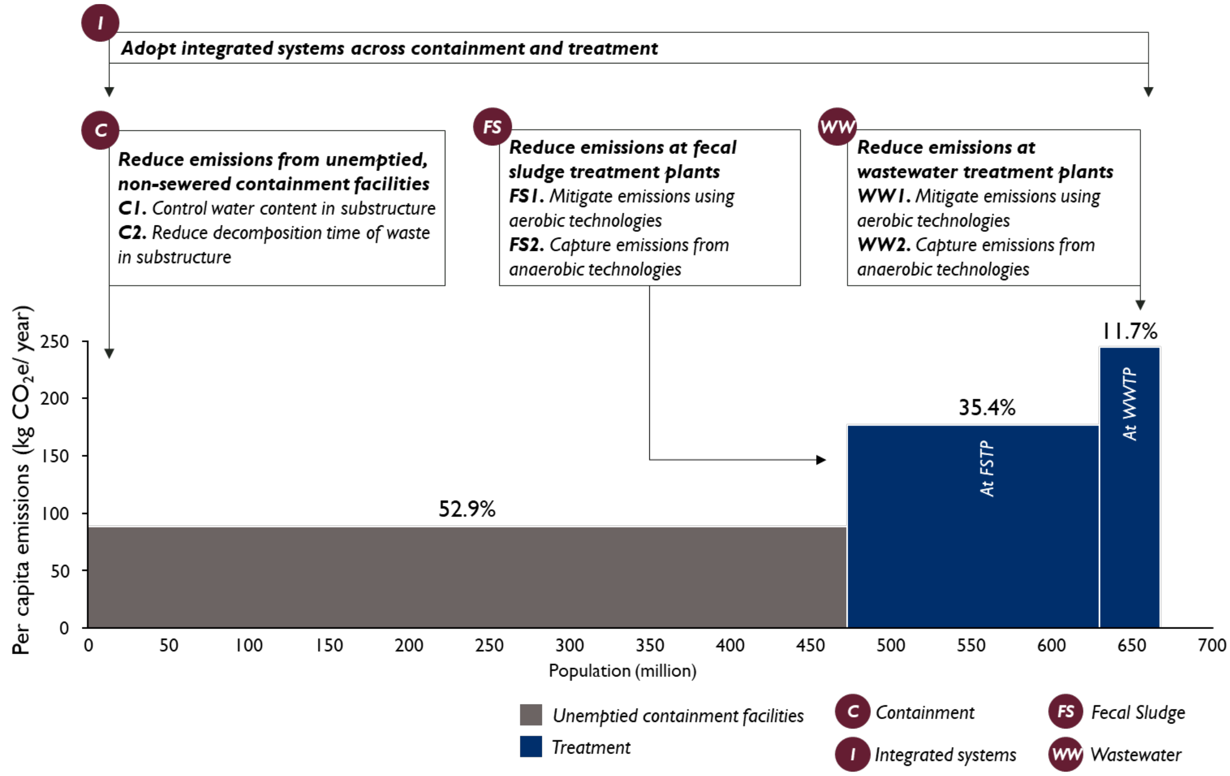
5.0 ABATEMENT APPROACHES

The analysis in the previous chapter highlights the need for interventions at both the containment and treatment stages in LMICs to address the impact of human waste on climate change due to urban population growth and the push toward the achievement of SDG 6.2.

The study identified a set of theoretical abatement approaches to reduce emissions at the containment and treatment stages based on a technical understanding of the key sources and drivers of emissions from Section 4.0.

These approaches can be classified into four broad categories and mapped to the sources of emissions in the 2030 scenario (refer to Figure 9).

Figure 9. Projected annual per capita methane emissions (kgCO_2e/year), population split (million) by source of emissions (2030), and approaches to reduce methane emissions in 2030



The first set of approaches aims to **reduce emissions from unemptied, non-sewered containment facilities** by influencing the degree of anaerobic conditions in the substructure. These approaches include:

- **Controlling water content (C1)** in the substructure, which determines the degree of anaerobic decomposition (as explained in Box 1). This involves limiting the water entering the substructure.
- **Reducing decomposition time (C2)** for which waste is allowed to stay in the substructure. Experts and select literature state that the intensity of anaerobic conditions increases the longer the fecal sludge remains unemptied (Nwaneri et al. 2008; Reed 2014).

The second set of approaches **reduces the emissions at fecal sludge treatment plants.** This can be achieved by:

- **Mitigating emissions using aerobic technologies (FS1);** and
- **Capturing the methane emissions from anaerobic technologies (FS2).**

The third set of approaches **reduces the emissions at wastewater treatment plants.** Similar to the above, this can be achieved by:

- **Mitigating emissions using aerobic technologies (WW1);** and
- **Capturing the methane emissions from anaerobic technologies (WW2).**

The final set of approaches involves **integrated systems that mitigate or capture emissions across containment and treatment (I).** These systems can use one or many of the approaches mentioned above.

It is worth noting that the approaches for containment facilities and integrated systems are implemented at the household or community level with specific cleansing and flushing practices and need to be analyzed separately for wet and dry containment facilities.

The subsequent sections present an assessment of various technologies, service models, and behavior changes that use the above approaches to abate methane to arrive at immediate- and medium-term recommendations for the sector.

6.0 ASSESSMENT OF INTERVENTIONS

The study scanned for interventions (i.e., technologies, service models, and behavior changes) that use the approaches identified in Section 5.0 and assessed their potential for adoption in LMIC contexts. The assessment was based on the following four criteria:

- **Abatement potential,** relative to prevalent technologies, service models, and behaviors.
- **Implementation maturity** (i.e., the observed prevalence in LMICs);
- **Operational feasibility** for households (e.g., ease of use and maintenance) and implementers (e.g., land, energy, and operational requirements); and
- **Financial viability,** in terms of affordability for households and level of investment and reuse potential for implementers.

As mentioned in Section 2.2.2, the study did not assess interventions with low abatement potential for their implementation maturity, operational feasibility, or financial viability. The objective of the assessment was to identify:

- Interventions with high abatement and implementation potential for LMICs that can be adopted in the immediate term;
- Promising interventions that still have key evidence gaps to scale their adoption in LMICs; and
- Approaches without any promising interventions.

6.1 ABATEMENT IN CONTAINMENT FACILITIES

The assessment of interventions for abatement approaches in containment facilities (introduced in Section 5.0) indicates that:

- **Individual toilet usage** and **lining of pits can reduce water content in the substructure (C1)** for dry containment facilities, but no technologies exist for wet containment facilities.
- **Scheduled emptying** can **reduce the decomposition time (C2)** for dry and wet containment facilities, but this needs further evidence.

6.1.1 C1. CONTROL WATER CONTENT IN SUBSTRUCTURE

Individual toilet usage, as promoted by the SDGs, may reduce emissions from dry pit latrines with pits above the groundwater table level (refer to Figure 5), as fewer users lead to less urine entering the pit and slower filling of the pit, and can be a relatively inexpensive shift for households.[15] Individual usage may not reduce emissions in areas where the substructure lies below the groundwater table level because water can continue entering the substructure regardless of the number of users. Additionally, as noted in Section 4.1, the MCFs of shared dry latrines relative to individual dry latrines need to be validated further. However, the study believes individual toilet usage is still a promising abatement intervention, given the current evidence on the MCF differences and the general public health benefit of shifting to individual toilet usage.

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[15] While the same number of people using individual facilities will generate the same amount of waste as when they share facilities, the lower water content and filling rate within the individual substructure will reduce the degree of anaerobic decomposition, as compared to a shared substructure. This will lower emissions per person.

Lining of pits can reduce emissions (refer to Figure 6) for dry pit latrines with pits below the groundwater table, as this prevents water from entering the substructure. However, it is currently not a part of the sector's definition of safely managed sanitation, contributing to the continued prevalence of unlined pits. Pit lining might also be expensive for households in LMICs. For example, in Malindi, Kenya, lined pit latrines cost USD 1,041, while households are only willing to pay USD 367 for them (Delaire et al. 2021).

Experts also cited **urine-diverting dry toilets (UDDTs)** to separate urine from the waste at the user interface and substructure technologies like **dehydration vaults and raised pits** as potential technologies to reduce water content in dry containment facilities. Of these, the study observed only UDDTs in isolated LMICs, and mostly as a component of integrated systems (Container-Based Sanitation Alliance, n.d.). The exact abatement potential, feasibility, and viability are unclear across these three technologies.

For wet containment facilities, there appears to be a technological gap for containment facilities that can control water content. Septic tanks may have lower emissions than pour-flush pit latrines (shown in Figure 6), as they allow some of the water to leach out near the surface. However, the MCF used in this study for septic tanks is still relatively high (MCF 0.5). Multiple experts also indicated that high water content in containment facilities with wet user interface technologies invariably contributes to anaerobic conditions in the substructure.

6.1.2 C2. REDUCE TIME FOR ANAEROBIC DECOMPOSITION

There has been a range of **demand generation and activation** interventions attempting to shift household behavior and increase demand for emptying services.[16] Examples include behavior change communication in Lusaka, Zambia, and the FSM call center in Kampala, Uganda (Deutsche Gesellschaft fuer Internationale Zusammenarbeit [GIZ] 2017). However, their operational and financial requirements are not well-documented in literature. Additionally, their abatement potential may be limited. Theoretically, these interventions should lead to frequent emptying and, hence, a reduction in time for anaerobic decomposition. However, the impact of these interventions on emptying frequency is unclear and reliant on the decision of households.

Scheduled emptying is a service model currently in the pilot stages that addresses the uncertainty by assigning a predetermined schedule (e.g., every three years) and route for regular emptying (Box 2 illustrates the model implemented in Wai, India [Rao et al. 2020]). This intervention can have significant abatement potential, even for wet containment facilities. For example, a 2021 study of septic tanks in Hanoi, Vietnam, found that median methane emission rates for those emptied every zero to five years were about 43.0 percent lower than those emptied at intervals over five years (approximately 8 versus 14 grams/capita/day) (Huynh et al. 2021). However, the precise impact of different emptying schedules on MCFs of different containment facilities is not known.

Multiple countries (e.g., Zambia, Indonesia [Bustraan et al. n.d.]) have seen active promotion of scheduled emptying, but the current implementation is limited to a few smaller cities (with populations of less than 100,000) in LMICs. Evidence from these contexts suggests high operational feasibility through engagement of private providers for service delivery and financial viability through implementation of a sanitation tax to cover the emptying service operational costs. However, further

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[16] Demand generation involves activities to drive the awareness of and interest in hygienic sanitation behaviors and improved sanitation products and services (USAID 2018). Demand activation involves direct sales and marketing activities carried out to persuade customers to convert product awareness and interest into a purchasing decision (USAID 2018).

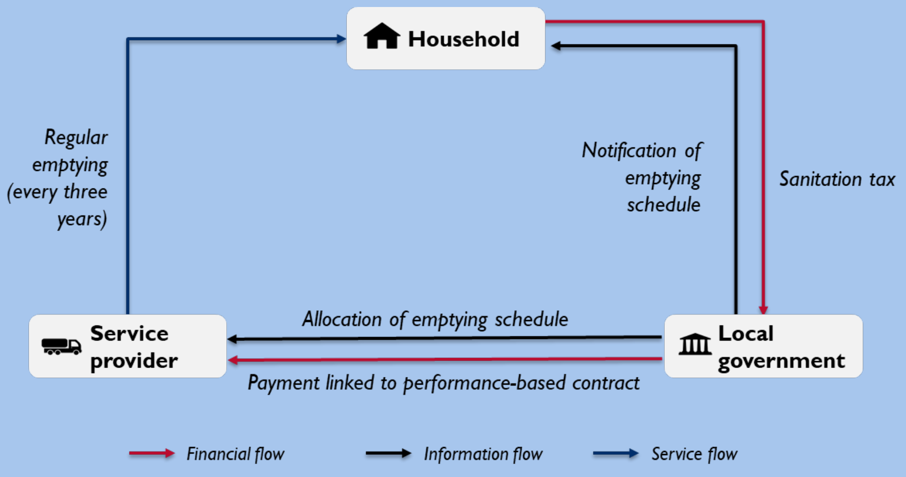
evidence is required to understand the refinements needed in the model for scaling it to more and larger cities.

Finally, scheduled emptying does not require new construction of containment facilities and can reduce emissions from existing facilities. The impact of interventions requiring new constructions (such as those in the previous section) may be limited, as only a portion of the population is likely to invest in new constructions in a given time period. It is worth noting that waste collected through scheduled emptying should be accompanied with appropriate treatment plants that abate methane (as discussed in Sections 6.2 and 6.3) to ensure abatement across the sanitation system.

Box 2. Illustrative example of scheduled emptying in Wai, India

The scheduled emptying service in Wai (as visualized in Figure 10) addresses low household demand for emptying by fixing the emptying frequency to every three years, for which. Households pay in advance for the service through a sanitation tax. The supply of services is undertaken achieved through public-private partnerships between the local government and private service providers. Private providers are incentivized to comply with allocated desludging requirements through a contract that links payment disbursement to service fulfillment incentivizes private providers to comply with allocated desludging requirements.

Figure 10. Scheduled emptying in Wai, India



Source: Adapted from Center for Water and Sanitation, CEPT University.

6.2 ABATEMENT AT FECAL SLUDGE TREATMENT PLANTS

As noted in Section 2.1, waste streams from sanitation systems in LMICs can be categorized as fecal sludge and wastewater (discussed in the subsequent sections). Fecal sludge is the resulting waste stream from non-sewered sanitation systems, primarily includes sanitation waste (excreta, urine, flush, and cleansing water), and is treated at fecal sludge treatment plants.

Fecal sludge received at treatment plants can have varying characteristics, such as TS, BOD, and organic strength, based on the containment usage, technology, and emptying frequency (Strande et al. 2014).

Literature and experts note that the fecal sludge received at treatment plants can be broadly categorized into (Strande, Ronteltap, and Brdjanovic 2014; Tayler 2018):

- Highly stabilized, concentrated sludge, typically from dry containment facilities that have been emptied after several years;
- Highly stabilized, diluted sludge, typically from wet containment facilities (or dry containment with seepage of groundwater) that have been emptied after several years; and
- Partially stabilized sludge from recently emptied containment facilities.

The treatment of fecal sludge goes through the following stages (see Figure 11) (adapted from Strande, Ronteltap, and Brdjanovic 2014):

- **Solid-liquid separation:** Separation of solid and liquid content of wastewater or thickening of fecal sludge (Rashmi and Devatha 2021);
- **Stabilization or biological decomposition:** Bacterial decomposition of the waste's organic content, measured by the percentage of BOD removal (AOS Treatment Solutions 2018);
- **Dewatering/drying:** Removal of water bound to the sludge particles that is not removed by sedimentation during the solid-liquid separation stage (Ministry of the Environment n.d.); and
- **Pathogen removal:** Removal of remaining nutrients and pathogens from the decomposed waste prior to discharge, or removal of pathogens only for reuse (Chahal et al. 2016).

Treatment plants can produce a range of end products, some of which offer the potential for reuse. There may also be a screening stage, but this does not have an impact on methane emissions.

The liquid effluent from the solid-liquid separation and dewatering stages is treated using wastewater technologies (described in Section 6.3). In LMIC contexts, this treatment can happen at the fecal sludge treatment plant or at a co-located wastewater treatment plant. To ensure treatment goals are achieved, the stage and technology selection for treating this effluent needs to account for the fact that the total solids in fecal sludge is often several times higher than in wastewater.

It is also worth noting that highly stabilized sludge may not need biological decomposition, and concentrated sludge can often skip solid-liquid separation (Strande, Ronteltap, and Brdjanovic 2014). However, FSTPs usually receive heterogeneous sludge, and implementers need to conduct surveys and sampling of fecal sludge received to understand its characteristics. As such, most implementers will design FSTPs for all the stages.

The technology choices at each stage determine the methane emissions at FSTPs. The assessment of interventions for treatment of fecal sludge indicates that:

- Unplanted drying beds and mechanical presses (specifically, belt and screw presses) are well-established aerobic technologies for solid-liquid separation.
- Aerobic technologies for biological decomposition have limited implementation evidence, but emissions from anaerobic technologies can be captured through flaring or in-house use (though the latter needs more experimentation).
- Co-composting and black solider fly larvae are promising aerobic technologies for pathogen reduction with significant reuse potential.

6.2.1 FS1: MITIGATE EMISSIONS USING AEROBIC TECHNOLOGIES AT FECAL SLUDGE TREATMENT PLANTS

The study developed a long list of technology options for the different treatment stages cited in literature or by experts, with the aim of identifying promising aerobic technologies that can mitigate methane emissions (see Figure 11).

Solid-liquid separation

For solid-liquid separation, the study identified unplanted drying beds and mechanical pressing as promising technologies that can be used in specific contexts.

Unplanted drying beds are grounds with layers of sand and gravel with an underdrain system that carries the percolated effluent away from the bed. These beds are typically used for the dewatering stage but can be used for solid-liquid separation if the sludge has a high solid content (greater than 3 percent) and the treatment volume is low (since they have high land requirements) (Tayler 2018). Unplanted drying beds are simple to construct and require limited technical skills to operate, making it a good choice for LMIC contexts. Multiple experts cited the prevalence of unplanted drying beds in LMICs. Some examples of implementation are in Indonesia (Tayler 2018), Senegal (Strande, Ronteltap, and Brdjanovic 2014), and SSA (Goussanou et al. 2023).

Mechanical pressing uses mechanical force to separate solid sludge from the liquid effluent. It generally requires a reliable electricity supply, skilled labor, an expensive chemical polymer that coagulates the solid particles for separation, and an effective supply chain for spare parts. Mechanical presses have a low lifetime ownership cost and are compact and quick (able to process sludge with a total solids content as low as 1 percent without requiring a proportionate increase in the land requirement) (Tayler 2018). Belt presses and screw presses are the two most widely used variants in LMIC contexts. Other variants also exist, but their usage has only been observed for dewatering.

Biological decomposition

Aerobic biological decomposition of fecal sludge requires more experimentation as there appears to be a gap for well-established aerobic technologies.

Literature cites the use of **aerobic digesters** and **mechanical aeration ponds** for treating sludge in WWTPs (discussed in the next section). However, their implementation for fecal sludge treatment plants in LMICs has been observed in limited contexts (e.g., aerobic digesters in Baliwag, Philippines [Center for Science and Environment n.d.] and mechanical aeration ponds in Jakarta, Indonesia [Soeters, Mukheibir, and Willetts 2021]).

Similarly, literature and experts cite the **Omni Processor** as a possible option for methane abatement (Rowles, Morgan et al. 2022). It uses end-to-end thermal treatment (via pyrolysis) in a single, compact machine. There are negligible methane emissions since the methane released is immediately oxidized in the reactor's pyrolysis zone. However, its uptake in LMICs remains limited, and it faces challenges. The study found inconsistent information on the operational and financial requirements for its adoption. For example, literature cites the technology as being relatively inexpensive since the energy production from the thermal system can offset total costs (Rowles et al. 2022). An implementer in Senegal indicated that it only requires intermittent professional involvement to upgrade parts or conduct quality checks post-installation. However, interviewed implementers of traditional treatment plants in India perceive it to be expensive and cited potential challenges in procuring spare parts manufactured abroad and maintenance by local staff unfamiliar with the technology. There also appears to be low trust in its treatment efficiency due to a lack of testing of treated waste, as cited by an implementer in Kenya.[17]

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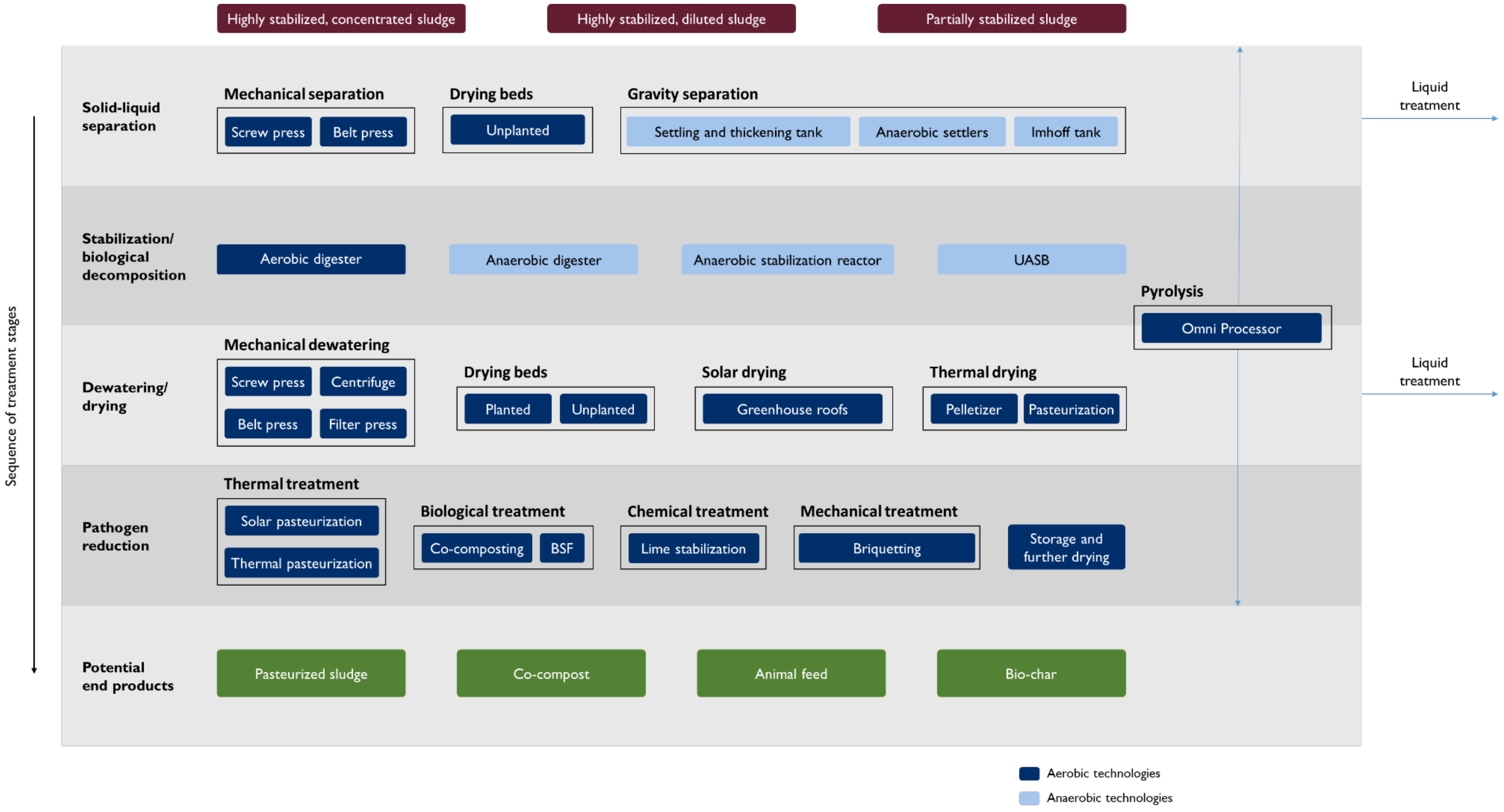
[17] Denotes degree of decomposition of the waste's organic content, measured by the percentage of biological oxygen demand and total solids removal (Ruhela et al. 2021).

Figure 11. Technology processes and choices for fecal sludge treatment plants



Acronyms: BSF: black soldier fly; UASB: upflow anaerobic sludge blanket

Dewatering/drying

The technology choice for dewatering/drying does not have a significant impact on methane emissions since all the shortlisted technologies are aerobic in nature.

Pathogen reduction

A few technology choices are highly aerobic, and current evidence indicates that they have significant reuse and implementation potential in LMICs.

Composting is a biological process that involves microorganisms that decompose organic matter under controlled, predominantly aerobic conditions. The resulting end product is stabilized organic matter that can be used as a soil conditioner (Ronteltap, Dodane, and Bassan 2014), highly prevalent in treatment plants across LMICs (National Institute of Urban Affairs 2019; Tayler 2018; WaterAid 2019). Composting requires space, but the capital and operating costs are relatively low (Strande et al. 2018), and the process does not require significant technical expertise or monitoring once the carbon-to-nitrogen (C:N) ratio is fixed. A C:N ratio between 20 and 30 ensures biological availability, as the organisms degrading organic matter need carbon as a source of energy and nitrogen to build cell structure.

Co-composting fecal sludge with other waste streams can help achieve optimal composting conditions with the appropriate C:N ratio. Literature cites examples of co-composting with agricultural waste in Haiti (Preneta et al. 2013), food/kitchen waste in Kenya and Nepal (Rao and Doshi 2018), and municipal solid waste in Bangladesh (Enayetullah and Sinha 2013). The reuse products from co-composting can also cover a significant portion of operational costs. For example, the FSTP in Devanahilli covered 33 percent of costs from the sale of co-compost and 8 percent from the sale of vegetables grown on-site using compost (Consortium for DEWATS Dissemination Society [CDD] 2020). Compared to composting, operating a co-composting plant and generating a safe product with value require technical and managerial skills to monitor the C:N ratio on an ongoing basis (Strande et al. 2018). One of the interviewed implementers also mentioned the lack of clear guidelines for the use of fecal sludge compost, and demand remains a challenge. Overall, experts and literature cite co-composting as common and feasible where other waste streams are easily available (Otoo et al. 2018).

Black soldier fly (BSF) larvae treatment refers to an aerobic treatment process wherein BSF larvae feed on fecal waste, grow in size, and reduce the wet weight of the waste. It has been observed for different waste streams (e.g., food and market waste) in isolated LMIC contexts (Joly and Nikiema 2019), and for biological decomposition of fecal sludge at plants as a part of container-based sanitation (CBS), an integrated system (Soeters, Mukheibir, and Willetts 2021).

BSF larvae treatment seems promising for LMICs. It has a lower retention time relative to co-composting due to the natural aerobic decomposition of waste by BSF larval action, as validated by one of the interviewed implementers (based in Kenya). It does require a large land area for surface ventilation and the growth of the larvae (Soeters, Mukheibir, and Willetts 2021), but it reduces odor and may not require technically skilled staff (Joly and Nikiema 2019), as validated by the implementer in Kenya. However, the technology is still relatively nascent and faces some challenges. Literature indicates that current BSF larvae treatment plants involve high capital expenditure, driven by research to establish operating procedures for optimal decomposition and generation of reuse products (Soeters, Mukheibir, and Willetts 2021). This up-front investment might not be required for future implementation once the standard operating procedures are established. Two reuse products are generated post-treatment: compost from treated fecal sludge for agricultural use and animal feed from the fed larvae. However, the actual revenue potential (e.g., the market size and customer demand) from the sale of animal feed needs to be understood better. An implementer from India also stated that despite the low technical requirements, BSF larvae can still be an operationally tedious process and may still cause some foul odor.

6.2.2 FS2: CAPTURE EMISSIONS FROM ANAEROBIC TECHNOLOGIES AT FECAL SLUDGE TREATMENT PLANTS

The study identified three interventions for capturing methane emissions from anaerobic technologies:

- **Flaring** involves the burning of methane produced as a by-product of treatment to convert it to CO_2, which has a 25-fold lower GWP than methane over a 100-year period (United States Environmental Protection Agency 2022a).
- **In-house use** involves capturing the methane produced by anaerobic technologies and harnessing it as fuel or electricity, typically with minimal processing, for use at a small scale within the treatment facility.
- **Outbound distribution** involves optimizing anaerobic digestion to generate maximum biogas yield, storing and processing[18] the methane produced to generate fuel or electricity, and then transporting it through gas cylinders, pipelines, or the electricity grid for sale outside the facility.

Flaring or in-house use of methane generated from anaerobic digesters appears promising. Anaerobic digesters are containers, that facilitate the breakdown of organic material by micro-organisms in the absence of oxygen. This anaerobic digestion produces biogas and nutrient-rich by products that can further be utilized for energy. Out of all the different gases produced, methane is most commonly by-product from the digestion of organic matter (Science Direct 2014).

Flaring is cost effective and easy to implement. It only requires inexpensive infrastructure depending on the characteristic of the methane released (e.g., scrubbing and purifying might be required[19]), which can be operated without the involvement of a specialized professional, as indicated by an implementer from India. Moreover, no energy input is required for transportation, as the gas flows across short distances due to natural pressure. Flaring has been observed in multiple LMICs and it has inherent advantages, as stated by implementers from India and Madagascar. However, its adoption is less widespread relative to that of anaerobic treatment technologies with direct release of biogas into the atmosphere. This is possibly because implementers historically have assigned low priority to methane abatement. Implementers from India mentioned that climate impact has emerged as a consideration only recently; in the past, the focus had been solely on public health objectives, which flaring does not address.

Sources have observed **in-house use** of methane captured from fixed/floating dome anaerobic biogas digesters in several LMICs (Ghimire 2007), but the scale is limited to the community level (Sibisi and Green 2005). It requires greater involvement of professionals—for monitoring and ensuring optimal anaerobic conditions to generate biogas, as mentioned by implementers in Madagascar and India—than flaring but still appears to be feasible. Literature suggests that the higher operational requirements can be offset by the conversion of biogas to electricity or fuel (Duffy 2017).

However, implementers have cited challenges that warrant further investigation. In-house use benefits from the input of additional carbon-rich waste streams to balance the C:N ratio of human waste for

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[18] Processing the released methane for in-house or outbound use includes scrubbing the methane to remove CO_2 and H_2S for improving the methane content.

[19] Scrubbing and purifying refers to removing unwanted suspended particles (PM 2.5 and PM 10) and gases like CO_2, H_2S and N_2 by bubbling the gaseous mixture through a scrubbing liquid like amine (Integrated Flow Solutions LLC, 2018).

optimal methane yield. However, even then, the yield may be sufficient only for fueling small in-house kitchen units, which contributes to low incentives for its adoption. Implementers from Madagascar and India cited that electricity generation, such as for use in a combined heat and power engine, requires specific machinery and that the biogas yield at a community-level plant may be insufficient for this. The yield may improve at a larger scale, but sources have not observed this, and experts state that this will require biogas storage infrastructure (adding to costs). Additionally, there may be some stigma attached to using biogas generated from human waste that may have been co-treated with other waste (Mittal, Ahlgren, and Shukla 2018; Emersan n.d.).

Outbound use of biogas, while promising from a revenue generation potential, faces high operational and financial challenges even in developed contexts. The literature scan did not find examples of outbound usage of biogas in LMICs, and multiple experts interviewed validated this finding. It may be unsuitable for immediate adoption in LMICs because of high operational and financial requirements. Capital investment in sophisticated infrastructure is required for the storage, processing, and transportation of biogas (International Renewable Energy Agency ([IRENA] 2018). Professionals are needed to ensure optimal anaerobic conditions for biogas yield (e.g., maintaining the ideal C:N ratio through co-treatment) and to monitor the storage and distribution processes. Transportation and distribution of the gas often require energy-intensive machinery (such as bottling and pressurizing units), which may not be able to rely exclusively on the biogas produced within the facility. Additionally, adoption is limited because of the absence of established markets for biogas from human waste and the need to create distribution channels. Moreover, the local regulatory framework for biogas generation and distribution (e.g., for supplying electricity to the public grid) also emerged as a key consideration for adopting the intervention for interviewed implementers. Given these considerations, adoption of outbound use as compared to direct release of biogas into the atmosphere or flaring/in-house use may be less promising and requires innovation to reduce the degree of these barriers.

6.3 ABATEMENT AT WASTEWATER TREATMENT PLANTS

Wastewater is the resulting waste stream from sewered sanitation systems, including sanitation waste (excreta, urine, flush, and other cleansing material) and non-sanitation waste (e.g., bath and kitchen drain water), and is treated at WWTPs.

Wastewater received at treatment plants is less varied than fecal sludge, as wastewater from different sources is homogenized in sewers (Strande et al. 2018).

Similar to fecal sludge, wastewater is treated in stages (see Figure 12):

- **Primary treatment:** Removal of floating and suspended solids by mechanical means (Kumar, n.d.).
- **Secondary treatment:** Biological degradation of organic material by micro-organisms under controlled conditions (Kumar n.d.).
- **Sludge handling:** Treatment of sludge that is removed from wastewater in preceding stages.
- **Tertiary treatment:** Further purification of wastewater by removal of pathogens for its recycling (Kumar n.d.).

The assessment of interventions for treatment of wastewater indicates that:

- Clarifiers are an aerobic option for the primary treatment stage with widespread usage across developed contexts.

- Activated sludge processes (ASPs), constructed wetlands, and aerobic digesters are aerobic options for secondary treatment stage, but can be implemented in contexts with appropriate energy availability.
- Methane capture needs more experimentation in LMICs, even though there are examples from more developed contexts, as it has low yield potential due to low organic strength.

6.3.1 WW1: MITIGATE EMISSIONS USING AEROBIC TECHNOLOGIES AT WASTEWATER TREATMENT PLANTS

Primary treatment

Clarifiers are an aerobic option for the primary treatment of wastewater. Primary clarifiers consist of large tanks to remove solids, including sludge, that settle by gravity to the bottom of the tank; therefore, they have low operational requirements. Clarifiers are highly prevalent in developed contexts (Arif, Sorour, and Aly 2020) and are usually followed up by ASPs for secondary treatment of wastewater. Clarifiers can be of various types—the simplest of clarifiers (e.g., sedimentation clarifiers) usually require some energy and technical expertise.

Secondary treatment

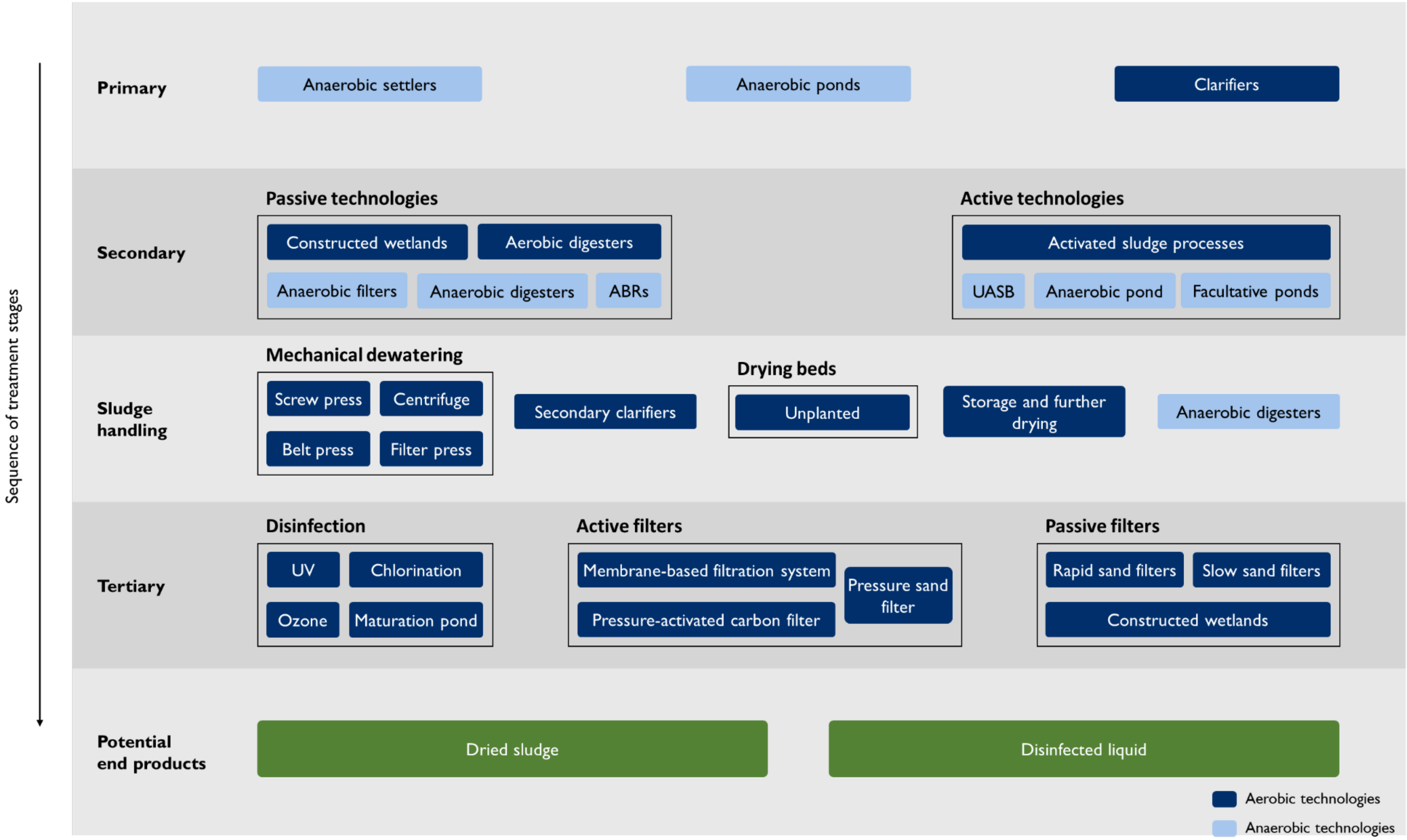
The study identified several active aerobic technologies for secondary treatment of wastewater, but their application may be limited to specific contexts, as they are either energy intensive and require technical expertise or are appropriate for specific types of wastewater.

Conventional **activated sludge processes** are compact two- or three-tank units that make use of aerobic microorganisms or mechanical aerators to decompose the organic content of the waste in the presence of oxygen and remove nutrients from wastewater to produce a high-quality effluent (Emersan n.d.). They are also prevalent in LMICs (Müllegger, Langergraber, and Lechner 2013). Professionals might be required for several aspects, such as maintaining biomass and electrical/mechanical operations. Trained workers can manage day-to-day operations (e.g., the rate of wastewater flow or sludge recycling) (Emersan n.d.). ASPs also require constant energy input to power the mechanical aerators. In addition, certain variants of ASPs, such as the membrane bio-reactor, entail higher capital investment in sophisticated machinery to aerate and treat the wastewater (Arif, Sorour, and Aly 2020). However, given their abatement potential, high prevalence, and compact size, ASPs may still be suitable for contexts where their energy and professional involvement requirements can be met.

Aerobic digesters resemble the conventional activated sludge process but exclude a wastewater feed and employ longer solids retention times (Judd 2022). Aerobic digesters are generally lower in capital cost than anaerobic digesters for plants below 20,000 m^3/d capacity, but they are more energy intensive, and the digested sludge is not easy to dewater mechanically (Judd 2022).

Constructed wetlands (CWs) are aerobic water-based treatment systems that consist of a physical filter bed made of sand or gravel and a biological ecosystem of aquatic plants. There are four variants of this system. CWs are usually land-intensive facilities and may require professional inputs and energy intermittently. These wetlands require low to moderate investment depending on the variant type (Emersan n.d.). They are prevalent in various developed (Tondera, Rizzo, and Molle n.d.) and developing (Abou-Elela & Hellal, 2012) contexts. One of the interviewed experts highlighted that CWs' applicability is limited to low-strength wastewater, and they are prone to clogging.

Figure 12. Technology processes and choices for wastewater treatment plants



Acronyms: ABR: anaerobic baffled reactor; UV: ultraviolet

It is also worth noting that the above aerobic technologies can lead to other GHGs, such as carbon dioxide (due to the use of greater energy) and nitrous oxide (due to nitrification during aerobic processes). The overall global warming impact of these GHGs, relative to the methane abated, needs to be understood better. Further, the abatement potential of these technologies assumes well-functioning plants. Failed aerated systems can lead to anaerobic "dead zones," which may lead to some methane emissions.

Sludge handling and tertiary treatment

The technology choice for sludge handling and tertiary treatment does not have significant impact on methane emissions since all the shortlisted technologies are aerobic in nature.

6.3.2 WW2: CAPTURE EMISSIONS FROM ANAEROBIC TECHNOLOGIES AT WASTEWATER TREATMENT PLANTS

Interventions to capture methane from anaerobic wastewater treatment technologies were not observed in LMICs (Müllegger, Langergraber, and Lechner 2013), which was validated by multiple interviewed experts. Experts indicated that the above challenges for methane capture from fecal sludge are exacerbated in the case of wastewater due to its low organic content and yield potential. Experts cited significant barriers to its adoption. Wastewater is highly diluted and has a lower organic strength (Mamera, van Tol, and Aghoghovwia 2022) and therefore generates a low yield of methane. Besides the low incentives resulting from the low yield, it also leads to operational challenges. For example, the low hydraulic pressure generated makes transporting the gas to the flaring site (even within the facility) challenging without external energy input, as cited by an Indian implementer. Larger plants with a high volume of waste can help increase the methane yield but can also drive up the overall cost of the facility. For instance, an interviewed implementer in Mexico cited the high infrastructure and energy costs of methane recovery from large-scale WWTPs as a reason for not adopting methane capture.

In contrast, in-house reuse of biogas in anaerobic digesters and combined heat and power (CHP) systems is common in developed contexts. CHP systems use biogas to generate heat and power a turbine or engine from the same heated system to generate electricity, while anaerobic digesters use the same methane as fuel to heat the digester (Metropolitan Area Planning Council 2014). Additionally, isolated examples of flaring emissions from anaerobic ponds exist in developed contexts (World Bank Group 2015). However, experts cited the outbound use of methane was as a challenge even for developed contexts for the reasons mentioned above.

6.4 INTEGRATED SYSTEMS ACROSS CONTAINMENT AND TREATMENT

Integrated sanitation systems are those that connect the containment, transfer, treatment, and discharge stages at the household or community level. The study found two types of integrated systems:

- **Technology + service** systems use a combination of technologies, service models, and behaviors across the containment, transfer, and treatment stages.
- **Technology-only** systems use common infrastructure for containment and treatment, doing away with the need to transfer the waste.

The assessment of interventions for integrated systems indicates that:

- **CBS** is a high-potential **technology + service** integrated system applicable for dry containment facilities.

- **Technology-only integrated systems** exist for both wet and dry containment facilities but face several barriers to adoption in LMIC contexts.

CBS (refer to Box 3 for a description of a CBS system) has been implemented in several urban LMIC contexts across the world by various organizations:

- **Sub-Saharan Africa:** Clean Team in Ghana, Loowatt in Madagascar, and Sanergy and Sanivation in Kenya
- **Latin America:** SOIL in Haiti, X-Runner in Peru, and Mosan in Guatemala
- **Asia:** Sanitation First in India

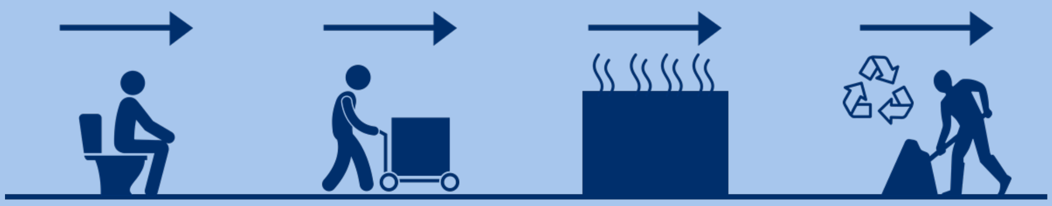
CBS has significant potential for methane abatement across the stages of the sanitation system:

- Containment emissions are minimal since no water seeps into the waste, and high emptying frequency minimizes the time allowed for anaerobic conditions.
- Treatment emissions can be controlled to a greater degree by adopting aerobic technologies like composting, or by capturing methane from the waste having relatively high organic content.
- Reuse of products (instead of discharge) supports carbon sequestration of fresh waste with high organic content by converting it to usable products like biomass and biogas fuels, fertilizer, or animal feed with lower GWP than methane emissions.

Box 3. Container-based sanitation system

CBS is an end-to-end offering wherein fecal sludge is hygienically collected from containment facilities designed with sealable and removable containers, taken for treatment, and safely disposed of or reused. The infographic in Figure 13 depicts the stages of the system.

Figure 13. Stages of a CBS system



CONTAINMENT	TRANSFER	TREATMENT	DISCHARGE/REUSE
Fecal sludge is collected and stored in sealed containers using urine-diverting dry toilets.	• Full containers are collected weekly or bi-weekly, and exchanged for empty, clean containers by emptying service providers. • The containers are placed in a vehicle to be transported to a treatment plant.	• The waste, which is homogeneous and dry fecal sludge, is emptied from containers and treated to reduce pathogens and potentially recover reuse products. • The containers are disinfected before reuse.	• Reuse products like compost, biogas, biomass fuel, and animal feed can be recovered from the fecal sludge. • Nutrients (such as nitrogen and phosphorous) may also be recovered from urine.

Source: Adapted from the Container Based Sanitation Alliance website.

CBS also appears to have some potential for adoption in urban LMIC contexts. CBS systems are cheaper than the prevalent sewered and non-sewered sanitation systems in LMIC contexts. A study of urban low-income settlements in Haiti, Ghana, Kenya, Peru, and Madagascar found typical CBS systems to be around 69.0 percent cheaper than sewered connections and around 13.0 percent cheaper than pit latrines (EY 2021).

CBS addresses the physical challenges associated with constructing and emptying traditional containment facilities (Russel and Montgomery 2020). Since CBS systems are compact, they are suitable for installation in dense, informal settlements. As they do not require underground pits, they are ideal for areas with a high groundwater table and that are flood prone. Moreover, CBS systems can be emptied fully and safely simply by removing the container. This removes the fear of pit collapse due to mechanical emptying services. CBS also has the advantage of relying on mobile infrastructure, making it suitable for households with insecure living tenures, such as those in humanitarian camps.

However, the scalability of CBS systems may be limited since evidence suggests they are unlikely to cover the majority of the population in LMIC contexts. On the demand side, CBS systems are non-aspirational for households because of their impermanent nature. Conversations with implementers and the literature scan highlighted that as customers become more affluent, they prefer shifting to more permanent structures (Dewhurst et al. 2019). On the supply side, while the technology infrastructure is scalable, the services required to operate the sanitation system are not. CBS systems involve challenges that are common to other non-sewered sanitation systems, but these are exacerbated due to the extremely high frequency (almost weekly) of emptying. CBS systems require high operational labor for frequent emptying of waste and involve logistical challenges for transportation, especially if treatment plants are located away from households (Russel et al. 2019). These requirements drive up operational expenditure, which remains unrecovered as the price to be paid by low-income households cannot be increased commensurately. Therefore, continued implementation of CBS systems is often reliant on donor funding and subsidies, such as in the case of Sanergy in Kenya. Moreover, governments in LMICs do not currently view CBS as an alternative to sewered sanitation systems, preventing a widespread push for adoption across contexts (Russel et al. 2019).

The study also found several **technology-only integrated systems** applicable for both wet and dry containment:

- **In situ household biogas digesters** capture and reuse the methane generated (e.g., the Deenbandhu digester in India, which converts the methane to cooking fuel [Moudgil 2019]) from both wet and dry containment facilities.
- **Composting toilets** promote aerobic decomposition of the waste from dry containment facilities to form compost (e.g., urine-diverting EcoSan toilets in India, Sierra Leone, and Kenya [Gupta 2014]).
- **Incinerating toilets** reduce the waste from dry containment facilities to CO_2 and ash using electric power (e.g., the Cinderella toilet in developed contexts [EOOS and WEDC 2014]).

However, there are several barriers to the adoption of these technologies in LMIC contexts.

At the household level, these systems are typically more expensive than conventional containment facilities. For example, household biogas digesters and composting toilets like the EcoSan cost ~USD 350 (Mittal, Ahlgren, and Shukla 2018) and between USD 250 and USD 375, respectively, in India. This is 1.6 to 2.5 times the cost of an improved, traditional containment facility like the VIP twin pit latrine (USD 150) (Moudgil 2019). While incinerating toilets are not observed in LMIC contexts, evidence from developed contexts suggests that they could cost 1.6 to 1.7 times the cost of composting toilets (CabinLife n.d.). These systems also require more space relative to conventional containment facilities, which may be limited in dense urban settlements.

Post-adoption, these integrated systems involve a high degree of technical complexity and household involvement to ensure optimal functioning (e.g., adding bulking agents to composting toilets and monitoring the C:N ratio of in situ household biogas digesters). Failing to ensure optimal functioning can pose public health hazards due to un-stabilized waste or gas leaks (Rajendran, Aslanzadeh, and Taherzadeh 2012). Composting toilets and in situ household biogas digesters also pose the challenge of low yield of compost or biogas from human waste alone. Co-treatment with kitchen or animal waste can enhance the yield, but this adds operational complexity for households.

Even at the community level, integrated systems face operational challenges, including technical capacity requirements for regular operations and maintenance and public health hazards due to gas leaks and human contact with untreated waste. The viability also does not appear to improve with scale. For example, in situ biogas digester facilities in prisons in Nepal and Rwanda remained reliant on donor funding and were unable to recover costs due to the low yield of biogas from human waste despite co-treatment with kitchen waste (Rao and Doshi 2018).

6.5 SUMMARY OF ABATEMENT INTERVENTIONS

The assessment in this chapter suggests that while methane abatement in sanitation is an emerging problem with relatively little focus so far, there are still promising interventions that might be relevant for methane abatement (refer to Figure 14 for a summary of the assessment). However, many will need to be made fit-for-purpose, as they were designed from a "safely managed sanitation" rather than a "methane abatement" principle. The key insights from the assessment are:

A few existing interventions have high abatement potential and appear promising for adoption in LMICs in the immediate term, at least in specific contexts. For dry containment facilities, individual toilet usage and lining of pits are well-established practices in LMICs and can reduce emissions in areas with low and high groundwater tables, respectively. Container-based sanitation is also appropriate for dense, informal settlements where households are willing to use non-permanent toilets. Solid-liquid separation of fecal sludge treatment through unplanted drying beds and mechanical pressing are aerobic options for specific contexts. Unplanted drying beds can be used where the treatment volume is low and the sludge has high total solids content. Mechanical pressing can be used where technical expertise is available along with supply chains of chemical polymers and mechanical parts to run the machinery. Co-composting of fecal sludge for pathogen reduction has reuse potential and can be implemented where additional waste streams and technical/managerial expertise are available. Flaring of methane at fecal sludge treatment plants is also an easy-to-implement practice but needs to be incentivized. Wastewater treatment with clarifiers for primary treatment and activated sludge processes or aerobic digesters for secondary treatment can be implemented where energy and technical expertise is available. Constructed wetlands can also be used for secondary treatment of low-strength wastewater.

Other interventions appear promising but have evidence gaps for scaling in LMICs. Scheduled emptying services will reduce emissions from existing dry and wet containment facilities and appear viable and feasible in smaller cities in LMICs, but they need abatement and implementation evidence from more and larger cities. For fecal sludge treatment, aerobic biological decomposition has only been observed in limited contexts. The use of BSF larvae for pathogen reduction and in-house use of biogas from anaerobic digesters have been observed more but require additional evidence on feasibility and viability at different scales. For wastewater treatment, flaring or in-house use of methane has been implemented successfully in developed contexts, but it is unclear how it needs to be adapted to the low-resource settings of LMICs.

A number of interventions appear less promising along the parameters assessed. These include interventions that indicate relatively low or unclear abatement potential (e.g., demand generation and activation for emptying services, dehydration vaults) or have relatively high or uncertain operational and financial requirements for LMICs (e.g., composting toilets, Omni Processor).

Some abatement approaches lack any promising interventions, such as for reducing emission in wet containment facilities and outbound distribution of methane captured at fecal sludge and wastewater treatment plants.

Figure 14, across the next four pages, summarizes the state of various approaches and interventions along the parameters assessed.

Figure 14. Summary of the state of abatement interventions for sanitation systems in LMICs

Approach	Intervention	Abatement potential	Implementation maturity	Operational feasibility	Financial viability (including reuse potential)
Reduce emissions from unemptied, non-sewered containment facilities					
C1 Control water content in substructure					
For dry containment facilities	Individual toilet usage	◐ Expert-validated **MCF 0.10** for pits above GWT but relative difference to shared toilets needs further evidence	● Prevalent in **multiple LMICs** as promoted under SDGs	◐ Requires **new installations**	● Generally **affordable**
	Lining of pit	● Expert-validated **MCF 0.10** for pits below GWT	● Observed but not prevalent in **multiple LMICs** as not promoted under SDGs	◐ Requires **new installations**	◐ **Relatively more expensive** for households
	Urine-diverting dry toilet	**Unknown MCF** value and qualitative degree of abatement	◐ Observed in **isolated LMICs,** as a **part of integrated systems**	**Unknown** due to limited evidence	
	Upgraded pit (raised pit, dehydration vault)	**Unknown MCF** value and theoretical impact of abatement	○ **Not observed**	**Unknown** due to limited evidence	
For wet containment facilities	-	*Gap in observed interventions*			
C2 Reduce time for anaerobic decomposition					
For both dry and wet containment facilities	Demand generation and activation for emptying	◐ **Theoretical impact,** but value depends on household behavior	● Observed in **multiple LMICs**	**Unknown** due to limited evidence	
	Scheduled emptying	● **High theoretical impact** as per literature, but precise MCF unknown	◐ Evidence from **isolated LMICs** at a **small scale**; recently highly promoted in sector	● **Feasible** in smaller cities and does not require new installations	● **Viably financed** through a sanitation tax in smaller cities

ⓧ *Abatement approach* *Value of parameter:* ● *High* ◐ *Medium* ○ *Low*

Note: Abatement potential of all interventions is either "high" or "medium," as the study did not assess interventions with low abatement potential for their implementation maturity, operational feasibility, or financial viability.

Figure 14. Summary of the state of abatement interventions for sanitation systems in LMICs (cont.)

Approach	Intervention	Abatement potential	Implementation maturity	Operational feasibility	Financial viability (including reuse potential)
Adopt integrated systems across containment and treatment					
I **Adopt integrated systems across containment and treatment**					
For wet containment facilities	In situ household biogas digester	● **Negligible CH_4 emissions** due to capture as biogas	🔵 Evidence from **isolated LMICs**	🔴 **High technical complexity** for households to monitor optimal conditions for biogas production	🔴 **High investment** for households; cooking fuel can be used in-house but has **low yield**
For dry containment facilities	Composting toilet	● Expert-validated **MCF 0.04**	● Evidence from **multiple LMICs**	🔴 **High technical complexity** for households to ensure aerobic decomposition	🔴 **High investment** for households; compost can be used as a soil amendment product but has **low yield**
	Incinerating toilet	● Expert-validated **MCF 0.01**	🔴 Evidence from **isolated developed contexts**	**Unknown** due to limited evidence	
	Container-based sanitation	● **Low emissions** as per empirical evidence in literature	● Evidence from **multiple LMICs**	🔵 **Feasible in contexts** with no sewered access and willingness to adopt temporary toilets	🔵 **Cheaper than alternatives for households** but requires donor funding/ subsidies to cover operational costs

⊗ *Abatement approach* *Value of parameter:* ● *High* 🔵 *Medium* 🔴 *Low*

Acronyms: CH_4: Chemical formula for methane

Note: Abatement potential of all interventions is either "high" or "medium," as the study did not assess interventions with low abatement potential for their implementation maturity, operational feasibility, or financial viability.

Figure 14. Summary of the state of abatement interventions for sanitation systems in LMICs (cont.)

Treatment stage	Intervention	Abatement potential	Implementation maturity	Operational feasibility	Financial viability (including reuse potential)
Reduce emissions at fecal sludge treatment plants					
FS1 Mitigate emissions by using aerobic technologies					
Solid-liquid separation	Unplanted drying beds	● **Aerobic technology**	● Evidence from **multiple LMICs**	◐ **Simple infrastructure,** and limited **technical expertise** but **high land requirement**	◐ **Moderate investment;** majorly made of natural materials
	Mechanical pressing	● **Aerobic technology**	● Evidence from **multiple LMICs**	◐ **Reliance** on continuous supply of **expensive chemical polymers** and **mechanical parts**	◐ **Moderate investment,** low ownership cost
Biological decomposition	Aerobic digester	● **Aerobic technology**	○ Observed in **isolated LMICs**	**Unknown** due to limited evidence	
	Mechanical aeration ponds	● **Aerobic technology**	○ Observed in **isolated LMICs**	**Unknown** due to limited evidence	
	Omni Processor	● Methane released but immediately **converted to CO_2 by pyrolysis**	◐ Evidence from **isolated LMICs**; limited uptake	**Unclear** due to inconsistent information across sources	
Pathogen reduction	Co-composting	● **Aerobic technology**	● Evidence from **multiple LMICs**	◐ **Professional involvement** required; **co-treatment** increases complexity	◐ **Moderate investment;** compost can be sold as **soil amendment product**, based on demand and local guidelines
	Black soldier fly larvae treatment	● **Aerobic technology**	◐ Evidence from **isolated LMICs** as a part of **integrated systems** at the community level	◐ **Land-intensive facility** with low retention time, professional involvement, and energy input	◐ **Moderate investment;** fed larvae can be sold as **animal feed** but the revenue potential is unknown
FS2 Capture emissions from anaerobic technologies					
Across stages	Flaring	◐ **Negligible CH_4 emissions** although conversion to CO_2	● Observed but not prevalent in **multiple LMICs** due to low incentives for adoption	● **Simple infrastructure and no energy** input for transportation due to high hydraulic pressure of gas	● **Minimal investment** for combustible chimney
	In-house use	● **Negligible CH_4 emissions** due to capture as biogas	◐ Evidence from **multiple LMIC contexts,** but mostly at the **community level**	◐ **Low professional involvement** and **no energy** input requirement; co-treatment increases complexity	● **Low investment** required; cooking fuel or electricity can be used within the facility but yield potential is low
	Outbound use	● **Negligible CH_4 emissions** due to capture as biogas	○ Evidence from **isolated developed contexts**	○ **High energy and professional involvement** to monitor conditions and operate machinery	○ **High investment** in sophisticated machinery to collect, process, and distribute gas through public networks

Abatement approach *Value of parameter:* ● *High* ◐ *Medium* ○ *Low*

Acronyms: CO_2: Chemical formula for carbon dioxide

Note: Abatement potential of all interventions is either "high" or "medium," as the study did not assess interventions with low abatement potential for their implementation maturity, operational feasibility, or financial viability.

Figure 14. Summary of the state of abatement interventions for sanitation systems in LMICs (cont.)

Treatment stage	Intervention	Abatement potential	Implementation maturity	Operational feasibility	Financial viability (including reuse potential)
Reduce emissions at wastewater treatment plants					
WW1 Mitigate emissions by using aerobic technologies					
Primary	Clarifiers	● **Aerobic technology**	● Evidence from **multiple LMICs**	● **Low operational requirements**	◐ **Moderate investment** to set up tank
Secondary	Activated sludge processes	● **Aerobic technology**	● Evidence from **multiple LMICs**	◐ Compact facility, **feasible in contexts** with interim technical expertise and constant energy availability	◐ **Moderate investment** for conventional variant; sophisticated variants are expensive
	Aerobic digester	● **Aerobic technology**	● Evidence from **multiple LMICs**	◐ More **energy intensive** and requiring non-mechanical dewatering	◐ **Lower investment** than anaerobic digesters for smaller capacities
	Constructed wetlands	● **Aerobic technology**	● Evidence from **multiple LMICs**	◐ Land-intensive facility not requiring professional input, **feasible in contexts** with interim energy availability	◐ **Moderate investment**
WW2 Capture emissions from anaerobic technologies					
Across stages	Flaring, in-house and outbound use	◐ **Negligible CH_4 emissions** through conversion to CO_2 or capture as biogas	◐ Evidence from **developed contexts** for **gas reuse** and **CHP systems**	**Unknown** due to limited evidence	

⊗ *Abatement approach* *Value of parameter:* ● *High* ◐ *Medium* ○ *Low*

Note: Abatement potential of all interventions is either "high" or "medium," as the study did not assess interventions with low abatement potential for their implementation maturity, operational feasibility, or financial viability.

7.0 THE WAY FORWARD

The study aimed to quantify methane emissions from sanitation systems in LMICs and guide future research and interventions to abate methane in the face of the global climate crisis. The key insight from the study is that anthropogenic methane emissions from sanitation systems will grow substantially in the future if prevalent anaerobic technologies continue to be adopted. Alternative technologies, service models, and behaviors are in various stages of maturity, and some technological and evidence gaps exist.

Given the overall urgency of the climate crisis, action is needed today to start curbing methane emissions from sanitation systems. The study proposes four categories of activities to start developing methane-abating sanitation systems in urban LMIC contexts:

- **Implement** interventions that show abatement and implementation potential for specific contexts.
- **Experiment** with promising interventions that have evidence gaps through implementation research to generate evidence for scaled implementation in LMICs.
- **Innovate** to develop interventions that address gaps in the identified abatement approaches.
- **Create a favorable enabling environment** to increase awareness of the climate impact of sanitation systems, and incentivize the adoption of more climate-friendly technologies, service models, or behaviors.

Figure 15 summarizes the priority actions within each activity category, and the subsequent sections provide additional detail for each activity category.

Figure 15. Summary of actions needed for methane abatement in sanitation

Implement

Adopt for specific context:

- Water content control in **dry containment** facilities through **individual usage**, **lining of pits,** and **container-based sanitation**
- **Solid-liquid separation** through **unplanted drying beds** or **mechanical pressing, pathogen reduction** and **reuse** through **co-composting** for **fecal sludge treatment**
- **Flaring** of **methane captured** from anaerobic **fecal sludge treatment**
- **Primary wastewater treatment** through **clarifiers** and **secondary treatment** through **aerobic digesters, activated sludge processes,** or **constructed wetlands**

Experiment

Address evidence gaps through implementation research for:

- Reduction of decomposition time (especially for **wet containment** facilities) through **scheduled emptying**
- **Biological decomposition** through **aerobic technologies, pathogen reduction** and **reuse** at fecal sludge treatment facilities through **black soldier fly larvae**
- **In-house use** of methane captured from anaerobic **fecal sludge treatment**
- **Flaring** or **in-house use** of **methane captured** from anaerobic **wastewater treatment**

Innovate

Address technical gaps through research and development on interventions for:

- **Emissions reduction** in substructure of **wet containment** facilities
- **Capturing methane** for **outbound use** from anaerobic decomposition at **treatment plants**

Enabling environment

Short term

- **Advocacy and dissemination** for increasing awareness and promoting promising solutions
- **Decision support tools** and measurement of **emission factors**
- Landscape of **climate financing** opportunities

Medium term

- **Guidelines and policies** for adopting promising solutions
- **Monitoring and tracking emissions** to understand impact of interventions and inform refinements
- **Financing mechanisms** for addressing viability challenges

7.1 IMPLEMENT

Figure 16 presents interventions with established abatement and implementation potential for both containment (at least for dry containment) and treatment. These can be implemented (e.g., by including them in programming guidelines) for specific contexts as they can lead to reducing emissions in the immediate term. For example, although CBS is not a universal solution, adoption by the population using dry pit latrines with unlined pits below the groundwater table in urban SSA can reduce projected methane emissions in 2030 by around ~12.0 percent.[20, 21]

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[20] We estimate that 9.3 percent of the population uses dry pit latrines with unlined pits below the groundwater table in the 2030 scenario. This was assumed to be the target population adopting CBS because: (1) CBS is typically adopted by low-income households, who are more likely to have unlined pits rather than lined pits or septic tanks; and (2) CBS is relevant for contexts with high groundwater tables since its container is completely sealed (reducing the scope for seepage).

[21] % of reduction in emissions due to CBS = (Total emissions in 2030 scenario - Emissions if target population adopts CBS)/Total emissions in 2030 scenario:

- Emissions if target population adopts CBS = (Per capita emissions from CBS x target population that adopts CBS) + (Total emissions in 2030 scenario - 2030 emissions from target population).
- Per capita emissions from a CBS user for one year were calculated assuming an MCF of 0.01 at containment and an MCF of 0.1 at treatment (assuming composting is used at the treatment stage).

Many of these interventions still face challenges to adoption and may require actions in the enabling environment, such as increasing awareness and providing incentives and financial support, as described in Section 6.0. Figure 16 summarizes the suitable contexts and critical challenges for these interventions.

Figure 16. Interventions for promotion in the immediate term

Interventions	Applicable context	Critical challenges for adoption
Dry containment facilities		
Individual usage of toilets	Areas with low groundwater table	Requires **new installations**
Lining of pits	Areas with high groundwater table	Requires **new installations,** is **not promoted** in SDGs, and is **expensive** for households
Container-based sanitation	Dense, informal settlements	Has **high operational costs** and is **non-aspirational** for households
Fecal sludge treatment		
Unplanted drying beds for solid-liquid separation	Fecal sludge with high total solids and low treatment volume	Has high **land requirement**
Mechanical presses for solid-liquid separation	Fecal sludge with low total solids	Requires availability of **chemical polymer** and **mechanical spare parts**
Co-composting for pathogen reduction	Areas where additional waste streams and land are available	Requires **technical and managerial capacity**
Flaring of methane	Existing anaerobic fecal sludge treatment facilities	Presents **low incentives** for implementers
Wastewater treatment		
Clarifiers for primary treatment	Areas where energy is available	No critical challenges for adoption
Activated sludge processes for secondary treatment	Areas where energy and skilled professionals are available	Requires high **capital investment** and involves **greater operational complexity**
Aerobic digesters for secondary treatment	Areas where energy is available	Has **longer retention times** and digested sludge **cannot be dewatered mechanically**
Constructed wetlands for secondary treatment	Low strength wastewater	Prone to **clogging** of filter beds, has high **land requirement**

7.2 EXPERIMENT

The following section presents select interventions that appear promising for LMICs but will benefit from targeted implementation research to address specific evidence gaps (refer to Figure 17 for a list of potential research questions).

Scheduled emptying can theoretically reduce emissions and has been implemented viably in a few contexts through partnerships with the private sector. Many LMICs are also actively considering this option for extending safe emptying services citywide. Current implementation evidence is limited to smaller cities, and the precise impact on emissions from different containment facilities with different emptying schedules is unknown. Implementation research should focus on:

- Change in MCFs of different containment facilities on different emptying schedules;
- Key refinements to existing models for scaled implementation; and

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- Total emissions in 2030 scenario and the 2030 emissions from target population were obtained from the estimates from the modeling exercise.

- Costs and appropriate financing mechanisms (e.g., sanitation tax) for scaled implementation.

Aerobic technologies like **aerobic digesters** and **mechanical aeration ponds** for the biological decomposition of fecal sludge have been observed in limited contexts in LMICs. Thermal treatment systems that carry out end-to-end treatment have been observed (like in the Omni Processor), but their viability and feasibility for LMICs is unclear. Implementation research should focus on:

- Barriers and drivers for adoption of aerobic digesters and mechanical aeration technologies at fecal sludge treatment plants; and
- Viability and feasibility of thermal treatment systems for end-to-end treatment at fecal sludge treatment plants.

BSF larvae treatment is an aerobic process with reuse potential that appears to require minimal energy and professional involvement for its operations. Implementation in LMIC contexts has been limited to integrated systems like CBS at a community level. The feasibility and viability of adopting BSF larvae at different scales are unclear. Additionally, the potential of animal feed as an additional revenue stream is not well understood. Implementation research should focus on:

- Change in operating procedures and costs at different scales and as part of standalone treatment plants; and
- Revenue potential from the sale of fed larvae as animal feed.

In-house use of methane captured from **anaerobic digesters at fecal sludge treatment plants** has only been observed at a community-level scale in LMICs. The degree of cost offsetting from the use of biogas is also unclear, especially at larger-scale plants, given that its observed use is limited to powering small sections of the facility. Multiple implementers have stated the need for co-treatment to get sufficient yield. Additionally, there might be a stigma attached to using biogas from human waste. Implementation research should focus on:

- Degree of cost offsetting through the use of biogas at different scales;
- Impact of using multiple carbon-rich waste-streams for co-treatment on biogas yield and operating models; and
- Barriers to adoption of in-house biogas use at different scales.

Flaring or in-house use of methane captured from anaerobic treatment of wastewater has been observed at CHP plants in developed countries for generating heat and electricity from the same system (Metropolitan Area Planning Council 2014). However, it is unclear if and how these technologies can be adapted for the low-resource settings in LMICs. Implementation research should focus on:

- Viability and feasibility of flaring or in-house use of methane for anaerobic wastewater treatment in LMICs;
- Refinements required for adapting these interventions for low-resource settings; and
- Supporting technologies and enabling environment conditions to promote adoption.

Figure 17. Potential research questions for implementation research

Experiment

Interventions	Potential research questions for implementation research
C *Reducing decomposition time through* ***scheduled emptying***	• *How is the MCF of different containment facilities impacted by different emptying schedules?* • *How can current models for scheduled emptying be adapted for scaling in large cities?* • *What are the costs for implementing this model and possible mechanisms for financing it (e.g., through a sanitation tax) at scale?*
FS1 *Biological decomposition through* ***aerobic technologies***	• *What are the key barriers and drivers for adoption of these aerobic technologies at fecal sludge treatment plants of other LMICs?* • *What is the operational feasibility and financial viability of thermal treatment systems for end-to-end treatment at fecal sludge treatment plants?*
FS1 *Pathogen reduction and reuse through* ***black soldier fly (BSF) larvae***	• *How do operating procedures and costs for BSF larvae treatment change at different scales?* • *What is the revenue potential from the sale of fed larvae as animal feed?*
FS2 ***In-house use of methane*** *from anaerobic fecal sludge treatment*	• *How much can in-house use of methane offset costs for the facility at different scales?* • *How does the co-treatment of fecal sludge with other waste streams impact biogas generation and what are the operational models for procurement?* • *What are the barriers to adoption of in-house use of biogas at different scales?*
WW2 ***Flaring*** *or* ***in-house*** *use of* ***methane captured*** *from anaerobic wastewater treatment*	• *What is the operational feasibility and financial viability of flaring and in-house use of methane?* • *What are the requirements for adaptation of these technologies in low-resource setting?* • *What supporting technologies and enabling environment conditions are requirement to increase adoption?*

C *Reduce emissions from non-sewered containment*
FS1 *Reduce emissions from fecal sludge treatment*
FS2 *Capture emissions from fecal sludge treatment*
WW2 *Capture emissions from wastewater treatment*

7.3 INNOVATE

The following section presents approaches that lack interventions or have interventions with prohibitively high operational or financial barriers. These approaches require innovation through research and development and may need to be supported by actions in the enabling environment (refer to Figure 18 for a list of potential research questions).

There is a technological gap for **reducing emission from wet containment facilities,** even though 38.2 percent of the population with unemptied, non-sewered containment facilities will use them in the 2030 scenario, as per the study's model. Septic tanks are the only available technology that controls water content through the leaching of water, but their MCF is cited to be relatively high (MCF 0.5). Water conservation fixtures, such as the Aquatron, can limit the water entering the substructure, but they have not been adapted for the containment technologies in LMICs (Aquatron n.d.). One of the interviewed experts also highlighted filter materials like activated carbon that may be installed at the top of the ventilation pipes to absorb emissions but mentioned the need for more research on them. Innovation should focus on:

- Technological changes to septic tanks that can reduce water content in the substructure; and
- Other technologies (e.g., water conversation fixtures) to reduce emissions from wet containment facilities.

Capturing methane for **outbound use** from anaerobic decomposition has only been observed in isolated developed contexts at wastewater treatment plants and is a gap for fecal sludge treatment plants. It requires investment in infrastructure for collection, storage, and distribution of methane as well as the involvement of professionals for optimal generation of biogas. While the revenue potential from biogas is cited as an opportunity in literature, markets and distribution channels for biogas do not currently exist. Literature and experts cite on-site bottling (Kapoor and Vijay 2019) and centralized utilization centers (Misrol et al. 2021) as possible approaches, but these have not been implemented at scale. Innovation should focus on:

- Identifying technologies that can reduce the infrastructure cost of storage and processing at the facility (e.g., on-site bottling);
- Identifying distribution channels that can transport the biogas with low costs and infrastructure requirements (e.g., centralized utilization centers); and
- Developing markets by increasing customer demand for biogas and creating supply networks for inputs like additional waste streams.

Figure 18. Potential research questions for innovation research

	Interventions	Potential research questions for implementation research
Innovate	C ***Reducing emissions*** *from wet containment facilities*	• *What technological changes are required for septic tanks to reduce water content?* • *What other technologies could reduce emissions from a wet containment facility?*
	FS2 WW2 ***Capturing methane*** *for* ***outbound use*** *from anaerobic decomposition at treatment plants*	• *What technologies can reduce the cost of storage and processing of methane at the treatment plants (e.g., on-site bottling)?* • *How can biogas be distributed at low costs and with minimal infrastructure in LMIC contexts (e.g., centralized utilization centers)?* • *What actions are required on the demand (e.g., customer demand generation) and supply side (e.g., supply networks for additional waste streams for co-treatment) for developing markets for biogas in LMICs?*

C *Reduce emissions from non-sewered containment*
FS2 *Capture emissions from fecal sludge treatment*
WW2 *Capture emissions from wastewater treatment*

7.4 CREATE AN ENABLING ENVIRONMENT

A favorable enabling environment is required to incentivize the adoption of interventions with the potential for methane abatement. The specific activities will vary in the short and medium term.

In the **short term**, the sector can focus on three activities.

First, **advocacy and dissemination** are needed to influence global guidelines and national-level regulatory frameworks to include methane abatement, with time-bound targets, as a stated goal. Currently, global guidelines such as SDGs and national-level regulations do not integrate the climate implications of sanitation and largely focus on public health considerations. Several implementers of treatment technologies also stated that they do not consider the methane emissions of their plants, as it is not prescribed in local regulations. Advocacy and dissemination efforts need to focus on:

- Increasing awareness of the degree of methane emissions that sanitation may be contributing to in LMIC contexts; and

- Ensuring the prescription of technologies, service models, and behavior changes (e.g., in programming guidelines) from the perspective of both public health and climate impact.

Second, **development of decision support tools and emission factors** to quantify and track methane emissions can support increasing awareness of the climate impact of sanitation systems and the promotion of specific interventions. Decision support tools can guide implementers in choosing appropriate interventions for their context. Scientifically measured emission factors of different GHGs will also help decision-making. Currently, the IPCC only provides MCFs for 4 out of 22 non-sewered containment facilities and 16 out of 37 treatment technologies that were considered in this study.[22, 23] The emission factors for methane estimated by this study can serve as a starting point to fill this gap, but they should be validated further by field testing. Additionally, they do not cover other GHG emissions (such as carbon dioxide and nitrous oxide). Determining emission factors of different GHGs for a range of sanitation interventions can help researchers understand the tradeoffs between interventions and their overall impact on the climate. The emission factor data can also be integrated into decision support tools.

Third, **research on climate finance opportunities** can support financing the adoption of interventions that face financial barriers (both for households and institutions). Currently, climate financing is not being leveraged in sanitation despite its potential.

For example, an implementer of the Omni Processor did not consider climate financing even though it can theoretically cover around 37.4 percent of its capital expenditure.[24] Similarly, an implementer of CBS models in Kenya highlighted that despite having estimated the carbon credits of their intervention, the process of obtaining approvals for carbon credits is challenging. The sector will benefit from understanding the challenges of unlocking climate financing, which is nascent in general and particularly nascent for non-sewered sanitation in LMIC contexts.

In the **medium term**, three activities merit a focused effort.

First, **developing guidelines and policies** at the global and national levels can incentivize the adoption of methane abatement interventions identified through the research. These guidelines should explicitly account for the methane emission impact of systems and provide context-specific recommendations for systems and technologies that abate methane.

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[22] The total number of non-sewered containment facilities were sourced from the DHS classification of sanitation facilities. DHS provided 11 non-sewered sanitation facilities (which excludes sewered systems and open defecation). These 11 facilities were further split by shared vs. individual, to provide a total of 22 facilities.

[23] The study identified a long list of technologies across different sanitation systems and stages using sanitation compendiums, such as the Compendium of Sanitation Systems and Technologies by EAWAG (Tilley et al. 2014), WEDC's collection of contemporary toilet designs (EOOS and WEDC 2014), and technologies mentioned by IPCC across different reports (Bartram et al. 2019; Takahiko et al. 2014).

[24] % of capital expenditure for an Omni Processor (OP) offset by carbon credits = (Methane emissions abated by an OP in its lifetime * Carbon credit value for each unit of CO_2e offset)/Capital expenditure for an OP, where:

- Methane emissions abated by an OP in its lifetime = Maximum population served annually (100,000 [ONAS 2014]) * ~100% of annual per capita emissions (since an OP has an MCF of 0.01 as validated by an expert, abating ~100% of emissions) for current FSTPs derived from the study's model (0.176 tCO_2e) * Assumed lifetime of an OP (10 years).
- Carbon credit value for each unit of tCO_2e offset = USD 2 (Konrad-Adenauer-Stiftung 2020).
- Capital expenditure for an OP = USD 942,066, adjusted for USD 2021 (ONAS 2014).

Policies, especially at the national level, can be designed to increase the uptake of promising interventions. This can include:

- Encouraging the adoption of containment facilities and integrated systems that can abate methane at scale and have proven to be safe;
- Explicitly promoting emptying services for non-sewered sanitation and acknowledging the climate impact of such models; and
- Specifying emission thresholds for various treatment technologies, similar to thresholds established for public health metrics (such as BOD removal).

Second, **monitoring and tracking emissions** can help implementers not only understand the impact of interventions but also pivot and implement new interventions if needed. To this end, the development of more accurate emission factors and decision support tools in the short term can support more accurate emission estimates and tracking in a variety of contexts. For observed measurements, technologies—such as satellites, drones, and sensors (the costs of which are reducing) (McKinsey and Company 2021)—can be used where possible. These will provide the required baseline and target data required for leveraging climate financing.

Third, **establishing financing mechanisms** can help interventions achieve scale and address the lack of incentives and affordability and viability challenges for adoption in LMIC contexts. This needs to happen in two phases:

- The sector can first pilot financing mechanisms that emerge from the landscaping of climate finance opportunities.
- Based on results from pilot studies, successful financing mechanisms can be leveraged to promote the adoption of abatement interventions. The timelines for this are likely to match the overall growth in carbon markets. For example, voluntary carbon markets are expected to reach USD 50 billion in 2030, which is a 15-fold increase from today (Blaufelder et al. 2021).

APPENDIX A: ESTIMATING EMISSIONS FROM SANITATION IN LMIC CONTEXTS

This section provides details on the process followed for modeling anthropogenic methane emissions from urban sub-Saharan Africa (SSA) (excluding South Africa).[25] It is organized into four sections, one for each step of the process:

- Step 1: Selecting the sample geography and year.
- Step 2: Developing the model logic.
- Step 3: Gathering model inputs.
- Step 4: Defining future scenario.

STEP 1: SELECTING THE SAMPLE GEOGRAPHY AND YEAR

Selecting the sample geography

The study needed to select a sample geography that was representative of a low- and middle-income country (LMIC) context. The team chose urban SSA as the sample LMIC context for the following reasons:

- Urban regions are likely to be the primary source of methane emissions in the future due to two reasons—urban regions will constitute a significant share of the total population (~68.0 percent of the global population in 2050 compared to 55.0 percent in 2018 [United Nations Department of Economic and Social Affairs 2018]), and they will likely see an increase in the prevalence of treatment plants to treat the generated human waste—both of which can increase methane emissions.
- SSA was chosen because it is a priority region for WASH funders due to the currently low coverage of safely managed sanitation (~21.0 percent [World Health Organization (WHO) United Nations Children's Fund (UNICEF) Joint Monitoring Programme (JMP) n.d.]). Additionally, a prior study done in Kampala, Uganda, provided critical context-specific data, such as technology configurations and levels of decomposition at each treatment stage in fecal sludge and wastewater treatment plants (WWTPs) for the region, which is unavailable for other LMIC contexts (Johnson et al. 2022).
- South Africa was excluded from the modeling exercise as its prevalence of sewered systems is significantly higher than the rest of urban SSA, which would skew the estimations for an LMIC. For example, ~80.0 percent of the population of South Africa is connected to sewered sanitation systems (National Department of Health [NDoH], Statistics South Africa [Stats SA], South African Medical Research Council [SAMRC], and ICF 2019) compared to only ~6.0 percent for the rest of SSA (Demographic and Health Surveys [DHS] n.d.). All subsequent mentions of "urban SSA" in the appendix refer to urban SSA, excluding South Africa.

The learnings from analyzing urban SSA can be extrapolated to other LMIC contexts to a degree since the trends used in the model to project future methane emissions, i.e., urban population growth and push to achieve Sustainable Development Goals (SDGs), apply across LMICs.

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[25] Henceforth, the term "urban SSA" will refer to "urban SSA, excluding South Africa."

Selecting the sample year

The team had to choose a year to estimate emissions because:

- Several indicators of climate change are measured on an annual basis, such as global mean temperatures, the decline in emissions required to meet objectives like the 1.5-degree pathway, and global and regional total emissions. Estimations at an annual level allow for a comparison of emissions from sanitation in LMIC contexts to these indicators.
- Variables to calculate emissions in both, the Intergovernmental Panel on Climate Change (IPCC) methodology and the Kampala study, require yearly values.

The study chose 2020 as the reference year for two reasons:

- The most recent population estimates that could be sourced at the time of the study for urban regions in SSA countries were for 2020.
- The most recent data available for global methane emissions at the time of the study was for 2020 (McKinsey and Company 2021).

STEP 2: DEVELOPING THE MODEL LOGIC

The model quantified methane emissions across the two sanitation systems in LMICs—sewered systems and non-sewered systems—and the practice of open defecation (refer to Figure 1):

- Sewered sanitation systems refer to those where the waste collected at the defecation site is connected to the disposal site through a sewerage network.
- Non-sewered sanitation systems refer to those where waste collected at the defecation site is stored at (or near) the defecation site and then transported to the disposal site by emptying service providers.
- Open defecation refers to the practice of defecating in the open, such as in fields, bushes, forests, ditches, streets, canals, or other open spaces.

Both sewered and non-sewered sanitation systems include four discrete stages for the management of human waste:

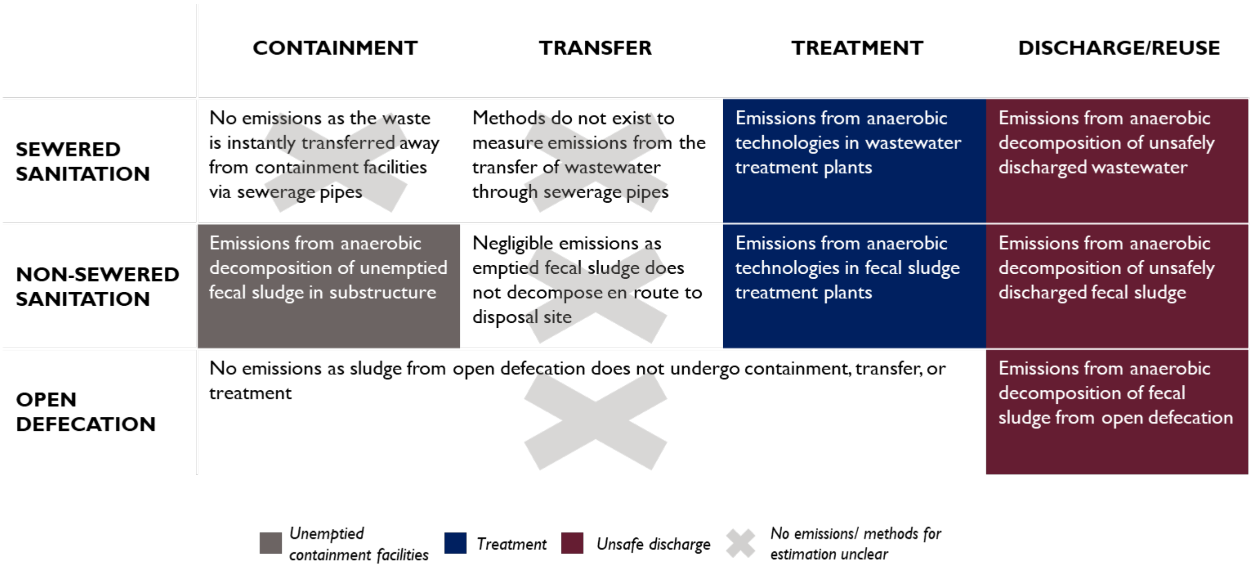
- **Containment** refers to the combination of technologies used for the collection and storage of human waste near the defecation site, in facilities used by individual or multiple households, including:
    - **User interface** technology, through which the user accesses the sanitation system during defecation; it can include pans or urinals to collect the waste, and wet or dry flushing and cleansing mechanisms.
    - **Substructure** technology to store the waste collected by the user interface; it can include pits or tanks and can be lined (with material like cement or bricks) or unlined.
- **Transfer** refers to the technology or service used to transport the waste from the containment site to the disposal site.
- **Treatment** refers to the series of technologies, typically at a treatment facility or plant located away from the containment facility, used for converting the waste to non-hazardous compounds safe for discharge into the environment.

- **Discharge** refers to the methods by which waste is ultimately returned to the environment, either post-treatment, which avoids environmental contamination and public health risks, or unsafely without prior treatment.

Open defecation does not include containment, transfer, or treatment of the waste, but only **unsafe discharge** of the waste into the environment without any treatment, which can lead to environment contamination and public health hazards.

The study identified three primary sources of anthropogenic methane emissions across the stages of different sanitation systems (refer to Figure 19).

Figure 19. Sources of methane emissions from sanitation systems as quantified by the study



	CONTAINMENT	TRANSFER	TREATMENT	DISCHARGE/REUSE
SEWERED SANITATION	No emissions as the waste is instantly transferred away from containment facilities via sewerage pipes	Methods do not exist to measure emissions from the transfer of wastewater through sewerage pipes	Emissions from anaerobic technologies in wastewater treatment plants	Emissions from anaerobic decomposition of unsafely discharged wastewater
NON-SEWERED SANITATION	Emissions from anaerobic decomposition of unemptied fecal sludge in substructure	Negligible emissions as emptied fecal sludge does not decompose en route to disposal site	Emissions from anaerobic technologies in fecal sludge treatment plants	Emissions from anaerobic decomposition of unsafely discharged fecal sludge
OPEN DEFECATION	No emissions as sludge from open defecation does not undergo containment, transfer, or treatment			Emissions from anaerobic decomposition of fecal sludge from open defecation

Unemptied containment facilities *Treatment* *Unsafe discharge* *No emissions/ methods for estimation unclear*

Total annual anthropogenic methane emissions from sanitation systems can be calculated as the sum of emissions across the sources (refer to Figure 20):

- **Unemptied containment facilities:** Emissions from unemptied, non-sewered containment facilities where the fecal sludge is allowed to decompose in the substructure over a long period of time. The team assumed that emissions from emptied, non-sewered containment facilities in a given year are zero. This marginally underestimates emissions because:
  - According to experts interviewed during the study, emissions from recently emptied, non-sewered containment facilities are significantly lower than emissions from unemptied, non-sewered containment facilities since increasing emptying frequency increases aerobic conditions within the pit.
  - The proportion of emptied, non-sewered containment facilities in a given year is low (only 25 percent[26] of the population with non-sewered containment facilities in urban SSA).

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[26] The team assumed 25 percent based on a review of several studies. Refer to Table 4 for assumptions on proportion of population availing emptying services in a given year.

- **Treatment:** Emissions from anaerobic treatment technologies at fecal sludge treatment plants (FSTPs) and wastewater treatment plants (WWTPs), which treat the fecal sludge and wastewater from emptied non-sewered and sewered containment facilities, respectively.

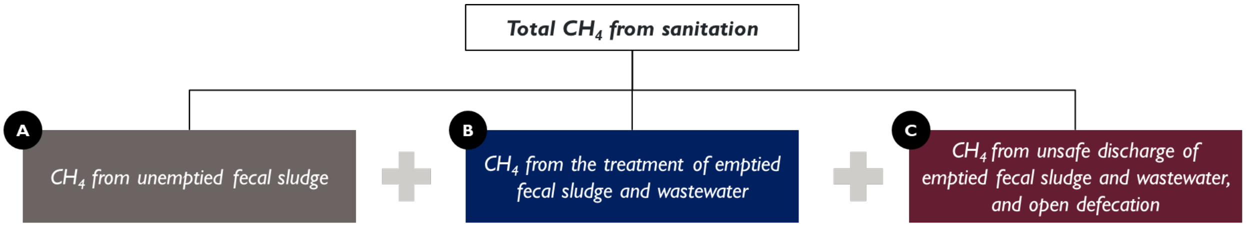
- **Unsafe discharge:** Emissions from emptied fecal sludge and wastewater that are discharged in the open without any prior treatment, and from open defecation.

The team excluded the following as sources of emissions:

- **Containment for sewered systems** because the waste is instantly transferred away from containment facilities to the disposal site through sewerage pipes.
- **Transfer for non-sewered and sewered systems** because:
  - For non-sewered systems, fecal sludge is collected and transferred to the disposal site instantly, which does not allow adequate time for decomposition (and hence emissions) en route.
  - For sewered systems, literature and experts suggest some emissions occur in the wastewater moving through the sewerage pipes (due to the presence of dissolved methane in wastewater), but methods do not exist to measure these emissions.

- **Containment, transfer, and treatment for open defecation** because fecal sludge from open defecation is neither contained nor transferred, but unsafely discharged into the environment without treatment.

Figure 20. Total emissions from sanitation



Note: CH_4 is the chemical formula of methane.

To calculate emissions from the three sources (refer to Figure 20) the team referred to methods from the study conducted in Kampala, Uganda (Johnson et al. 2022), and the IPCC (Bartram et al. 2019). The team primarily referred to the study in Kampala, Uganda, as it was a novel study that designed approaches specifically for non-sewered sanitation systems, which are more prevalent in LMIC contexts. The approaches in the study were specifically relevant for calculating emissions from unemptied fecal sludge and treatment. For emissions from unsafe discharge, the team used methods from IPCC, which provided a generalized approach to calculate emissions when country-specific discharge pathways are not applicable. This was relevant for the study since emissions were estimated at a continent level.

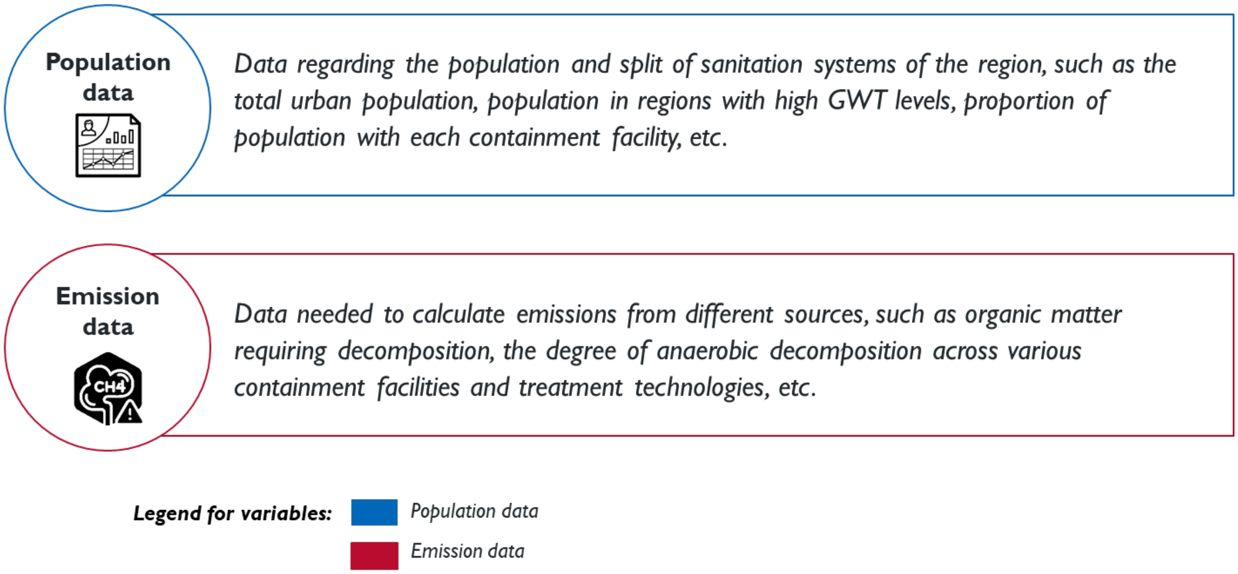
The team developed two values for emissions—an optimistic case to develop a lower end and a pessimistic case to develop a higher end of total emissions to deal with uncertainties in the values for some variables. These included:

- Values for certain variables calculating emissions that lacked consensus in literature and among experts; and
- Data for some demographic variables to estimate the population split across containment facilities in urban SSA that was not available.

The variables that were modified for each case varied by the source of emissions. The sub-sections on the logic for each source list the variables that were modified, and the section on Step 3: Gathering Model Inputs provides the values for these variables.

The rest of this section details the logic used by the team to estimate emissions from each of the three sources in Figure 20. It includes equations to estimate emissions from the sources, key modeling assumptions, and the input variables that were required for the equations. Input data in the equations were categorized into two types (refer to Figure 21).

Figure 21. Input types



Population data

Data regarding the population and split of sanitation systems of the region, such as the total urban population, population in regions with high GWT levels, proportion of population with each containment facility, etc.

Emission data

Data needed to calculate emissions from different sources, such as organic matter requiring decomposition, the degree of anaerobic decomposition across various containment facilities and treatment technologies, etc.

Legend for variables: 🟦 *Population data*

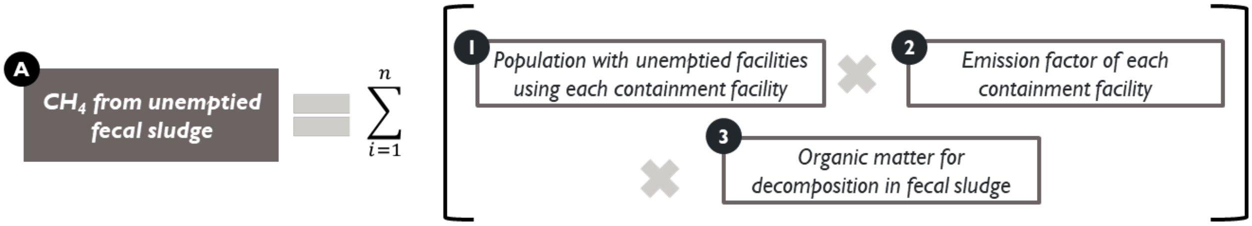
🟥 *Emission data*

Note: Refer to section on Step 3: Gathering Model Inputs and Step 4: Defining Future Scenarios for a full list of all required input variables with their description, values, and sources/assumptions for 2020 and 2030 emissions, respectively.

Unemptied fecal sludge

Emissions from unemptied fecal sludge were calculated using the equation in Figure 22, which provides the sums of emissions from the different types of containment facilities.

Figure 22. Equation for emissions from unemptied fecal sludge



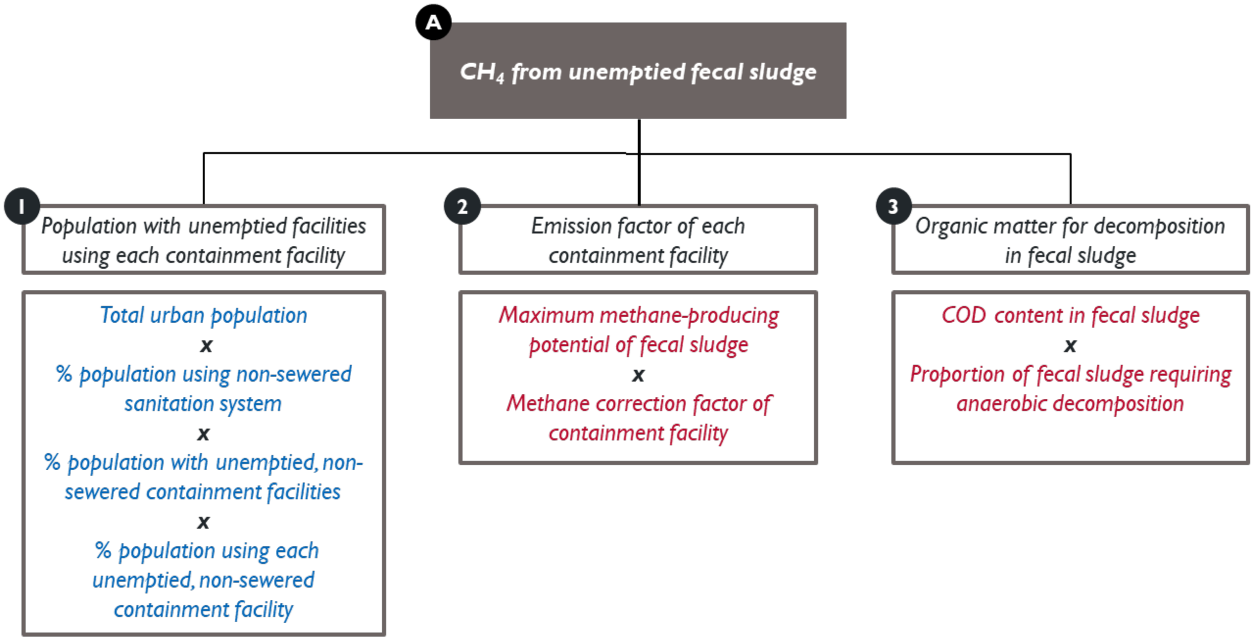
$\sum_{i=1}^{n}$ *sum of emissions from different types of containment facilities in a year, where n denotes the total number of containment facilities in urban SSA*

Note: CH_4 is the chemical formula of methane.

The equation is a function of three variables requiring various inputs, as detailed in Figure 23:

- The population with unemptied containment facilities using each type of non-sewered containment facility (e.g., unlined dry pit latrine, shared and individual septic tanks). The team assumed that the split of the population across unemptied, non-sewered containment facilities is the same as the split across all non-sewered containment facilities.
- Emission factor for each containment facility, which is the degree to which the containment facility promotes anaerobic decomposition of the fecal sludge.
- Organic matter for decomposition, which is the total organic content in the fecal sludge requiring anaerobic decomposition.

Figure 23. Inputs required for calculating emissions from each unemptied containment facility



Acronyms: COD: chemical oxygen demand

The team modified three variables in the equation for calculating the optimistic and pessimistic cases from unemptied fecal sludge:

- **Percent of the population using each unemptied, non-sewered containment facility** since the source dataset did not provide data on the proportion of users with lined vs. unlined pits, which required the team to make certain assumptions as this distinction has a significant impact on the level of emissions.
- **Chemical oxygen demand (COD) content in fecal sludge** since the IPCC provided a range for the level of organic matter in waste for Africa, and the difference in values of this range impacted emissions from unemptied fecal sludge.
- **Proportion of fecal sludge requiring anaerobic decomposition** since the Kampala study used only a fractional value for the amount of organic matter in the fecal sludge in the substructure requiring anaerobic decomposition, while IPCC suggested that all of the organic matter in the fecal sludge requires anaerobic decomposition.

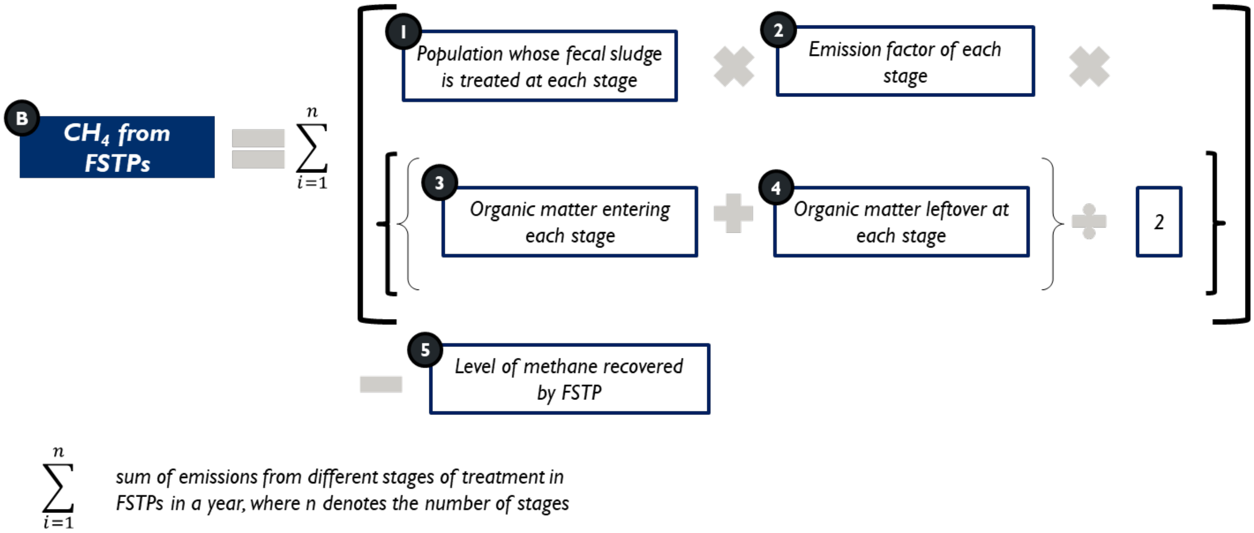
All variables, along with their values (for both cases), descriptions, sources, and assumptions are provided in the section on Step 3: Gathering Model Inputs.

Treatment of emptied fecal sludge and wastewater

The emissions from the treatment of emptied fecal sludge and wastewater are calculated as the emissions from FSTPs and WWTPs.

The emissions from an FSTP are calculated using the equation in Figure 24, which is a sum of emissions across various stages and treatment processes at the treatment plant, minus any methane that was recovered by the plant.

Figure 24. Equation to calculate emissions from an FSTP

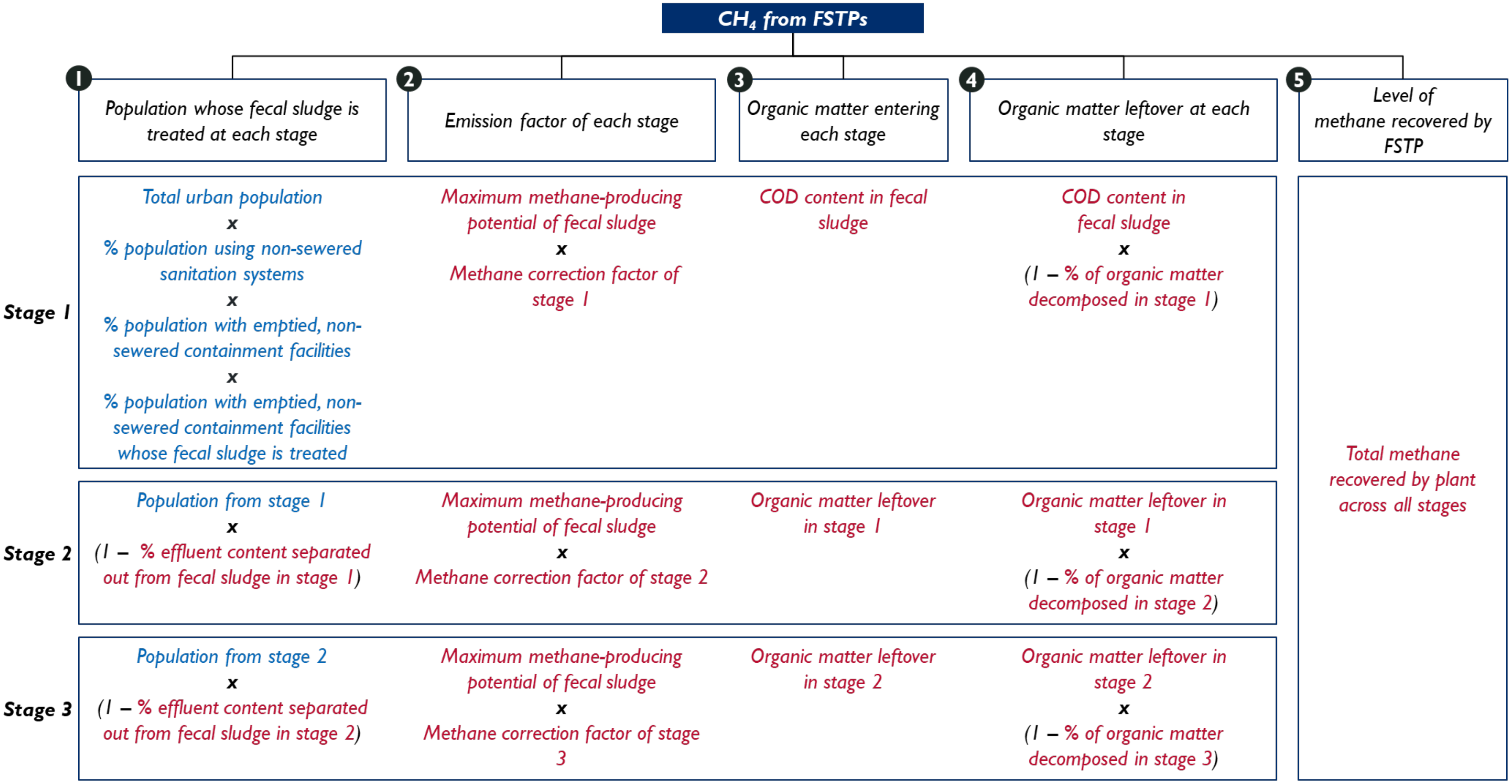


Acronyms: FSTP: fecal sludge treatment plant

The equation is a function of five variables, each requiring a specific calculation for every stage of the treatment plant (refer to Figure 25). The variables are as follows:

- Population whose fecal sludge is treated at each stage, which is a function of the proportion of the total population whose fecal sludge is treated at the treatment plant, and the population equivalent of the proportion of effluents in the fecal sludge.
- The emission factor for the stage, which is the degree to which the treatment process promotes anaerobic decomposition of the fecal sludge.
- An average of:
  - The level of organic matter that enters each treatment stage, which is the total organic content that requires decomposition at each stage; and
  - The level of organic matter left over after treatment at each stage.
- The amount of methane recovered by the treatment plant to be reused or flared.

__Figure 25. Variable equations for estimating emissions from modeled FSTP__



CH_4 from FSTPs

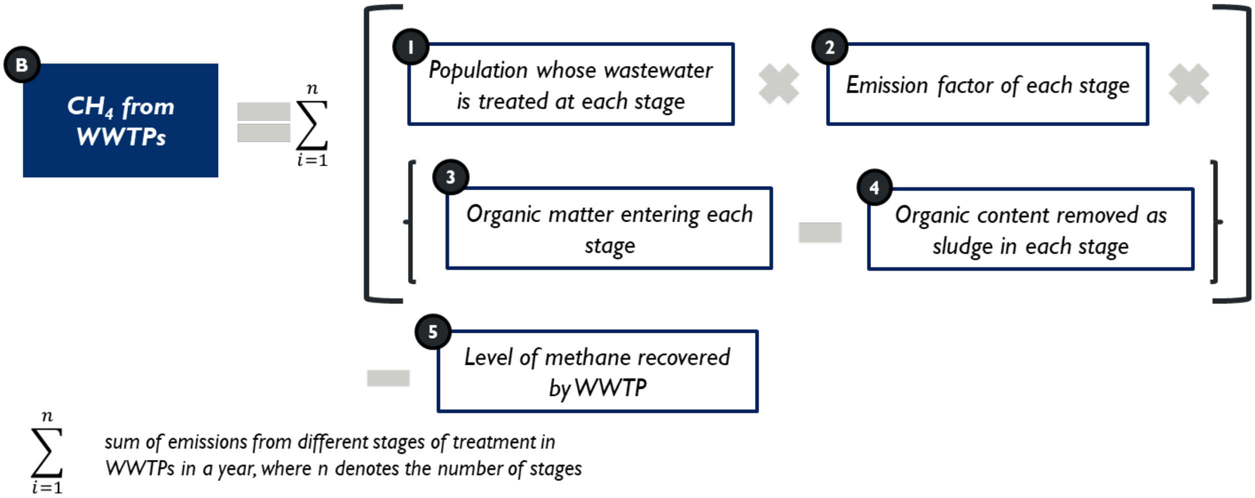
	① Population whose fecal sludge is treated at each stage	② Emission factor of each stage	③ Organic matter entering each stage	④ Organic matter leftover at each stage	⑤ Level of methane recovered by FSTP
Stage 1	Total urban population **x** % population using non-sewered sanitation systems **x** % population with emptied, non-sewered containment facilities **x** % population with emptied, non-sewered containment facilities whose fecal sludge is treated	Maximum methane-producing potential of fecal sludge **x** Methane correction factor of stage 1	COD content in fecal sludge	COD content in fecal sludge **x** (1 – % of organic matter decomposed in stage 1)	Total methane recovered by plant across all stages
Stage 2	Population from stage 1 **x** (1 – % effluent content separated out from fecal sludge in stage 1)	Maximum methane-producing potential of fecal sludge **x** Methane correction factor of stage 2	Organic matter leftover in stage 1	Organic matter leftover in stage 1 **x** (1 – % of organic matter decomposed in stage 2)	
Stage 3	Population from stage 2 **x** (1 – % effluent content separated out from fecal sludge in stage 2)	Maximum methane-producing potential of fecal sludge **x** Methane correction factor of stage 3	Organic matter leftover in stage 2	Organic matter leftover in stage 2 **x** (1 – % of organic matter decomposed in stage 3)	

Note:

- *The effluent content separated from the fecal sludge is passed on to a WWTP for treatment in the modeled approach.*

Emissions from a WWTP are calculated using the equation in Figure 26, which is a sum of emissions from various stages and treatment processes at the treatment plant, minus any methane that was recovered by the plant.

Figure 26. Equation to calculate emissions from a WWTP



The equation is a function of five variables, each requiring a specific calculation for every stage of the treatment plant (refer to Figure 27). The variables are as follows:

- Population whose wastewater is treated at each stage, which is a function of the total population whose wastewater is treated; the population equivalent of the amount of sludge in the wastewater,[27] and the population equivalent of the amount of effluents received from the FSTP;
- Emission factor for the stage, which is the degree to which the treatment process promotes anaerobic decomposition of the wastewater;
- Level of organic matter that enters each treatment stage, which is the total organic content requiring decomposition in each stage;
- Level of organic matter removed as sludge at each stage, which is the amount of fecal sludge (represented as the population equivalent) that is separated from the wastewater in stages 1 and 2; and
- The amount of methane recovered by the treatment plant to be reused or flared.

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[27] The FSTP and WWTP configuration modeled includes the transfer of effluents from the fecal sludge received at an FSTP to a WWTP. Conversations with experts suggested that this interlinkage may be common in several SSA contexts.

Figure 27. Variable equations for estimating emissions from modeled WWTP

CH_4 from WWTPs

	❶ Population whose wastewater is treated at each stage	❷ Emission factor of each stage	❸ Organic matter entering each stage	❹ Organic content removed as sludge in each stage	❺ Level of methane recovered by WWTP
Stage 1	*(Total urban population* ***x*** *% population using sewered sanitation system* ***x*** *% population whose wastewater is treated)* **+** *Population equivalent of effluents passed on from FSTP*	*Maximum methane-producing potential of wastewater* ***x*** *Methane correction factor of stage 1*	*COD content in wastewater*	*COD content in wastewater* ***x*** *% of sludge content in wastewater in stage 1*	*Total methane recovered by plant across all stages*
Stage 2	*Population from stage 1* ***x*** *(1 – % sludge content separated out from wastewater in stage 1)*	*Maximum methane-producing potential of wastewater* ***x*** *Methane correction factor of stage 2*	*COD content in wastewater in stage 1* ***x*** *(1 – % organic matter decomposed in stage 1)*	*Organic matter entering stage 2* ***x*** *% of sludge content in wastewater in stage 2*	
Stage 3 - *Treatment of sludge*	*(Population from stage 1* ***x*** *% sludge content separated out from wastewater in stage 1)* **+** *(Population from stage 2* ***x*** *% sludge content separated out from wastewater in stage 2)*	*Maximum methane-producing potential of wastewater* ***x*** *Methane correction factor of stage 3*	*COD content in wastewater*	—	

Note:

- *In the third stage, the variable "Organic content removed as sludge" is zero since this stage only treats sludge, which is separated from the wastewater in stage 1 and stage 2.*

The study modeled the FSTP and WWTP configurations from the Kampala study (namely the Lubigi treatment plant configuration in Kampala) (Johnson et al. 2022):

- FSTP: Thickening tank, followed by a drying bed, and ending with storage of fecal sludge.
- WWTP: Anaerobic pond followed by a facultative pond, and a drying bed to treat fecal sludge separated out in the first two stages.

These configurations were modeled because a scan of literature on FSTPs and WWTPs across LMIC contexts, and anecdotal evidence from sector experts, suggested that these are common configurations in LMIC contexts. A scan of FSTPs in LMIC contexts across various studies indicated that ~40 percent of plants used a thickening unit in the first stage and ~65 percent of these were in combination with a drying bed (National Institute of Urban Affairs 2019; Klinger et al. 2019; Steiner et al. 2002; Odey et al. 2019). Another study suggested that in four SSA countries (Senegal, Algeria, Burkina Faso, and Ghana), stabilization ponds (such as anaerobic and facultative ponds) were used in 55 percent–100 percent of the WWTPs in each country (Müllegger, Langergraber, and Lechner 2013).

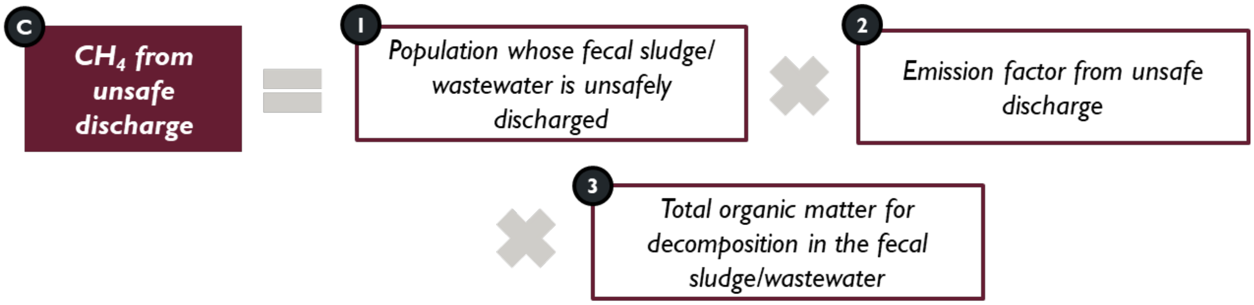
The team modified only one variable for calculating the optimistic and pessimistic case for emissions in 2020, **COD content of fecal sludge (or wastewater),** to account for the range of values provided by IPCC for Africa.

All variables, along with their values (for both cases), descriptions, sources, and assumptions are provided in the section on Step 3: Gathering Model Inputs.

Unsafe discharge of wastewater, emptied fecal sludge, and open defecation

Emissions from unsafe discharge—for emptied fecal sludge, wastewater, and open defecation—were calculated using the equation in Figure 28.

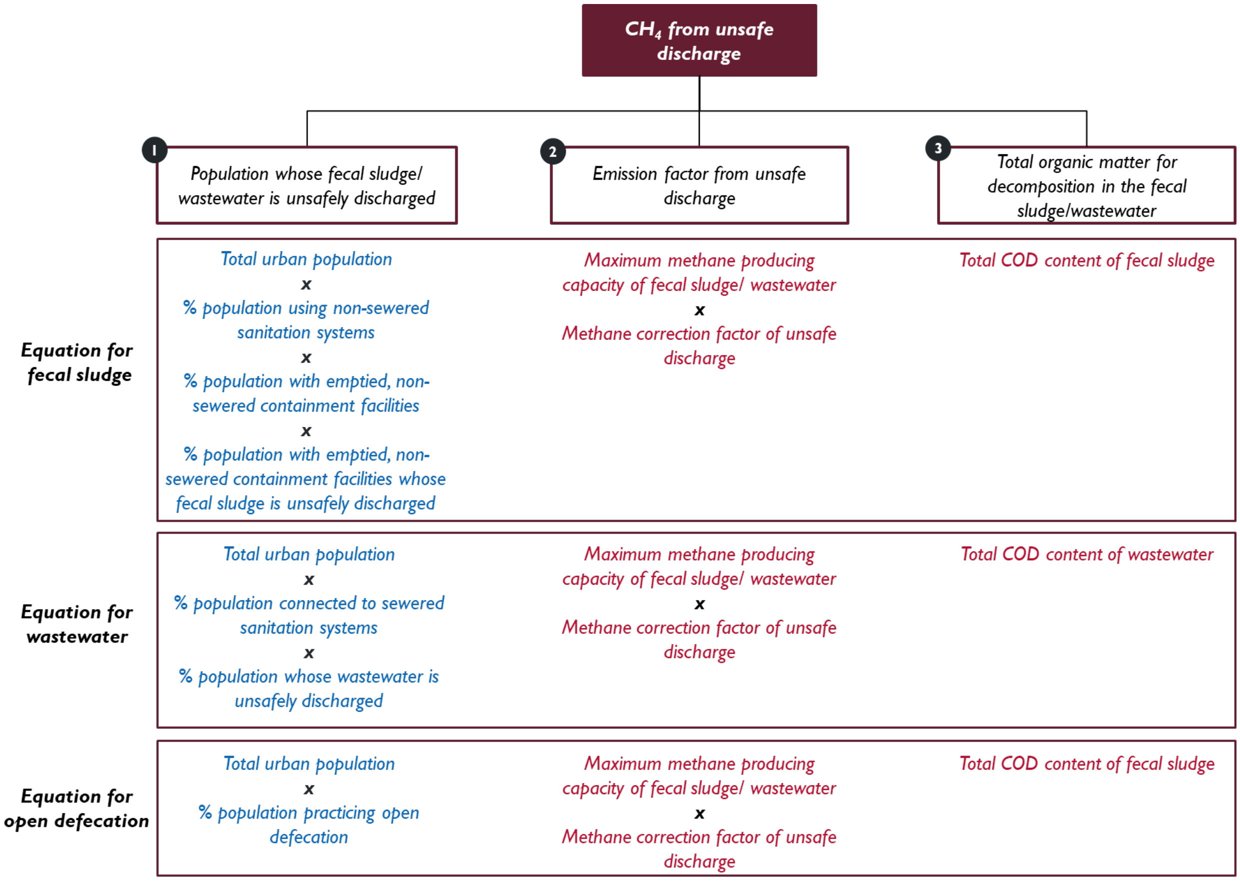
Figure 28. Equation for emissions from unsafe discharge



The equation is a function of three variables, calculated using the inputs in Figure 29:

- Population whose fecal sludge or wastewater is unsafely discharged due to open dumping of untreated emptied fecal sludge or wastewater, or open defecation;
- The emission factor from unsafe discharge, which is the degree to which open dumping promotes anaerobic decomposition of the fecal sludge or wastewater; and
- The total organic matter that requires decomposition in the fecal sludge or wastewater.

Figure 29. Variable equations for estimating emissions from each type of unsafe discharge



	❶ Population whose fecal sludge/ wastewater is unsafely discharged	❷ Emission factor from unsafe discharge	❸ Total organic matter for decomposition in the fecal sludge/wastewater
Equation for fecal sludge	*Total urban population* *x* *% population using non-sewered sanitation systems* *x* *% population with emptied, non-sewered containment facilities* *x* *% population with emptied, non-sewered containment facilities whose fecal sludge is unsafely discharged*	*Maximum methane producing capacity of fecal sludge/ wastewater* *x* *Methane correction factor of unsafe discharge*	*Total COD content of fecal sludge*
Equation for wastewater	*Total urban population* *x* *% population connected to sewered sanitation systems* *x* *% population whose wastewater is unsafely discharged*	*Maximum methane producing capacity of fecal sludge/ wastewater* *x* *Methane correction factor of unsafe discharge*	*Total COD content of wastewater*
Equation for open defecation	*Total urban population* *x* *% population practicing open defecation*	*Maximum methane producing capacity of fecal sludge/ wastewater* *x* *Methane correction factor of unsafe discharge*	*Total COD content of fecal sludge*

The team modified two variables in the equations for calculating the optimistic and pessimistic case from unsafe discharge to account for uncertainties in the methods proposed by IPCC and experts in the sector:

- **Methane correction factor (MCF) for unsafe discharge** since the value provided by IPCC for unsafe discharge into water bodies[28] (when the type of water body is unknown) was contested by a sector expert. The expert recommended using a slightly higher MCF, as IPCC values assumed more aerobic pathways (such as flowing rivers) than those in LMIC contexts (which may also include stagnant open drains or ponds).
- **COD content in fecal sludge and wastewater** to account for the range that IPCC provides for the organic matter in waste for Africa.

STEP 3: GATHERING MODEL INPUTS

As discussed in the previous section, the team sourced two types of input data for calculating methane emissions from sanitation—population and emissions data. These variables are also differentiated with blue and red text, respectively, in the previous section (refer to Figure 21).

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[28] IPCC suggests that untreated waste in LMIC contexts is disposed in water bodies (Bartram et al. 2019).

Population data on the split by sanitation systems in urban SSA was largely sourced using the latest DHS datasets of 24 SSA countries. The latest DHS datasets available for each country range across 2014–2021, with the majority (23 out of 24) being within three years of 2020. The team assumed that the split of the population by containment facilities of the urban population for a country has not significantly changed during this time period. The sum of the population split by containment facilities of these 24 countries was considered representative of urban SSA (without South Africa), as these countries contribute to ~79 percent of the urban sub-Saharan African population, excluding South Africa. Additionally, the team also referred to several shit flow diagrams (SFDs) (SFD Promotion Initiative n.d.) and sources such as the World Bank, government websites, etc. Table 3 provides all the population variables, their input values, description, sources, and assumptions.

Emissions data was sourced using the IPCC values (Bartram et al. 2019), the Kampala study (Johnson et al. 2022), and certain assumptions developed by the team. The preference for sources (in descending order) was as follows:

- Values from IPCC;
- Values from the Kampala study, where values were unavailable from IPCC; and
- Assumptions developed by the study team and validated by experts.

Table 4 provides all the emission variables, their input values, description, sources, and assumptions. The emission variables are categorized by emission source, given that emission data significantly vary by the source of emissions.

For variables with different values for the optimistic and pessimistic cases, the value column of Table 3 and Table 4 provides both values. For all other variables, there is only one value in the value column.

Table 3. Population data for 2020

Input Variable	Description	Value	Source/Assumption
Urban population of SSA, excluding South Africa	Total population of urban SSA, minus the urban population of South Africa	435,817,915	Total urban SSA population sourced from (World Bank n.d.). Total urban South Africa population sourced from (World Bank n.d.).
Population using sewered systems	Proportion of total urban SSA population connected to sewered network	5.63%	Sourced from DHS datasets (DHS n.d.).
Population using non-sewered systems	Proportion of total urban SSA population with non-sewered containment facilities	93.27%	Sourced from DHS datasets (DHS n.d.).
Population practicing open defecation	Proportion of total urban SSA population practicing open defecation	1.10%	Sourced from DHS datasets (DHS n.d.).
Treatment levels for sewered systems			
Proportion of wastewater treated	Proportion of population with sewered sanitation systems whose wastewater is treated	33.33%	Sourced from multi-city SFD of 32 sub-Saharan African cities (SFD Promotion Initiative n.d.).
Proportion of wastewater unsafely discharged	Proportion of population with sewered sanitation systems whose wastewater is unsafely discharged	66.67%	Sourced from multi-city SFD of 32 sub-Saharan African cities (SFD Promotion Initiative n.d.).
Level of annual emptying for non-sewered systems			
Proportion of non-sewered containment facilities emptied	Proportion of total urban SSA population with non-sewered containment facilities whose pits are emptied during the year	25.0%	For this study, the model assumes that approximately 25.0% of non-sewered containment facilities are emptied in a given year in urban SSA, based on a review of multiple literature sources: • Studies of 16 cities (predominantly capital or large) in SSA provide a high estimate of 30.4%-58.0% for the proportion of households with non-sewered containment facilities that empty them in a year (refer to Table 2). • In contrast, a multi-country study of 32 SSA cities (including smaller towns such as Bure in Ethiopia, Bignona in Senegal, and Kasungu in Malawi) estimated that only 40.0% of the population with non-sewered containment

<table>
<tr><th colspan="2">Input Variable</th><th>Description</th><th>Value</th><th>Source/Assumption</th></tr>
<tr><td colspan="2"></td><td></td><td></td><td>facilities had ever emptied them (SFD Promotion Initiative n.d.). This study suggests that the proportion of the population emptying in a year would be much lower than 40.0% and the high estimates of 30.4%-58.0% from the other studies.
• To balance the different estimates and the fact that emptying frequency is likely to be very low in peri-urban areas or small towns (due to availability of space to build new substructures and lack of emptying services), the study assumes 25.0% to be a reasonable estimate of the proportion of households emptying their facilities in a given year.</td></tr>
<tr><td colspan="2">Proportion of non-sewered containment facilities unemptied</td><td>Proportion of total urban SSA population with non-sewered containment facilities whose pits are unemptied during the year</td><td>75.0%</td><td>Calculated as 100.0% - Proportion of non-sewered containment facilities emptied.</td></tr>
<tr><td colspan="5">Treatment levels for fecal sludge from emptied, non-sewered containment facilities</td></tr>
<tr><td colspan="2">Proportion of fecal sludge treated</td><td>Proportion of population with emptied, non-sewered containment facilities whose fecal sludge is treated</td><td>22.22%</td><td>Sourced from multi-city SFD of 32 sub-Saharan African cities (SFD Promotion Initiative n.d.).</td></tr>
<tr><td colspan="2">Proportion of fecal sludge unsafely discharged</td><td>Proportion of population with emptied, non-sewered containment facilities whose fecal sludge is unsafely discharged</td><td>77.78%</td><td>Sourced from multi-city SFD of 32 sub-Saharan African cities (SFD Promotion Initiative n.d.).</td></tr>
<tr><td colspan="5">Proportion of population with unemptied, non-sewered systems using each type of containment facility</td></tr>
<tr><td colspan="5">Overall assumption: The split of the population across unemptied, non-sewered containment facilities is the same as the split across all non-sewered containment facilities (sourced as described below).</td></tr>
<tr><td>Septic tanks</td><td>Shared</td><td>Proportion of population with unemptied containment facilities using shared septic tanks</td><td>9.54%</td><td>Sourced from DHS datasets (DHS n.d.).
Categorized “Flush to septic tank” toilet facility as “Septic tanks.”</td></tr>
<tr><td>Septic tanks</td><td>Individual</td><td>Proportion of population with unemptied containment facilities using individual septic tanks</td><td>15.95%</td><td>Sourced from DHS datasets (DHS n.d.).
Categorized “Flush to septic tank” toilet facility as “Septic tanks.”</td></tr>
</table>

Input Variable		Description	Value	Source/Assumption
Dry pit latrines with unlined pits	Shared, pit below groundwater table (GWT)	Proportion of population with unemptied containment facilities using shared dry pit latrines with unlined pits below the GWT	Optimistic: 4.66% Pessimistic: 8.16%	Sourced from DHS datasets (DHS n.d.). Categorized “VIP toilets,” “Composting toilets,” and “Pit latrines with/without slab or open pit” as “Dry Pit latrines.” For classification of lined vs. unlined: • For pessimistic case, 2020 emissions: – Assumed 25% of “VIP toilets,” “Composting toilets,” and “Pit latrines with slabs” have lined pits; and – Assumed all remaining toilets categorized as “Dry pit latrines” have unlined pits. • For optimistic case, 2020 emissions: – Assumed 75% of “VIP toilets” and “Pit latrines with slabs” have lined pits; and – Assumed all remaining toilets categorized as “Dry pit latrines” have unlined pits. For classification of “below” vs. “above” GWT: • Estimated percent of areas with GWT level zero to seven meters below ground level based on a visual analysis of GWT map (MacDonald et al. 2012) for countries in SSA and classified these areas as “high GWT”; • Assumed percent of urban population living in areas with high GWT is equal to percent of area with high GWT for each country; • Assumed that split of containment facilities across population in regions with high GWT was the same as the split at the country-level; and • Assumed 50 of population in areas with high GWT have their pits below the GWT. This was done to account for the fact that not all pits in
Dry pit latrines with unlined pits	Individual, pit below GWT	Proportion of population with unemptied containment facilities using individual dry pit latrines with unlined pits below the GWT	Optimistic: 3.86% Pessimistic: 6.37%	
Dry pit latrines with unlined pits	Shared, pit above GWT	Proportion of population with unemptied containment facilities using shared dry pit latrines with unlined pits above the GWT	Optimistic: 12.17% Pessimistic: 21.12%	
Dry pit latrines with unlined pits	Individual, pit above GWT	Proportion of population with unemptied containment facilities using individual dry pit latrines with unlined pits above the GWT	Optimistic: 9.79% Pessimistic: 15.71%	
Dry pit latrines with lined pits	Shared	Proportion of population with unemptied containment facilities using shared dry pit latrines with lined pits	Optimistic: 18.68% Pessimistic: 6.23%	
Dry pit latrines with lined pits	Individual	Proportion of population with unemptied containment facilities using individual dry pit latrines with lined pits	Optimistic: 12.64% Pessimistic: 4.21%	

Input Variable		Description	Value	Source/Assumption
				areas of high GWT will have pits deep enough to be below the GWT. The classification of “below” and “above” GWT affects only unlined pits, as water can only seep through such containment facilities, and will, therefore, significantly affect the anaerobic conditions within the pits.
Wet pit latrines	Shared	Proportion of population with unemptied containment facilities using shared wet pit latrines	7.22%	Sourced from DHS datasets (DHS n.d.). Categorized all “Flush/washable toilets” as “Wet pit latrines.”
Wet pit latrines	Individual	Proportion of population with unemptied containment facilities using individual wet pit latrines	5.48%	Sourced from DHS datasets (DHS n.d.). Categorized all “Flush/washable toilets” as “Wet pit latrines.”

Table 4. Emissions data for 2020

Input Variable	Description	Value	Source/Assumption
All emission sources			
Global warming potential (GWP) of methane	Measure of how much energy the emissions of one ton of methane will absorb over a given period of time, relative to the emissions of one ton of carbon dioxide (CO_2). The team converted emission values to CO2 equivalent (CO_2e) to express their impact on global warming. CO_2e is considered to be the standard unit to measure and compare the carbon footprints of various greenhouse gases (GHGs).	25	Sourced CH_4 to CO_2e conversion value from (United States Environmental Protection Agency2022a). The team used the 100-year GWP of CH_4 to convert emission values to CO_2e since that is the most commonly used time horizon while calculating GWP (United States Environmental Protection Agency 2022c; Gillenwater 2010).
Maximum methane-producing capacity of fecal sludge and wastewater	The maximum methane-producing capacity of fecal sludge or wastewater if all waste were was decomposed anaerobically	0.25	Assumed the default value provided by IPCC (Bartram et al. 2019).
COD content of fecal sludge (FS)	The total quantity of organic matter requiring decomposition present in the fecal sludge of one person per year	Optimistic: 35.04 Pessimistic: 39.42	Sourced from IPCC-provided range of biological oxygen demand (BOD) for Africa (Bartram et al. 2019): • COD = 2.4 BOD

Input Variable		Description	Value	Source/Assumption
				• Kg BOD/cap/year = g BOD/cap/day x 0.001 x 365 • IPCC-provided range for BOD (g/day/person) is 35–45 for Africa. Given fecal sludge has a higher BOD content than wastewater, used a range of 40–45 for fecal sludge. • Lower end provides 35.04 Kg COD/cap/year and higher end provides 39.42 Kg COD/cap/year.
COD content of wastewater		The total quantity of organic matter requiring decomposition present in the wastewater of one person per year	Optimistic: 30.66 Pessimistic: 35.04	Sourced from IPCC-provided range of BOD for Africa (Bartram et al. 2019): • COD = 2.4 BOD • Kg BOD/cap/year = g BOD/cap/day x 0.001 x 365 • IPCC-provided range for BOD (g/day/person) is 35–45 for Africa. Given wastewater has a lower BOD content than fecal sludge, used a range of 35–40. • Lower end provides 30.66 Kg COD/cap/year and higher end provides 35.04 Kg COD/cap/year
Percentage of COD content in fecal sludge requiring anaerobic decomposition		Proportion of the fecal sludge requiring anaerobic decomposition	Optimistic: 70% Pessimistic: 100%	Optimistic value sourced from (Johnson et al. (2022). Pessimistic value sourced from FSG key informant interviews (KIIs).
MCF values for different containment facilities				
Septic tanks	Shared	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.50	Sourced IPCC-recommended value for septic tanks. Technology separates effluents (liquid content) from the fecal sludge and allows the floating liquid to seep out through a pipe at the top of the tank, reducing water content for shared and individual usage.
Septic tanks	Individual	The level to which the containment facility promotes anaerobic decomposition, thereby	0.50	Sourced IPCC-recommended value for septic tanks. Technology separates effluents (liquid content) from

Input Variable		Description	Value	Source/Assumption
		releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.		the fecal sludge and allows the floating liquid to seep out through a pipe at the top of the tank, reducing water content for shared and individual usage.
Dry pit latrines with unlined pits	Shared, pit below GWT	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.70	Sourced IPCC-recommended value for wet pit latrines. Unlined pits allow for water from the GWT to seep into the pits for shared and individual usage.
Dry pit latrines with unlined pits	Individual, pit below GWT	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.70	Sourced IPCC-recommended value for wet pit latrines. Unlined pits allow for water from the GWT to seep into the pits for shared and individual usage.
Dry pit latrines with unlined pits	Shared, pit above GWT	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.40	Assumed lower end of IPCC-provided range (0.4–0.6) for communal latrines in dry climates/with pits above the GWT.
Dry pit latrines with unlined pits	Individual, pit above GWT	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.10	Sourced IPCC-recommended value for latrines in dry climate/with pits above the GWT for a small number of users.
Dry pit latrines with lined pits	Shared	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.40	Assumed lower end of IPCC-provided range (0.4–0.6) for communal latrines in dry climates/with pits above the GWT.
Dry pit latrines with lined pits	Individual	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.10	Sourced IPCC-recommended value for latrines in dry climate/with pits above the groundwater table for a small number of users.
Wet pit latrines	Shared	The level to which the containment facility promotes anaerobic decomposition, thereby	0.70	Sourced IPCC-recommended value for wet pit latrines. No provision for the poured water to escape the pit,

Input Variable		Description	Value	Source/Assumption
		releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.		making it highly anaerobic for shared and individual usage. Even in the case of unlined pits in dry soils, the continued use of water for cleansing will lead to retention of water within the pit and in the surrounding soil.
Wet pit latrines	Individual	The level to which the containment facility promotes anaerobic decomposition, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.70	Sourced IPCC-recommended value for wet pit latrines. No provision for the poured water to escape the pit, making it highly anaerobic for shared and individual usage. Even in the case of unlined pits in dry soils, the continued use of water for cleansing will lead to retention of water within the pit and in the surrounding soil.
Treatment of emptied fecal sludge and wastewater				
Total methane recovered by FSTP		The total amount of CH_4 recovered (captured and processed) in a year by the treatment plant	0	Assumed to be 0 as it appears that most treatment plants in LMIC contexts do not capture or process methane as per FSG KIIs.
Total methane recovered by WWTP		The total amount of CH_4 recovered (captured and processed) in a year by the treatment plant	0	Assumed to be 0 as it appears that most treatment plants in LMIC contexts do not capture or process methane as per FSG KIIs.
MCF of first stage (thickening tanks) at FSTP		The level to which the process used in the treatment stage is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.90	Sourced from Kampala study (Johnson et al. 2022).
COD reduction of first stage (thickening tanks) at FSTP		The level to which organic content in the inflowing fecal sludge is decomposed during the treatment stage	60%	Sourced from Kampala study (Johnson et al. 2022).
Percent of effluent content separated out from fecal sludge in stage 1		The total effluent content entering each stage of the treatment process	20%	Sourced from Kampala study (Johnson et al. 2022).
MCF of second stage (drying beds) at FSTP		The level to which the process used in the treatment stage is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition	0.25	Sourced from Kampala study (Johnson et al. 2022).

Input Variable	Description	Value	Source/Assumption
COD reduction of second stage (drying beds) at FSTP	The level to which organic content in the inflowing fecal sludge is decomposed during the treatment stage	50%	Sourced from Kampala study (Johnson et al. 2022).
Percent of effluent content separated out from fecal sludge in stage 2	The total effluent content entering each stage of the treatment process	0%	Sourced from Kampala study (Johnson et al. 2022).
MCF of third stage (storage) at FSTP	The level to which the process used in the treatment stage is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition	0.25	Sourced from Kampala study (Johnson et al. 2022).
COD reduction of third stage (storage) at FSTP	The level to which organic content in the inflowing fecal sludge is decomposed during the treatment stage	70%	Sourced from Kampala study (Johnson et al. 2022).
Percent of effluent content separated out from fecal sludge in stage 3	The total effluent content entering each stage of the treatment process	0%	Sourced from Kampala study (Johnson et al. 2022).
MCF of first stage (anaerobic ponds) at WWTP	The level to which the process used in the treatment stage is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition.	0.80	Sourced from IPCC-recommended value for anaerobic deep lagoon.
COD reduction of first stage (anaerobic ponds) at WWTP	The level to which organic content in the inflowing wastewater is decomposed during the treatment stage	60%	Sourced from Kampala study (Johnson et al. 2022).
Percent of sludge content separated out from wastewater in stage 1	The total fecal sludge content entering each stage of the treatment process	50%	Sourced from Kampala study (Johnson et al. 2022).
MCF of second stage (facultative ponds) at WWTP	The level to which the process used in the treatment stage is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition	0.20	Sourced from IPCC-recommended values for anaerobic shallow lagoons and facultative lagoons.
COD reduction of second stage facultative ponds) at WWTP	The level to which organic content in the inflowing wastewater is decomposed during the treatment stage	60%	Sourced from Kampala study (Johnson et al. 2022).

Input Variable	Description	Value	Source/Assumption
Percent of sludge content separated out from wastewater in stage 2	The total fecal sludge content entering each stage of the treatment process	50%	Sourced from Kampala study (Johnson et al. 2022).
MCF of third stage (drying beds) at WWTP	The level to which the process used in the treatment stage is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition	0.25	Sourced from Kampala study (Johnson et al. 2022).
COD reduction of third stage (drying beds) at WWTP	The level to which organic content in the inflowing fecal sludge is decomposed during the treatment stage	50%	Sourced from Kampala study (Johnson et al. 2022).
Unsafe discharge of emptied fecal sludge and wastewater, and open defecation			
MCF of unsafe discharge	The level to which the decomposition process is anaerobic, thereby releasing methane. 0 denotes full aerobic decomposition and 1 denotes full anaerobic decomposition	Optimistic: 0.11 Pessimistic: 0.20	Sourced IPCC-recommended value for Tier 1 discharge (Bartram et al. 2019) for when discharge pathway is unknown for optimistic case. Assumed slightly higher value for pessimistic case based on KII recommendation that IPCC underestimates the emissions from unsafe discharge.

STEP 4: DEFINING FUTURE SCENARIO

The team projected emissions from sanitation in 2030 to understand the expected trend of methane emissions from sanitation systems as a proportion of total anthropogenic methane emissions in the region. This allowed the team to compare the key drivers of emissions between 2020 and 2030 and understand where interventions are required.

For 2030, the team projected emissions assuming growth in urban population and achievement of SDG 6.2,[29] using the pessimistic 2020 scenario as the baseline. Using the pessimistic case as the baseline allows planning for the worst-case scenario.

The team modeled 2030 emissions based on the following two trends (a population-level trend and a sanitation sector-level trend) that are applicable for most LMIC contexts:

- Urban population growth (United Nations Department of Economic and Social Affairs 2018; World Bank n.d.); and
- Achievement of SDG 6.2 which, although unlikely to be achieved by 2030 given the current progress, represents the directional push in the sector, and includes:
    - One hundred percent use of only individual and improved containment facilities, and an end to open defecation; and
    - One hundred percent treatment coverage of all emptied fecal sludge and wastewater.

The team sourced data on urban population growth in SSA based on urban population data provided by the World Bank (World Bank n.d.). The team changed variables for the population split across containment facilities based on the requirements mentioned for the SDGs. Table 5 provides the list of variables that were modified, their values in 2020 and 2030, and the assumptions the team made to modify values.

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[29] SDG 6.2 states, "by 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation, paying special attention to the needs of women and girls and those in vulnerable situations."

Table 5. Inputs modified for 2030 scenario

Input Variable		2020 Value	2030 Value	Source/Assumption
Total population		435,817,915	667,280,810	Assumed growth rate from 2020–2030 is the same as that for 2010–2020 years (53.11%). The growth rate for 2010–2020 was calculated as the compounded effect of yearly SSA urban growth rate as per (World Bank n.d.).
Population using sewered system		5.63%	5.63%	Assumed unchanged since SDG makes no recommendation on using non-sewered vs. sewered systems.
Population using non-sewered system		93.27%	94.37%	The percentage of the population practicing open defecation in 2020 is assumed to shift to non-sewered systems in 2030; open defecation is assumed to be zero as per SDGs.
Population practicing open defecation		1.10%	0%	Assumed to be zero as per SDGs.
Proportion of wastewater treated		33.33%	100%	All wastewater is assumed to be treated, as unsafe discharge is assumed to be 0 as per SDGs.
Proportion of wastewater unsafely discharged		66.67%	0%	Assumed to be zero as per SDGs.
Proportion of emptied fecal sludge treated		22.22%	100%	All emptied fecal sludge is assumed to be treated, as unsafe discharge is assumed to be zero as per SDGs.
Proportion of emptied fecal sludge unsafely discharged		77.78%	0%	Assumed to be zero as per SDGs.
Proportion of population with unemptied, non-sewered systems using each type of containment facility				
Septic tanks	Shared	9.54%	0.00%	Assumed to be zero as per SDGs.
Septic tanks	Individual	15.95%	25.50%	Assumed that all shared septic tank users become individual septic tank users (from 2020 pessimistic case).
Dry pit latrines with unlined pits	Shared, pit below GWT	8.16%	0.00%	Assumed shared usage to be zero as per SDGs. Assumed all unimproved toilet users shift to improved toilets (from 2020 pessimistic case), leading to an increase in the users of lined pits. Model assumes that 25% of users with improved toilets have lined pits. The shift from unimproved to improved systems will lead to an increase in usage of lined pits by 25% of the users that make this shift.[30]

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[30] For dry pit latrines, VIP latrines, composting toilets, and pit latrines with a slab, from DHS datasets were classified as "improved toilets." Pit latrines without a slab/open pits were classified as "unimproved toilets."

Input Variable		2020 Value	2030 Value	Source/Assumption
				Overall usage of dry pit latrines assumed unchanged as SDG makes no recommendation on use of water for latrines.
Dry pit latrines with unlined pits	Individual, pit below GWT	6.37%	13.16%	Assumed shared usage to be zero as per SDGs. Assumed all unimproved toilet users shift to improved toilets (from 2020 pessimistic case), leading to an increase in the users of lined pits. Model assumes that 25% of users with improved toilets have lined pits. The shift from unimproved to improved systems will lead to an increase in usage of lined pits by 25% of the users that make this shift.[31] Overall usage of dry pit latrines assumed unchanged as SDG makes no recommendation on use of water for latrines.
Dry pit latrines with unlined pits	Shared, pit above GWT	21.12%	0.00%	Assumed shared usage to be zero as per SDGs. Assumed all unimproved toilet users shift to improved toilets (from 2020 pessimistic case), leading to an increase in the users of lined pits. Model assumes that 25% of users with improved toilets have lined pits. The shift from unimproved to improved systems will lead to an increase in usage of lined pits by 25% of the users that make this shift.[32] Overall usage of dry pit latrines assumed unchanged as SDG makes no recommendation on use of water for latrines.
Dry pit latrines with unlined pits	Individual, pit above GWT	15.71%	33.19%	Assumed shared usage to be zero as per SDGs. Assumed all unimproved toilet users shift to improved toilets (from 2020 pessimistic case), leading to an increase in the users of lined pits. Model assumes that 25% of users with improved toilets have lined pits. The shift from unimproved to improved systems will lead to an increase in usage of lined pits by 25% of the users that make this shift.[33]

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[31] For dry pit latrines, VIP latrines, composting toilets, and pit latrines with a slab, from DHS datasets were classified as "improved toilets." Pit latrines without a slab/open pits were classified as "unimproved toilets."

[32] For dry pit latrines, VIP latrines, composting toilets, and pit latrines with a slab, from DHS datasets were classified as "improved toilets." Pit latrines without a slab/open pits were classified as "unimproved toilets."

[33] For dry pit latrines, VIP latrines, composting toilets, and pit latrines with a slab, from DHS datasets were classified as "improved toilets." Pit latrines without a slab/open pits were classified as "unimproved toilets."

Input Variable		2020 Value	2030 Value	Source/Assumption
				Overall usage of dry pit latrines assumed unchanged as SDG makes no recommendation on use of water for latrines.
Dry pit latrines with lined pits	Shared	6.23%	0.00%	Assumed shared usage to be zero as per SDGs. Assumed all unimproved toilet users shift to improved toilets (from 2020 pessimistic case), leading to an increase in the users of lined pits. Model assumes that 25% of users with improved toilets have lined pits. The shift from unimproved to improved systems will lead to an increase in usage of lined pits by 25% of the users that make this shift.[34] Overall usage of dry pit latrines assumed unchanged as SDG makes no recommendation on use of water for latrines.
Dry pit latrines with lined pits	Individual	4.21%	15.45%	Assumed shared usage to be zero as per SDGs. Assumed all unimproved toilet users shift to improved toilets (from 2020 pessimistic case), leading to an increase in the users of lined pits. Model assumes that 25% of users with improved toilets have lined pits. The shift from unimproved to improved systems will lead to an increase in usage of lined pits by 25% of the users that make this shift.[35] Overall usage of dry pit latrines assumed unchanged as SDG makes no recommendation on use of water for latrines.
Wet pit latrines	Shared	7.22%	0.00%	Assumed to be zero as per SDGs.
Wet pit latrines	Individual	5.48%	12.70%	Assumed that all shared wet pit latrine users become individual wet pit latrine users (from 2020 pessimistic case).

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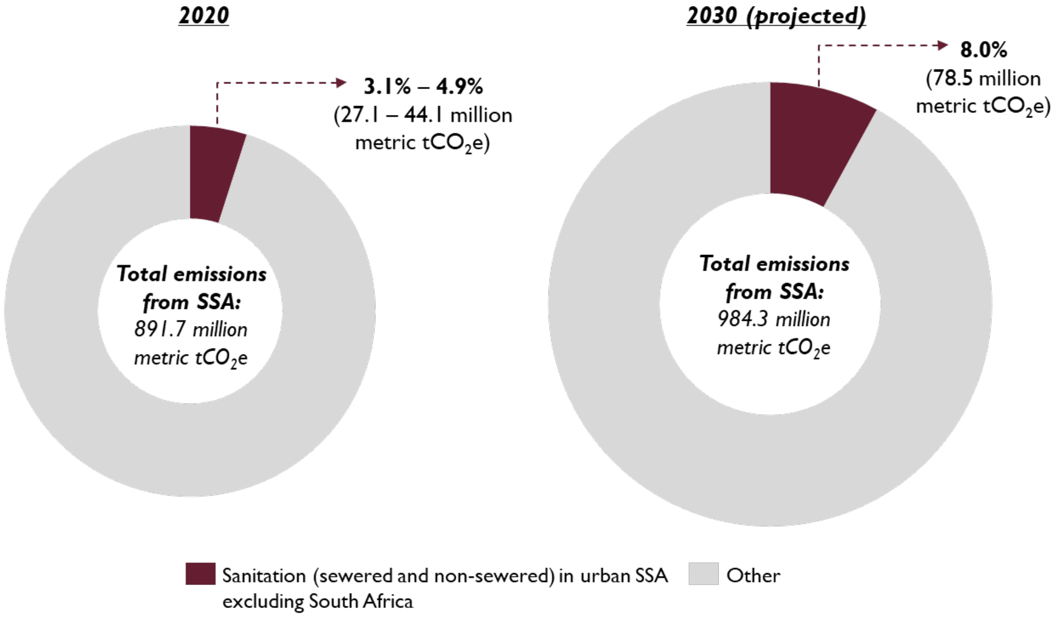
[34] For dry pit latrines, VIP latrines, composting toilets, and pit latrines with a slab, from DHS datasets were classified as "improved toilets." Pit latrines without a slab/open pits were classified as "unimproved toilets."

[35] For dry pit latrines, VIP latrines, composting toilets, and pit latrines with a slab, from DHS datasets were classified as "improved toilets." Pit latrines without a slab/open pits were classified as "unimproved toilets."

APPENDIX B: ESTIMATING SSA METHANE EMISSIONS IN 2020 AND 2030

This section presents the approach used for calculating the total anthropogenic methane emissions in sub-Saharan Africa (SSA) in 2020 and 2030 (refer to Figure 30).

Figure 30. Estimated emissions from sanitation in urban SSA as a proportion of total annual anthropogenic methane emissions in SSA



Acronyms: SSA: sub-Saharan Africa

Note: The size of the donut charts (reflecting the total emissions from SSA) in 2020 and 2030 is approximately to scale.

TOTAL ANTHROPOGENIC METHANE EMISSIONS IN 2020

The team calculated the **total anthropogenic methane emissions** in 2020 (891.7 million metric tons [t] CO_2e) by adding emission values from two sources:

- Estimated value of total anthropogenic annual methane emissions in 2020 as per McKinsey and Company (2021) = 850 million metric tCO_2e.[36]

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[36] All numbers from McKinsey and Company (2021) were converted from metric megaton (Mt) to metric tCO_2e by multiplying the number in the study by methane's carbon dioxide equivalent, which is 25 as per the United States Environmental Protection Agency (2022a).

- Modeled[37] value of methane emissions from non-sewered sanitation systems and open defecation in urban SSA[38] in 2020 (as these were not included in the value estimated by McKinsey and Company [2021]) = 41.7 million metric tCO_2e.

TOTAL ANTHROPOGENIC METHANE EMISSIONS IN 2030

The team estimated the **projected total annual anthropogenic methane emissions in 2030** (984.3 million metric tCO_2e) by adding emission values from two sources:

- Estimated value of projected total anthropogenic annual methane emissions in SSA in 2030 = 915 million metric tCO_2e, derived from McKinsey and Company (2021).
    - McKinsey and Company (2021) stated projected global methane emissions for 2030 as 10,500 million metric tCO_2e.
    - The team derived projected emissions for SSA in 2030, assuming that the share of SSA emissions as a proportion of the total emissions is the same as that in 2020.
- Modeled value of projected methane emissions from non-sewered sanitation systems and open defecation in urban SSA in 2030 (as these were not included in the value estimated by McKinsey and Company (2021) = 69.3 million metric tCO_2e.

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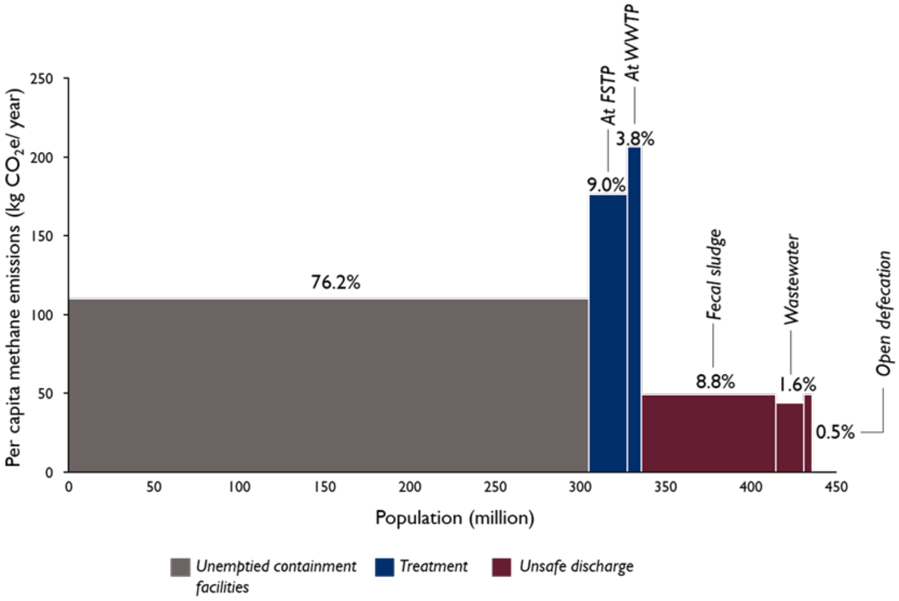
[37] For the approach of arriving at the modeled emissions in this study, refer to Appendix A.

[38] Urban SSA excludes South Africa in this appendix.

APPENDIX C: SPLIT OF EMISSIONS FROM UNEMPTIED CONTAINMENT FACILITIES

The gray bar in Figure 31 presents the annual per capita methane emissions and the population using unemptied containment facilities.

Figure 31. Annual per capita methane emissions (kgCO$_2$e/year) and population split (million) by source of emissions (2020)



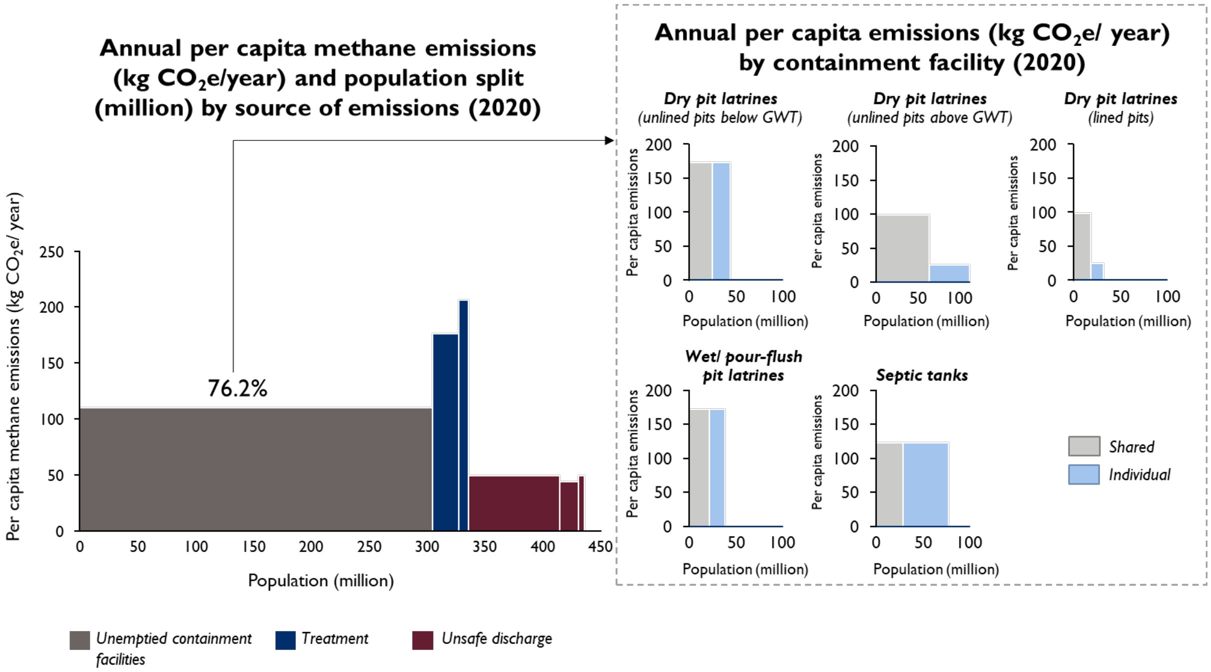
Acronyms: FSTP: fecal sludge treatment plant; WWTP: wastewater treatment plant

Notes:

- *Percentage values denote the contribution of each source to the total methane emissions. The height of the bars denotes the per capita emissions from each source, while the width denotes the population by the source of emissions. The area under the bar represents the total emissions from each source.*
- *The sum of the contribution of individual sources may not add up to 100 percent due to rounding.*

The per capita emissions from unemptied containment facilities are calculated as the weighted average (based on population) of annual per capita emissions from each type of containment facility. Figure 32 presents the per capita emissions split by containment facility.

Figure 32. Split of annual per capita emissions (kgCO_2e/year) by containment facility (2020)



Acronyms: GWT: groundwater table; CO_2e: carbon dioxide equivalent

Source: Based on FSG analysis.

Notes: The percentage value denotes the contribution of unemptied containment facilities to the total methane emissions. The height of the bars denotes the per capita emissions from each source, while the width denotes the population by the source of emissions. The area under the bar represents the total emissions from each source.

APPENDIX D: TREATMENT TECHNOLOGIES

The study scanned the following longlist of ~40 aerobic and anaerobic treatment technologies and their variants that are used for fecal sludge and wastewater treatment.

Table 6. Treatment technologies by waste stream

Technology Variant	**Aerobic technology (yes/no)**
Fecal sludge treatment	
Mechanical separation	
Screw press	Yes
Belt press	Yes
Unplanted drying beds	Yes
Gravity separation	
Settling and thickening tank	No
Anaerobic settlers	No
Imhoff tank	No
Aerobic digester	Yes
Anaerobic digester	No
Anaerobic stabilization reactor	No
Upflow anaerobic sludge blanket (UASB)	No
Pyrolysis	
Omni Processor	Yes
Mechanical dewatering	
Screw press	Yes
Belt press	Yes
Centrifuge	Yes
Filter press	Yes
Drying beds	
Planted drying beds	Yes
Unplanted drying beds	Yes
Solar drying	
Greenhouse roofs	Yes
Thermal drying	
Pelletizer	Yes
Pasteurization	Yes
Thermal treatment	
Solar pasteurization	Yes
Thermal pasteurization	Yes
Biological treatment	
Co-composting	Yes
Black soldier fly treatment	Yes
Chemical treatment	
Lime stabilization	Yes
Mechanical treatment	
Briquetting	Yes
Storage and further drying	Yes
Wastewater treatment	
Anaerobic settlers	No

Technology Variant	**Aerobic technology (yes/no)**
Anaerobic ponds	No
Clarifiers	Yes
Passive technologies	
Constructed wetlands	Yes
Aerobic digesters	Yes
Anaerobic filters	No
Anaerobic digesters	No
Anaerobic baffled reactor	No
Active technologies	
Activated sludge processes	Yes
UASB	No
Anaerobic pond	No
Facultative ponds	No
Mechanical dewatering	
Screw press	Yes
Belt press	Yes
Centrifuge	Yes
Filter press	Yes
Secondary clarifier	Yes
Drying beds	
Unplanted drying beds	Yes
Storage and further drying	Yes
Anaerobic digesters	No
Disinfection	
Ultraviolet	Yes
Ozone	Yes
Chlorination	Yes
Maturation pond	Yes
Active filters	
Membrane-based filtration system	Yes
Pressure-activated carbon filter	Yes
Pressure sand filter	Yes
Passive filters	
Rapid sand filters	Yes
Slow sand filters	Yes
Constructed wetlands	Yes

Note: Technologies were marked as aerobic or anaerobic based on expert validation.

APPENDIX E: KEY INFORMANTS

The research team would like to thank the following people for serving as key informants for the research or for leading us to the interviewed key informants:

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GLOSSARY OF TERMS

Terms	Definition
General Terms	
Aerobic decomposition	Decomposition of organic matter by microbial action in the presence of oxygen.
Anaerobic decomposition	Decomposition of organic matter by microbial action in the absence of oxygen, which generates methane as a by-product.
Anthropogenic methane	Methane emitted from human-influenced sources like landfills, oil and natural gas systems, agricultural activities, coal mining, and waste management.
Biological oxygen demand (BOD)	The amount of oxygen consumed by bacteria and other microorganisms while they decompose organic matter under aerobic conditions at a specified temperature. The BOD value serves as a proxy for the amount of organic content in waste.
Capture	Storage, processing, and usage of the methane (biogas) generated from an anaerobic treatment process. The three methods of methane capture from treatment plants include flaring the biogas, using it to power the facility, or distributing it for use outside the facility.
Carbon credit	A permit that allows governments, businesses, or private individuals to produce a certain amount of carbon emissions and which can be traded if the full allowance is not used. One credit permits the emission of one ton of CO2 or the equivalent in other greenhouse gases.
Carbon sequestration	Process of capturing and storing atmospheric CO2 long-term in plants, soil, geologic formations, and the ocean to reduce the amount of CO2 in the atmosphere.
Co-treatment	Treatment of multiple different waste streams (e.g., kitchen waste with fecal waste), usually done to either fully utilize the capacity of a treatment plant or balance the nutrients of the waste for proper decomposition.
Flaring	Burning of methane produced as a by-product of waste treatment to convert it to CO2, which has lower global warming potential than methane.
Global warming potential (GWP)	Measure of how much energy the emissions of 1 ton of methane will absorb over a given period of time, relative to the emissions of 1 ton of CO2 (CO_2). The GWP of methane is 25, meaning a discharge of a ton of methane is equivalent to emitting 25 tons of CO2.
Low- and middle-income countries (LMIC)	Countries with low-income or middle-income economies, defined by the World Bank as countries with a gross national income per capita of less than USD 12,695 (as of 2021).
Methane correction factor (MCF)	Measure of the level to which a system is anaerobic. Value of 0 denotes complete aerobic decomposition, and a value of 1 denotes full anaerobic decomposition.
Mitigation	Reduction in the generation of methane.
Organic strength	The amount of dissolved or suspended carbon-based (i.e., organic) compounds in fecal sludge or wastewater that can be oxidized biologically and determine the BOD of the waste to be treated.
Sanitation Terms	
Activated sludge process (ASP)	Multi-chamber unit that uses highly concentrated microorganisms either freely suspended or attached to a biofilm to aerobically decompose dissolved organic matter in wastewater after the solid-liquid separation stage.

Terms	Definition
Anaerobic biogas digester (ABD)	Sealed, oxygen-free tanks that facilitate the natural anaerobic degradation of fecal sludge, after the solid-liquid separation stage, by letting the waste sit and get decomposed.
Anaerobic pond	Static water bodies used to reduce BOD of wastewater at the solid-liquid separation stage through sedimentation.
Black soldier fly (BSF) larvae treatment	Aerobic treatment facility wherein BSF larvae feed on fecal waste, grow in size, and reduce the wet weight of the waste. Due to the high protein and fat content of the fed larvae, they can be used as animal feed post-treatment.
Clarifier	Tank used for separating solid and liquid content of wastewater by allowing the solids to settle at the bottom of the tank.
Composting	Aerobic treatment process wherein fecal waste is decomposed under controlled conditions such as temperature, moisture, aeration, and carbon to nitrogen (C: N) ratio, producing compost as a stable end-product.
Composting toilet	Technology that treats human waste through aerobic decomposition in a unit close to the containment facility and creates compost as a reuse product.
Constructed wetlands	Fabricated water-based treatment systems that comprise a physical filter bed and biological ecosystem of aquatic plants and microbial communities used to decompose the organic matter of wastewater after the solid-liquid separation stage.
Container-based sanitation (CBS)	End-to-end service provided across all stages of the sanitation system, wherein sludge is hygienically collected from toilets designed with sealable and removable containers, taken for treatment, and safely disposed of or reused.
Containment	A stage in the sanitation system involving a combination of technologies used for the collection and storage of human waste near the defecation site, in facilities used by individual or multiple households.
Dehydration vault	Substructure technology for dry containment facilities that uses ventilation and materials like lime or ash to reduce water content in the pit.
Discharge	A stage in the sanitation system during which waste is ultimately returned to the environment.
Drying beds	Open spaces used for dewatering fecal sludge after the heavy solids get settled during the solid-liquid separation stage. They are made permeable through drainage layers, with a lined cement bottom and perforated pipes attached at the base.
Emptying service	Emptying and transportation of fecal sludge from non-sewered containment facilities to the disposal site.
Facultative pond	Large, fabricated water bodies used for the sedimentation of wastewater and reduction of the organic content through simultaneous anaerobic and aerobic digestion at different depths of the pond.
Fecal sludge	Solid and liquid waste including urine, fecal matter, and flush and cleansing water coming from non-sewered toilets (e.g., pit latrines, septic tanks).
Incinerating toilet	Technology that treats human waste by burning it in a unit close to the containment facility and converting the waste to ash and CO2.
In-situ biogas digester	Technology that treats human waste through anaerobic decomposition in a unit close to the containment facility to produce methane (biogas) as a reuse product.
Integrated sanitation system	Sanitation systems that connect the containment, transfer, and treatment stages using common infrastructure through technologies and/or services combining the containment, transfer, and treatment stages.

Terms	Definition
Lined pit	Substructure of a pit latrine that is lined with bricks, sand, cement, or other durable materials to provide stability to the pit structure.
Non-sewered sanitation	A sanitation system where waste collected at the defecation site is stored at (or near) the defecation site and then transported to the disposal site by emptying service providers.
Omni Processor (OP)	Compact machine for treating fecal sludge that combines standard processes into a single system, including drying the sludge, incinerating the dried sludge (along with the discharge of filtered emissions), and producing reuse products like power, fly ash, and drinking water.
Open defecation	The practice of defecating in the open, such as in fields, bushes, forests, ditches, streets, canals, or other open spaces.
Raised pit latrine	Substructure technology that is built fully or partially above ground to prevent water from entering the pit in areas with high groundwater tables.
Safe discharge	Discharge of human waste into the environment (e.g., water bodies) after treatment, which does not contaminate the body receiving the discharge as the hazardous compounds are removed during treatment.
Safely managed sanitation	A method of managing human waste wherein containment facilities used separate the waste from human contact hygienically and are not shared with other households and where the collected waste is safely treated in situ or at a facility.
Sanitation system	Series of technologies and services for the management of sanitation waste. Sanitation systems (sewered and non-sewered) include four discrete stages—containment, transfer, treatment, and discharge.
Scheduled emptying	Periodic emptying service model wherein containment facilities are emptied as per a pre-determined route and schedule.
Sewered sanitation	A sanitation system in which the waste collected at the defecation site is connected to the disposal site through a sewerage network.
Substructure	Technology used to store the waste collected by the user interface in the containment facility; it can include pits or tanks and can be lined (with cement or bricks) or unlined.
Thickening tank	Sealed tank used at the solid-liquid separation stage for thickening the sludge by removal of the liquid content.
Transfer	A stage in the sanitation system including the technology or service used to transport the waste from the containment site to the disposal site.
Treatment	A stage in the sanitation system including a series of technologies, typically at a treatment facility or plant located away from the containment facility, used for converting the waste to non-hazardous compounds safe for discharge into the environment.
Treatment facility	Unit comprising a series of one or more treatment technologies.
Treatment technology	Machinery, processes, or methods used for converting wastewater and fecal sludge to non-hazardous compounds that are safe for discharge into the environment.
Unlined pit	Substructure of a pit latrine without any reinforcing material (such as bricks, sand, or cement) lining it.
Unsafe discharge	Discharge of human waste into the environment (e.g., water bodies) without prior treatment, which contaminates the body receiving the discharge, leading to public health risks.

Terms	Definition
Upflow anaerobic sludge blanket	Machine used to anaerobically decompose the dissolved or suspended organic matter in wastewater post solid-liquid separation, by using power to move wastewater up through a microbial layer called the sludge blanket.
Urine-diverting dry toilet (UDDT)	Non-sewered containment facility that has a divider in the interface to separate the urine from the feces before entering the pit.
User interface	Technology with which the user comes in contact during defecation at the containment facility; it can include the toilet, pan, or urinal used to collect the waste and have wet or dry flushing and cleansing mechanisms.
Wastewater	Domestic waste coming from sewered toilets including urine, fecal matter, flush and cleansing water along with non-sanitation waste (e.g., bath and kitchen drain water) flowing into the sewerage pipes.

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