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Whole-system analysis reveals high greenhouse-gas emissions from citywide sanitation in Kampala, Uganda

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Global estimates of emissions of greenhouse gasses do not take into account the complex service chain in rapidly growing cities in low- and middle-income countries. This paper presents an end-to-end analysis to estimate emissions from all stages of the sanitation-service chain, using Kampala in Uganda as an example. We show that emissions associated with long periods of storage of faecal waste in sealed anaerobic tanks (49%), discharge from tanks and pits direct to open drains (4%), illegal dumping of faecal waste (2%), leakage from sewers (6%), wastewater bypassing treatment (7%) and uncollected methane emissions at treatment plants (31%), are contributing to high levels of greenhouse-gas emissions. Sanitation in Kampala produces 189 kt CO_2 e per year, which may represent more than half of the total city-level emissions. Significant further empirical and modelling work is required to update estimates of greenhouse-gas emissions from sanitation systems globally.

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Biological decomposition of human faeces produces greenhouse gases (GHGs), including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2) when faecal sludge or wastewater is contained for sufficient time to allow microbial digestion. Indirect emissions arise from burning of fossil fuels to run sanitation operations and as embedded carbon in infrastructure.

Emissions from sanitation are being underestimated[1,2]. Most published literature focuses on wastewater-treatment technologies and discharge[3–8], with only a few estimating emissions from onsite containment[9,10]. No attempt has yet been published that considers both direct and indirect emissions from an entire sanitation system that combines sewers and onsite sanitation systems, along the whole sanitation-service chain from containment, up to treatment.

The Intergovernmental Panel on Climate Change (IPCC) models greenhouse-gas emissions from sanitation under the category of ‘waste’[11], and makes a link to ‘agricultural associated emissions’ because of the use of manure for fertiliser. The 2006 IPCC methods document proposes methane-correction factors (MCF) for the most common wastewater-treatment options, for ‘septic tanks’ and for four types of pit latrines based on expert judgement[12]. IPCC suggests that emission rates for methane can be linked to national income—with lower emission rates suggested for low- and middle-income countries. No guidance is provided for estimating nitrous oxide emissions from any systems beyond wastewater-treatment plants.

The 2019 IPCC update includes a few additional sanitation options and pathways, but there is insufficient information to enable a full modelling of potential emissions in a typical city with a mix of onsite and offsite sanitation systems managed imperfectly[13]. This affects the reliability of national estimates of emissions from sanitation. In this paper, we propose a framework that could be used to estimate the complete emission profile for a city-sanitation system, including direct and indirect emissions, from both onsite and offsite services, along the entire sanitation-service chain.

We estimated GHG emissions along the sanitation-service chain, including containment (at the toilet), emptying and transport and treatment. Three broad categories of emissions were considered: (a) direct emissions from faecal sludge and/or wastewater that is in the process of stabilisation; (b) operational emissions associated with the management, movement and aeration of faecal sludge and/or wastewater; and (c) embedded carbon entrained in constructed infrastructure (Table 1). We did not include emissions arising from downstream disposal or reuse of sludge or effluent after treatment. Reuse of treated sludge or effluent, for example, in agriculture, offsets emissions from other sources; the calculation of these offsets falls outside the purview of this paper.

We present the first attempt to make such an analysis using the city of Kampala as an example. Kampala was selected as it has good data availability and is served by both on-site (78%) and sewer-based (22%) sanitation. A summary of the sanitation system in Kampala is shown in Fig. 1. We used the SFD estimates for the proportion of the population whose faecal waste flows along each pathway, and used the 2018 estimated population of 2.25 million for the city as a whole. The general method is summarised in Supplementary Note 1.

The main finding is that for Kampala, sanitation produces 189 kt CO_2 e per year and may represent more than half of total city-level emissions. There are substantial opportunities to reduce overall emissions through improved management of sanitation.

Results

Resultant emission rates from typical on-site sanitation-containment systems. Per-capita-modelled direct methane- and

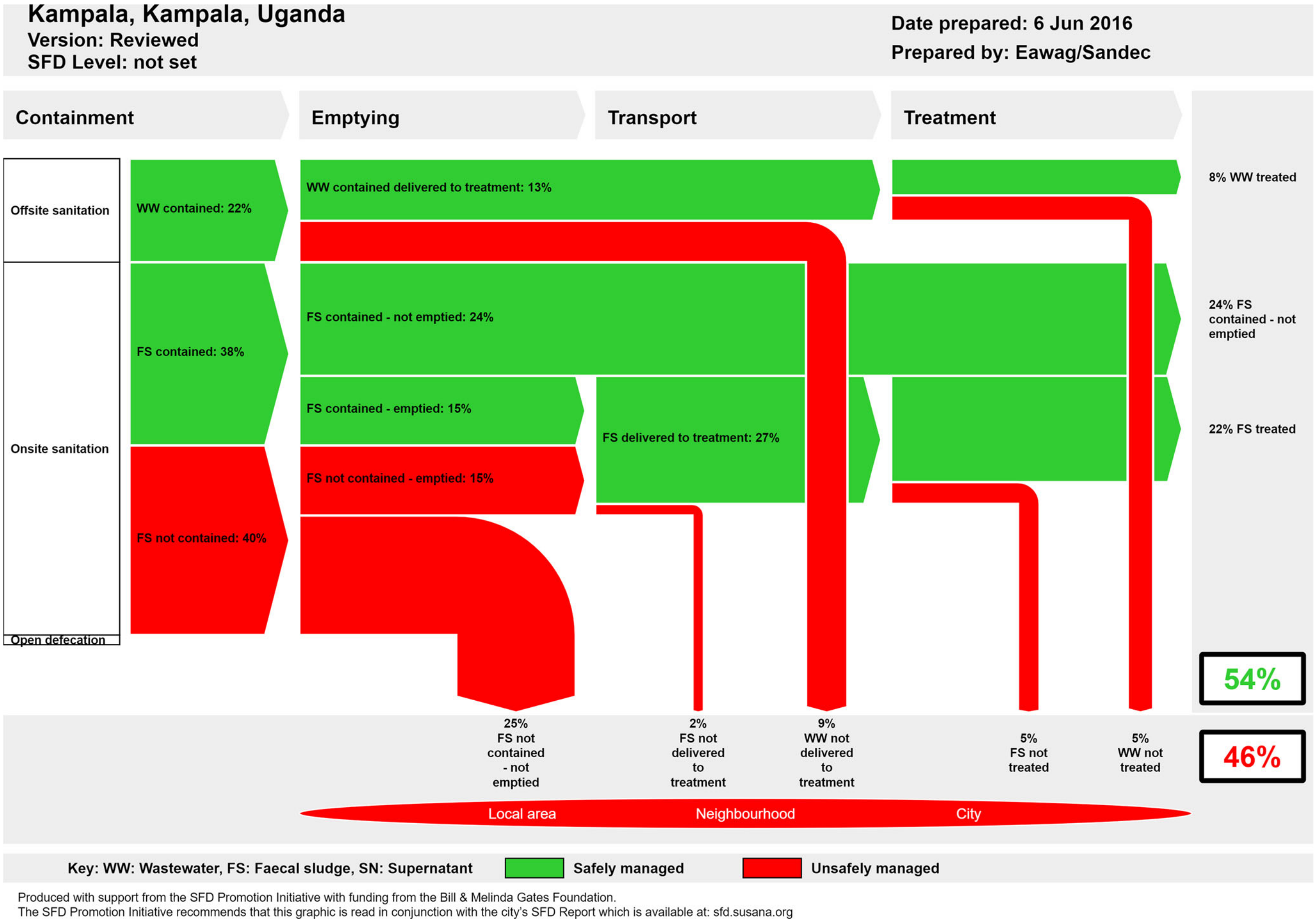
Table 1 Principal sources of greenhouse gas emissions from whole-chain sanitation systems (a) onsite systems, (b) offsite systems.

Sanitation service chain element	Category of emissions Containment	Emptying/ emptying and transport	Treatment	Disposal [a]
(a) Onsite systems (pit latrines, septic tanks and containers with road based transport)				
Direct	D1: CH_4 and N_2O from pits and tanks	D2: n/a	D3: CH_4 and N_2O from FSTP/ WWTP [b]	D4: CH_4 and N_2O from discharge/ reuse
Operational	O1: n/a	O2: CO_2 from truck fuel combustion	O3: CO_2 FSTP/WWTP energy use [b]	O4: n/a
Embedded carbon	E1: Materials to construct pits and tanks	E2: n/a	E3: materials in construction of FSTP/WWTP [b]	E4: n/a
(b) Offsite systems (with sewer based transport)				
Direct	D1: n/a	D2: CH_4 and N_2O from in-sewer wastewater	D3: CH_4 and N_2O from FSTP/ WWTP [b]	D4: CH_4 and N_2O from discharge/ reuse
Operational	O1: n/a	O2: CO_2 from pumping wastewater	O3: CO_2 FSTP/WWTP energy use [b]	O4: n/a
Embedded carbon	E1: n/a	E2: materials in construction of sewerage	E3: materials in construction of FSTP/WWTP [b]	E4: n/a

Source: Authors’ own.

[a] For the purposes of this paper, emissions downstream of treatment have not been considered.

[b] FSTP –faecal sludge treatment plant, WWTP – Wastewater treatment plant. In reality many treatment plants treat both faecal sludge from onsite systems and wastewater from sewerage.



Produced with support from the SFD Promotion Initiative with funding from the Bill & Melinda Gates Foundation.
The SFD Promotion Initiative recommends that this graphic is read in conjunction with the city's SFD Report which is available at: sfd.susana.org

Fig. 1 Excreta flow diagram (SFD) for Kampala (from Schoebitz et al.[14]). Aggregated faecal flows that are safely separated (green) and not safely separated (red) from human contact at the containment, emptying, transport and treatment stages of urban sanitation as a proportion of the total faecal waste produced by the population in Kampala, Uganda. The proportion of the population using offsite (sewered) sanitation, on-site sanitation (pits and tanks) and no sanitation (open defecation) is indicated by the size of the relevant division of the white bar on the left. Proportions of faecal waste that subsequently escape into the environment are indicated by the size of the red vertical arrows showing flows that enter the local area, neighbourhood or city-level drainage system, respectively.

nitrous-oxide emission rates from typical sanitation systems in Kampala are summarised in Tables 2 and 3, in Fig. 2, and in expanded form, in Supplementary Tables 1–4. The aggregate average rate of emissions from all containment systems in the city using a population-weighted average is 58.62 kgCO_2e/capita/year for methane and 15.13 kgCO_2e/capita/year for nitrous oxide.

The total embedded carbon for containment systems was calculated to be 3.7 ktCO_2/year (Supplementary Table 6). Operational carbon for containment was assumed to be negligible.

Resultant emissions from transport. Direct emissions from faecal sludge in trucks were considered negligible due to the relatively short time that faecal matter is in the transport phase compared with the containment and treatment phases. Emissions from sewers arise from biofilms and sediments and may emit methane at high rates[14]. There is a lack of data on sewer-sedimentation rates. In view of the relatively low coverage of sewerage that reaches treatment in Kampala (13%), we excluded this source from our calculation. Embedded carbon in the sewer network accounts for 0.97 ktCO_2/year (Supplementary Table 7)

Annual operational emissions from trucking faecal sludge were very low compared with emissions from storage, at 0.52 ktCO_2/year and from pumping wastewater, 0.024 ktCO_2/year (Supplementary Table 8).

Resultant emissions from treatment. The calculations for estimates of direct emissions from the two main treatment plants are in Supplementary Tables 9–12. The total annual direct emissions from treatment are 59 ktCO_2e/year, fairly evenly distributed between the wastewater treatment and faecal-sludge-treatment processes. Direct attribution of emissions from treatment to excreta that originated in on-site and offsite systems is complicated by the fact that solid and liquid fractions are both separated and later recombined at both treatment plants. Embedded emissions from treatment were low at 0.06 ktCO_2 (Supplementary Table 13). Total operational emissions at treatment are estimated to be 2.9 ktCO_2 (Supplementary Table 14).

Summary of resultant emission rates. The emissions rates on a per-capita annual basis for key elements of the sanitation system are summarised in Table 4. Emission rates from wastewater treatment (which in Kampala are dominated by ponds and trickling filters) and from typical containment systems, are significantly higher than rates from other elements of the system.

To assess the relative importance of emissions from the different excreta pathways in Kampala, these per-capita emission rates can be combined (Fig. 3 and refer to Fig. 1).

On the left of Fig. 2 are the emissions rates for excreta that originate in onsite systems with road-based transport. These emissions are dominated by methane that is generated in anaerobic

Table 2 Methane correction factors, emissions factors and per capita methane emission rates calculated for typical types of containment systems found in Kampala based on data from Nakagiri et al.[21].

Onsite containment classification	Condition descriptor [a]		Methane correction factor (MCF)	Emission factor (EF) = B_0 x MCF [b]	Emission rate kgCH$_4$/cap/year
Unlined Pit	1	Individual or shared toilets, sludge is permanently submerged by groundwater	0.70	0.175	3.175
	2	Individual or, more commonly, shared facilities, sludge is above the groundwater table even in the rainy season, surface water runoff and washing water raise moisture content	0.35	0.0875	1.587
	3	Individual facilities, sludge is above the groundwater table during the dry season only, low levels of surface and washing water runoff, DO levels are often low.	0.25	0.0625	1.134
Lined Pit [c]	1	Shared and has never been emptied	0.50	0.1250	2.268
	2	Shared and emptied once full	0.40	0.1000	1.814
	3	Individual household and has never been emptied	0.40	0.1000	1.814
	4	Individual household and emptied once full	0.30	0.0750	1.361
Septic tanks			0.35	0.0875	1.587
Flush toilet connected to pits	1	Un-lined pits with high moisture content	0.40	0.1000	1.814
	2	Lined pits with high moisture content	0.60	0.1500	2.721
Composting latrine		Largely aerobic	0.10	0.0250	0.454
Open defecation	1	To open drains during the rainy season	0.30	0.0750	1.361
	2	To open drains during the dry season	0.20	0.0500	0.907
	3	To the open environment, largely aerobic	0.10	0.0250	0.454

[a] See Supporting Information Tables SI-01, SI-03 for more details on this table.
[b] Where B_0 is the maximum methane producing capacity kg CH$_4$/kg COD by process in the local context.
[c] Mostly infiltrating except where grey water load is very high or there is a high groundwater table.

Table 3 Modelled nitrous oxide emissions factors and per capita nitrous oxide emission rates for typical containment systems in Kampala.

Onsite containment classification	Condition descriptor [a]		Assumed EF	Emission rates kgN$_2$O/cap/year
Unlined pit	A	Groundwater table is above contained sludge, resulting in reduced nitrification on the surface	0.0050	0.0367
	B	VIP[b] latrine with increased nitrification on the surface of pits	0.0090	0.0661
	C	Simple pit, largely aerobic conditions close to the surface but not penetrating to depth	0.0065	0.0477
Lined pit[c]	A	VIP[b] latrine with enhanced nitrification at the surface	0.0100	0.0734
	B	Simple pit, largely aerobic conditions	0.0075	0.0551
Septic tanks		Surface is not exposed– assume fully anaerobic	0.0050	0.0367
Flush toilet connected to pits	A	Un-lined simple pits	0.0060	0.0441
	B	Un-lined/ infiltrating VIP [b]	0.0080	0.0587
	C	Lined simple pit with infiltration	0.0065	0.0477
	D	Lined, partially sealed, pit latrines	0.0090	0.0661
Composting latrine		Designed for aerobic decomposition, it is assumed nitrification can occur throughout the pit with some denitrification	0.0100	0.0734
Open defecation	A	Degrade in open drains in the wet season	0.0090	0.0661
	B	Degrade in open drains in the dry season	0.0080	0.0587

[a] See Supporting Information Tables SI-02, SI-04 for more details on this table.
[b] Ventilated Improved Pit Latrine.
[c] mostly infiltrating except where grey water load is very high or there is a high groundwater table.

conditions in pits and tanks, in open drains when excreta are dumped after emptying and at the treatment plant. The rate of emissions is the highest for excreta that are emptied and either taken to treatment or dumped untreated. The category ‘not safely contained at the household level’ has relatively low emissions in Kampala because most of the excreta leaving these systems are leaching into the ground with relatively low associated emission rates. On the right of Fig. 2 are the emission rates for excreta that are transported in the sewer system. Emissions are again dominated by methane. In this category, excreta that are treated have the highest emission rates due to the dominance of anaerobic treatment processes with no methane capture.

Summary emission profile for the whole city system. These pathway-based emission rates were then combined with population data from the excreta flow diagram to build up a total emission profile (Table 5, Fig. 4, and see Supplementary Tables 16, 17). Total sanitation-associated emissions in Kampala are estimated to be 189ktCO$_2$e annually.

In Fig. 4, sanitation service-chain outcomes are shown as population-weighted flow arrows based on the method described by Peal et al.[15,16] and total annual emissions by service-chain outcome and category of emission.

Direct emissions from on-site containers, and direct emissions from treatment of both wastewater and faecal sludge dominate,

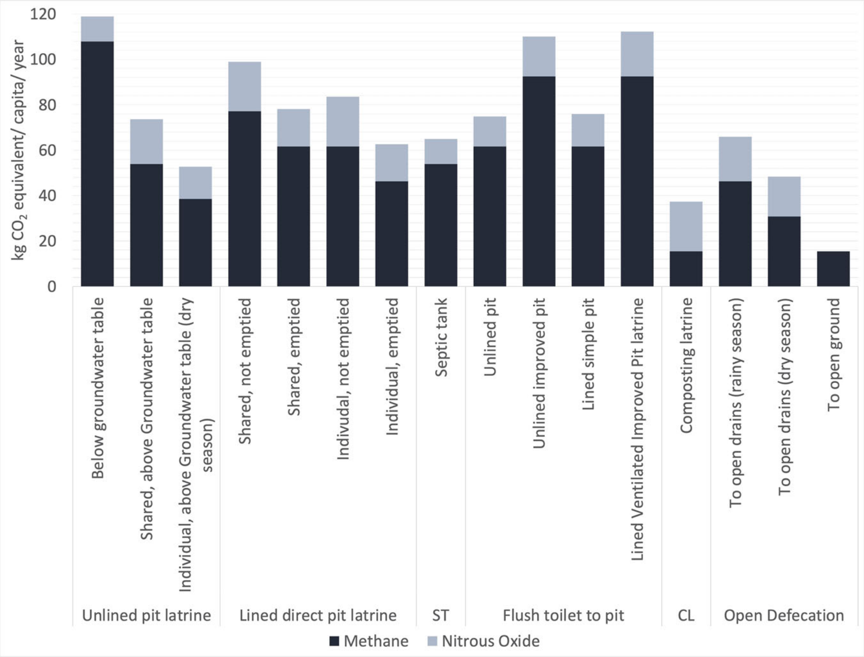


Fig. 2 Aggregate per-capita emission rates for typical sanitation containment systems in Kampala. Annual per-capita emissions of methane (black) and nitrous oxide (grey) expressed in kgCO$_2$ equivalent from containers (pits and tanks) in Kampala under observed operating conditions. Emissions rates were calculated using the IPCC method. Methane-correction factors and emissions factors were calculated using information about the extent of aerobic and anaerobic conditions observed inside containers by Nakagiri et al.[21].

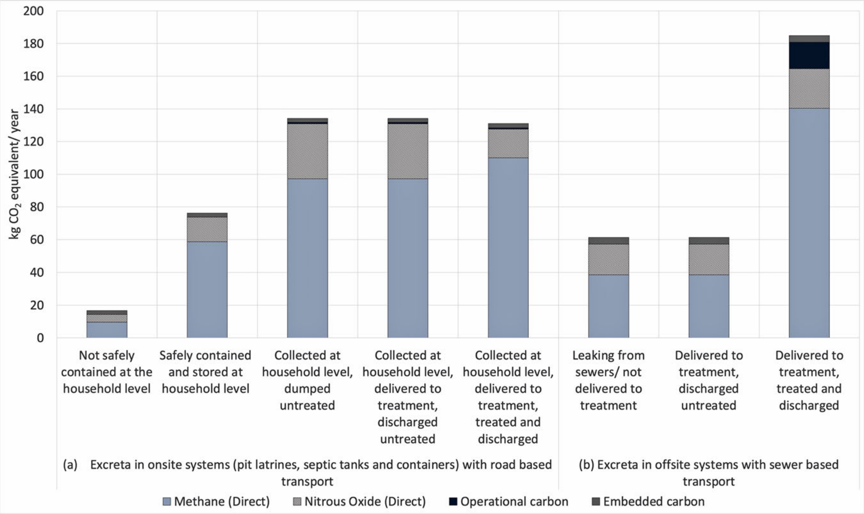


Fig. 3 Aggregate per-capita annual emissions from excreta in Kampala by sanitation pathway and ultimate fate. Vertical bars represent the total annual emissions associated with the excreta of one person travelling along the designated sanitation pathway from collection, through emptying and transport to treatment (where relevant) for on-site systems (**a**) and offsite systems (**b**). The direct emissions of methane (solid pale grey) and nitrous oxide (shaded grey), indirect operational emissions associated with trucking and pumping (black) and embedded carbon (solid dark grey) for each stage of sanitation are summed in each case. The second, fifth and eighth bars represent emissions from flows, which are safely separated from human contact (known as 'safely managed' sanitation). All other pathways result in risk of human exposure to faecal matter and leakage into the environment.

Table 4 Per capita annual emissions rates from sanitation system elements in Kampala (kgCO$_2$e/capita/year).

Sanitation service element	Direct CH$_4$	Direct N$_2$O	Operational CO$_2$	Embedded carbon	Total
Containment	58.63	15.13	-	2.43	76.18
Transport of faecal sludge in trucks	-	-	0.85	-	0.85
Treatment of faecal sludge	51.35	2.49	-	0.12	53.96
Transport of wastewater in sewers	-	-	-	4.06	4.06
Treatment of wastewater	140.27	24.34	16.16	0.02	180.79
Unsafe discharges to the environment	22.84	11.02	-	-	33.85

Table 5 Principal sources of greenhouse gas emissions from whole-chain sanitation systems (a) onsite systems, (b) offsite systems in Kampala.

Emission category[a]	Total emissions by category (tCO_2e)		
	(1) Containment	(2) Emptying/ emptying and transport	(3) Treatment
(a) Onsite systems (pit latrines, septic tanks and containers with road based transport)			
Direct (D)	Contained: 87,950	Delivered: 0	Treated: 26,650
	Not contained: 8,036	Not delivered: 2572	Not treated: 6429
Operational (O)	Contained: 0	Delivered: 556	All treatment: 0
	Not contained: 0	Not delivered: 0	
Embedded carbon (E)	All systems: 4,262	All trucks: 0	Treated: 59
			Not treated: 0
(b) Offsite systems (with sewer based transport)			
Direct (D)	Contained: 0	Delivered: 0	Treated: 29,629
	Not contained: 0	Not delivered: 11,572	Not treated: 6429
Operational (O)	Contained: 0	Delivered: 41	Treated: 2909
	Not contained: 0	Not delivered: 0	Not treated: 0
Embedded carbon (E)	All systems: 0	All sewers: 2011	Treated: 3
			Not treated 0

[a] Details of emissions categories are in Table 1.

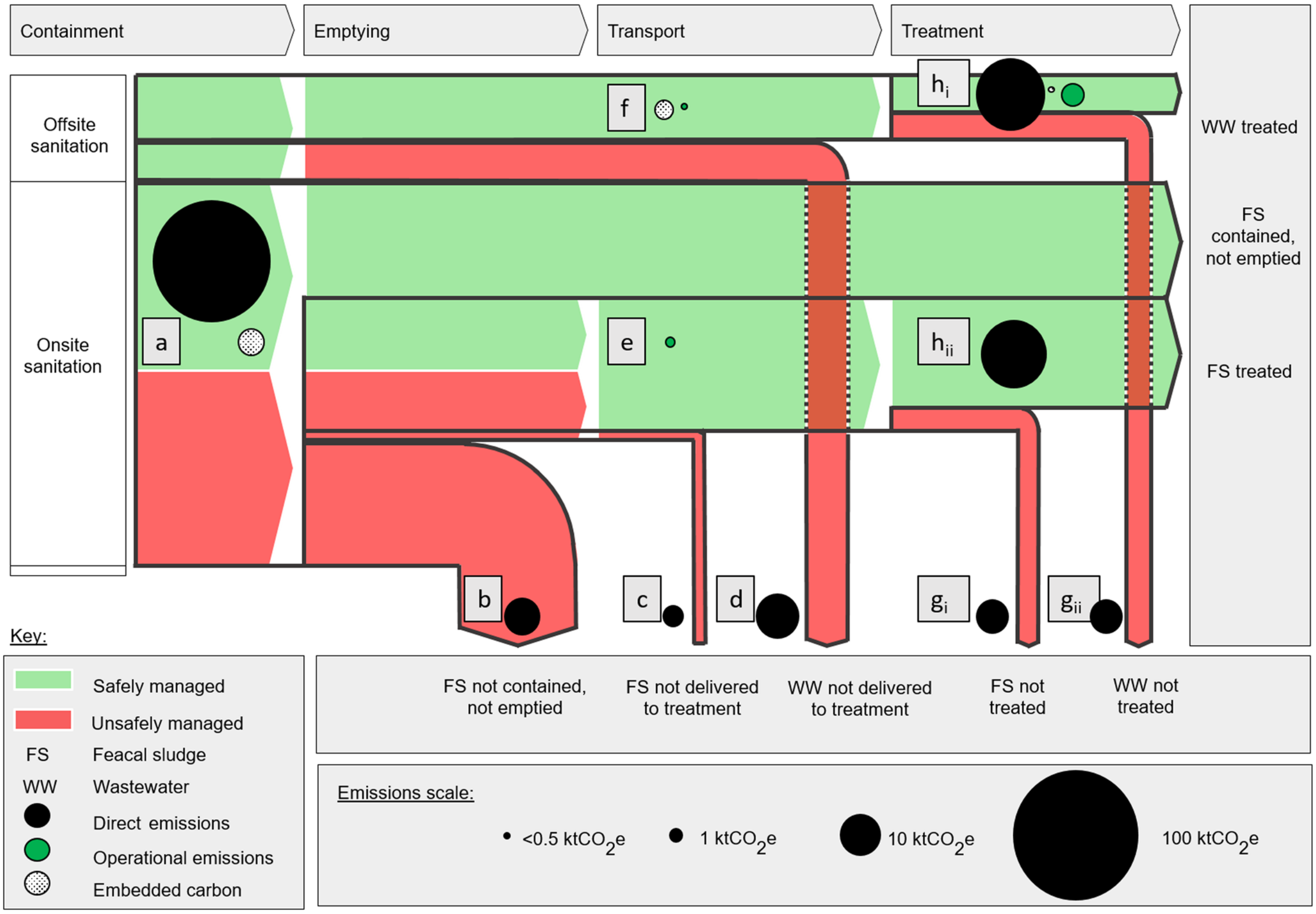


Fig. 4 Annual sanitation emissions for Kampala mapped to the excreta flow diagram. Total emissions from elements of the sanitation system in Kampala, showing direct emissions (black), operational emissions (dark green) and embedded carbon (grey). Area of circles indicates the scale of emissions in each case. Of the total emissions, 49% are from feacal matter-stored tanks and pits (**a**), 4% from discharges from tanks and pits direct to open ground or drains (**b**), 2% from illegal dumping of faecal waste (**c**), 6% leakage from sewers (**d**), a negligible amount (less than 1%) from transport of feacal waste by truck (**e**), 1% from transport of wastewater in sewers (**f**), 7% from wastewater and feacal sludge bypassing treatment ($\mathbf{g}_i + \mathbf{g}_{ii}$) and 31% from treatment plants ($\mathbf{h}_i + \mathbf{h}_{ii}$).

Table 6 Selected results from the sensitivity analysis for end-to-end GHG emissions from urban sanitation in Kampala, Uganda.

	Total emissions (ktCO2e per annum)						
	Baseline	Change in assumptions					
		Onsite: methane conversion factor (MCF)		Onsite N_2O emission Factor (EF)		COD production kg per capita per year	Truck efficiency
		+10%	+25%	+10%	+25%	+20%	+200%
Total emissions	189	196	207	191	194	213	194
%change		4%	9%	1%	2%	13%	2%
Total emissions from Onsite	137	144	154	138	141	156	141
%change		5%	13%	1%	3%	14%	3%
Total emissions from Offsite	53	53	53	53	53	58	53
%change		0%	0%	0%	0%	10%	0%

followed by emissions from waste dumped into open drains. Emissions from transport of both wastewater and faecal sludge are insignificant.

Sensitivity analysis. Sensitivity analysis shows that the model is relatively robust to most assumptions used to predict emissions from stabilization of sludges and wastewater. A summary of the sensitivity analysis is in Supplementary Table 18. Key findings from the sensitivity analysis are presented below in Table 6. The results of our modelling of theoretical emissions from various on-site sanitation systems have an impact on the overall results, but the leveraged change is low (a change of 10% in any value changes the resultant total emissions by less than 5%). The most significant assumption relates to total COD in faecal waste. A reduction or increase of 20% for the COD value changes the overall estimated emissions by approximately 13%.

Discussion

The highest *per-capita* emissions are associated with treatment of wastewater (181 $kgCO_2e$/capita/year), storage of faecal sludge in pits and tanks (76 $kgCO_2e$/capita/year), treatment of faecal sludge (54 $kgCO_2e$/capita/year) and unsafe discharges to open drains (34 $kgCO_2e$/capita/year). Sealed tanks, so-called septic tanks, and any toilets that are inundated with ground or surface water have higher emissions than dry latrines.

There is no correlation between faecal flows that are considered 'safely managed' and low emissions. There is also no evidence that on-site or offsite systems are inherently 'better' from an emissions perspective. Interventions that could immediately reduce emission therefore need to focus both on improved management of onsite sanitation containment (better and more frequent emptying and transport), and modifications to treatment, while continuing to improve the safe management of faecal matter from a public-health perspective. Where new or upgraded on-site sanitation investments are planned, this suggests the promotion of the use of smaller tanks, or the use of container-based systems, both of which might have a net positive impact on emissions. The addition of methane-capture technology at the treatment plants would require upfront investment, but could offer significant returns in terms of conversion of methane to power.

Our analysis suggests that estimates based on the IPCC method may seriously underestimate global emissions associated with sanitation. Our estimate of total emissions from sanitation in Kampala is significantly higher than previous estimates for the city. Based on an adaptation of the most recent city-level emission inventory from Lwasa[17] (see Supporting Information), our estimates suggest that emissions from sanitation may be underestimated by one-third. Sanitation could plausibly be contributing approximately half of total emissions from Kampala city.

The sanitation system in Kampala is typical of many rapidly growing cities in low- and middle income countries and relies on a blend of on-site and offsite sanitation. The city has relatively good management of sanitation, but our analysis shows that there are significant avoidable emissions occurring throughout the sanitation service chain. The use of systems that are often said to provide a higher level of service (e.g., so-called septic tanks) is not associated with better management of the service chain from the perspective of emissions. Overall, sewered systems perform relatively well in Kampala, but this does not imply a generalizable conclusion—the relative weight of emissions from onsite and offsite systems could vary significantly in different cities, depending on topography and design details. Emissions from trucking faecal sludge are not currently significant. There are other reasons to reduce the use of fossil fuels for road-based transport of faecal sludge, including its impact on air quality, but until direct emissions are controlled, the impact on the overall emission profile would be minimal.

The work presented here is based on a strong level of empirical information from Kampala. Many cities would struggle to carry out a similar analysis without collecting significant additional data. However, our model is based largely on IPCC methods and lacks verification from field observations. There is a pressing need for more observational data on emissions from real sanitation systems as they are found and operated in situ.

There is considerable uncertainty around our estimates and the absolute numbers should be treated with caution. However, this represents a significant improvement over previous methods that made blanket assumptions about the types of onsite and offsite systems likely to be found in cities such as Kampala. The results suggest that emissions from sanitation and their management could play a vital part in reducing greenhouse gasses, particularly methane, and as many low- and middle-income countries gear up to meeting SDG 6.2, there will be opportunities to make improvements in sanitation management and reduce the long-term impact on the climate.

Methods

In order to maximise the potential for comparability with established global estimates GHG emission rates were built up for each emission category from established IPCC methodology wherever possible. All emissions were converted to carbon dioxide equivalent (CO_2e) using the 100-year global warming potential (GWP) of each gas (34 for methane, 298 for nitrous oxide)[18].

Methane emission factor for typical sanitation containment and treatment systems. The IPCC estimates methane emissions for sanitation systems from chemical oxygen demand based on Eq. 1. Emission factors are derived from Eq. 2, summed for the population segment using each type of sanitation system.

$$\mathrm{CH_4} = \sum P \times \mathrm{COD} \times PR_{\mathrm{COD}} \times \mathrm{EF} \tag{1}$$

where; $\mathrm{CH_4}$ = total methane emissions from a given element of the system (kgCH$_4$/year), P = population using the system, COD = chemical oxygen demand from the excreta of each person (kg COD/cap/year), $\mathrm{PR_{COD}}$ = percentage reduction of chemical oxygen demand whilst in situ (0–1), EF = emission factor for each containment technology (kgCH$_4$/kg COD)

$$EF_c = B_0 \times \mathrm{MCF}_c \tag{2}$$

where; EF_C = emission factor for each containment technology, $\mathrm{B_0}$ = maximum methane-producing capacity kgCH$_4$/kg COD, $\mathrm{MCF_C}$ = methane correction factor for each containment technology

We used Eqs. 1 and 2 to model estimates of direct emissions from typical sanitation systems based on updated methane correction factors ($\mathrm{MCF_c}$). $\mathrm{MCF_c}$ varies from 0 (for a fully aerobic environment) to 1 (for a fully anaerobic environment)[19,20]. We developed new models for the types of latrines commonly found in Kampala based on field data provided by Nakagiri et al[21]. As inputs, we assumed a typical value for the COD of raw feaces (upstream of the toilet) of 71 kg COD/capita/day[22], and a typical value for PR of 70%[22,23]. The value of $\mathrm{B_0}$ is 0.25 kg CH$_4$/kg COD[12].

The methane-forming reaction, methanogenesis, occurs under obligate anaerobic conditions. A low dissolved oxygen (DO) level is a good indicator for higher rates of methane emission. DO falls when the loading is high, and correspondingly when dilution rates are low. DO will also tend to be lower at depth in static flow systems (i.e., within pit latrines or stagnant water bodies)[21]. DO also appears to fall in dry seasons and rise during the rains[24]. Consistent with DO, low oxidation reduction potential (ORP) of less than +50 mV indicates anoxic condition. Further, low ORP between −199 and −51 mV indicates acidic environment, ideal for methane formation[21]. Almost all pit latrines surveyed by Nakagiri et al.[21] were within low DO and acidic ORP. In sludges, within pits and tanks, or in wastewater and faecal sludge treatment plants, higher moisture content and acidic environment are associated with enhanced methanogenesis. Thus, lined/sealed containers, waterlogged toilets, water borne piped sewerage and anaerobic, high load or saturated treatment processes are all likely to be associated with higher methane emissions.

To establish values for $\mathrm{MCF_c}$, the physical characteristics of sludge inside containers are required, particularly the extent of aerobic and anaerobic conditions at different depths (see also Supplementary Method 1). Nakagiri et al.[21] examined the physical properties of sludge cores taken from a number of pits in Kampala. These data were combined with citywide sanitation data from Musabe[25] to produce emissions profiles for a set of 'typical types' of containers in the city using the IPCC method[11,13]. Details of the determination of $\mathrm{MCF_c}$ and EF for methane are in Supplementary Tables 1, 3 with a summary of the results shown in Table 2.

Methane emissions from treatment plants were calculated using a modified IPCC formula that is based on Reid et al.[20]

$$\mathrm{CH_4} = \Sigma[\mathrm{U\ x\ EF\ x(TOW)x(1-(L+S+R))}] \tag{3}$$

where methane emissions are expressed in kg CH$_4$/year and are summed for each treatment plant. U = effective population (the population equivalent of excreta from direct inflow to the process plus effluent from previous, usually drying, process), EF = emission factors (kg CH$_4$/kg COD) = $\mathrm{B_0} \times$ MCF, $\mathrm{B_0}$ = Maximum methane producing capacity kg CH$_4$/kg COD by process in the local context, MCF = methane correction factor, TOW = total organics in wastewater per year (kg COD/ year), L = proportion of organic component removed as effluent, S = proportion of organic component removed as sludge, R = proportion of methane recovered through capture processes

Detailed calculations are presented in the Supplementary Information.

Nitrous-oxide emission factors for typical sanitation containment and treatment systems. Nitrous oxide is produced during both nitrification and denitrification. Nitrification occurs at the surface facilitating the escape of nitrous oxide gas, and is therefore the more significant process. During denitrification nitrous oxide formed in an anaerobic zone may be dissolved into a liquid phase or converted to dinitrogen ($\mathrm{N_2}$) before it can escape as a gas[26]. The rate of nitrous oxide emission is therefore dependent on the extent to which aerobic conditions exist at the surface and anaerobic conditions below the surface. These can be impacted by both system design and operational conditions.

Nitrous oxide emissions are calculated based on Eq. 4 summed for the population segment using each type of sanitation system[11,13,21]:

$$\mathrm{N_2O} = \sum P \times N_I \times \mathrm{EF} \times \frac{44}{28} \tag{4}$$

where $\mathrm{N_2O}$ = total $\mathrm{N_2O}$ emissions (kg $\mathrm{N_2O}$/year), P = population using each sanitation facility (cap), $\mathrm{N_I}$= nitrogen influent from urine and faeces (kg N/cap/year), EF = emission factor for each sanitation facility (kg $\mathrm{N_2O}$-N/kg N), $\frac{44}{28}$ = conversion factor for $\mathrm{N_2O}$–N into kg $\mathrm{N_2O}$.

For containment, we used field-study-derived data[21,25] to generate modelled estimates for emission factors. We assumed a production of 4.672 kg N/capita /year in faeces and urine combined for Kampala (based on a reported value of 12.8 g/cap/day)[27]. For treatment processes we used the standard emission factors provided by IPCC[11,13]. Details of the resultant emission factors for nitrous oxide are in the Supplementary Tables 2, 4 with a summary of the results shown in Table 3.

Operational emissions (trucking). Operational emissions were calculated on the basis of fuel use for trucking faecal sludge (see also Supplementary Method 4). We used data from truck operations to estimate typical transport distances[28] and combined this with estimate of emissions factors for typical trucks, based on work conducted on the transport sector in South Africa[29]. The emissions from faecal sludge trucking were calculated using Eq. 5 summed for all known trucks operating in Kampala[28].

$$\mathrm{CO}_{2,T} = \sum N_T \times \mathrm{DT} \times EF_V \tag{5}$$

where $\mathrm{CO_{2,T}}$ = total CO$_2$ emissions from the transport of FS (kgCO$_2$/year), $\mathrm{N_T}$ = number trips made per year, DT = average distance travelled per trip (vehicle km), $\mathrm{EF_V}$ = emission factor for each type of vehicle within the FSM fleet (kgCO$_2$/vkm)

Data on truck journeys are summarised in Supplementary Table 8, which also shows the resultant total CO$_2$ emissions obtained by applying Eq. 5.

Operational emissions (pumping and aerating wastewater in sewers and treatment plants). Emissions associated with electricity or fuel usage (e.g., diesel) were calculated using Eqs. 6 and 7 for electricity and diesel respectively summed for each pumping station and/or treatment plant.

$$\mathrm{CO}_{2,el} = \sum C_{el} \times EF_{el} \tag{6}$$

where $\mathrm{CO_{2,el}}$ = CO$_2$ emissions associated with electricity usage (kgCO$_2$/year), $\mathrm{C_{el}}$ = electricity consumption (MWh/year), $\mathrm{EF_{el}}$ = emission factor (tCO$_2$e/MWh/year)

$$\mathrm{CO}_{2d} = \sum C_d \times EF_d \tag{7}$$

where $\mathrm{CO_{2d}}$ = CO$_2$ emissions associated with diesel usage (kgCO$_2$/year), $\mathrm{C_d}$ = diesel consumption (l/year), $\mathrm{EF_d}$ = emission factor (kg CO$_2$e/l diesel)

We used data on electricity and fuel usage in sewer and wastewater treatment operations and applied Eqs. 6 and 7 to obtain total operational emissions for wastewater operations. Supplementary Method 7 provides more details in the method and the results are broken down on Supplementary Table 14.

Embedded carbon in construction material. We used analytical estimation to model emissions associated with embedded carbon. Full details of the approach are in Supplementary Method 2 for containment, **3** for sewerage, and **6** for treatment plants. Quantities of materials in sanitation structures (toilets, sewers, treatment plants etc.) were estimated based on standard designs and information on the design of toilets in Kampala from Nakagiri, et al.[30]. Standard emission factors were applied[31–33]. Typical estimates of infrastructure design life were used to create an annual value. A summary of the emission factors used is shown in Supplementary Table 5 and details of the system-wise calculations are in Supplementary Tables 6, 7, 13.

Sanitation system in Kampala. In order to create the emission profile for the city sanitation system of Kampala, we used data from Nakagiri et al.[21], Kimuli et al.[24], Musabe[25], Schoebitz et al.[34], McConville et al.[35] and Lwasa[17]. The section below draws on all these sources.

According to the most recent estimate of excreta flows in Kampala, close to half ends up in the environment untreated[34]. Around one fifth of the population have sanitation connected to sewers; around a third of wastewater is treated, while two-thirds end up in drains or other water bodies. The remaining population primarily use onsite sanitation systems that are either unlined or lined pit latrines, or so-called septic tanks, many of which are shared. Two-thirds of the population, and many of the people who rely on onsite systems, live in informal low income settlement in low lying areas with high water table, and it is widely reported that most onsite systems are regularly inundated with surface water or flooded with ground water. Of the excreta collected in onsite sanitation systems, about one third remains safely stored in pit latrines and one third are stored in tanks and pits that are located in areas where there is significant risk of groundwater pollution. The remaining third are collected in tanks and pits that are emptied on average once every three years. During flood events there is evidence that many toilets located near to drains are flushed out, using a 'foot valve' or vertical gate at the bottom of the tank that can be lifted manually. A graphical summary of the sanitation system is shown in Fig. 1.

There are two major treatment plants, Lubigi and Bugolobi. The Lubigi plant comprises a series of waste stabilization ponds (anaerobic followed by facultative ponds) followed by drying beds for wastewater sludge. Faecal sludge from onsite sanitation is delivered to settling/thickening tanks; liquids are co-treated with wastewater in the stabilisation ponds, and solids in the drying beds. The faecal sludge treatment plant was reportedly already at design capacity of 400 m^3 faecal sludge per day within the first months of operation[28]. Lubigi receives 3,000 m^3 wastewater daily out of the 5,000 m^3 design capacity[35].

Bugolobi wastewater treatment plant consists of settling tanks with supernatant going to trickling filters, solids going to digesters (if operational) followed by drying beds[28]. While Bugolobi was not designed to co-treat faecal sludge, it nonetheless receives about 200 m^3 faecal sludge per day. The plant receives 13,000 m^3 wastewater daily out of the 32,000 m^3 design capacity[35].

The remaining three wastewater treatment plants in Kampala, Naalya, Ntinda and Bugolobi Flats have negligible capacity of 1,175 m^3/d[14], approximately 3% of the capacity of Lubigi and Bugolobi combined (37000 m^3). Based on the available data we therefore assume that of the excreta that are treated, 80 percent of wastewater and 33 percent of faecal sludge are treated at Bugolobi with the balance treated at Lubigi.

Emissions profile. To produce an emission profile across the entire system, the unit emissions rates calculated as described above were mapped onto the actual sanitation service profile for Kampala using the excreta-flow diagram or SFD for the city[34]. The process is described in Supplementary Methods 8. Peal et al.[16] note that significant system failures occur in typical urban sanitation systems in Sub-saharan Africa. This confirms the findings of Schoebitz et al.[34]. Many system failures result in discharges to the open stormwater drainage network. Because the drains are sometimes dry we used the mean of the emission rates for untreated waste discharged to open drains in the wet and dry seasons to estimate methane and nitrous oxide emissions caused by flows to open drains (see 'No facility' emission rates in Supplementary Table 4). We assumed that all illegal dumping and discharges upstream of the treatment plants went to open drains. However, failures at containment were divided. Shoebitz et al. report that most 'failed' containment results in infiltration to the groundwater that is assumed to have negligible impact on emissions[34]. A quarter of failures at containment are assumed to result in pits and tanks being flushed out to drains during flood events.

Data availability

The datasets generated during the current study are available at https://doi.org/10.5518/1110.

Code availability

Supplementary information is provided to outline the details of the calculations making up this model. A copy of the Excel based model used to assemble these estimates is deposited at https://doi.org/10.5518/1110.

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Author contributions

The work described in this paper was conceptualised and developed by Evans‡. The modelling of on-site emission factors was carried out by Johnson‡ under the supervision of Zakaria‡, Way and Evans. Ground truthing of relevant contextual information was done by Nkurunziza‡. Direct emission calculations from containers and treatment were checked by Camargo-Valero‡. The first end-to-end calculation was carried out by Zakaria. The initial draft of this manuscript was prepared by Zakaria from a report prepared by Johnson. Paper formulation and editing was overseen by Evans. All authors made text contributions and contributed to the final edit. All authors have given approval to the final version of the paper. ‡These authors contributed equally.

Competing interests

The authors declare no competing interests.

Additional information

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