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Article

Non-Sewered Sanitation Systems' Global Greenhouse Gas Emissions: Balancing Sustainable Development Goal Tradeoffs to End Open Defecation

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Abstract: Discharge of excreta into the environment and the use of decentralized sanitation technologies, such as septic tanks, pit latrines and ecological sanitation variants (i.e., container-based sanitation), contribute to greenhouse gas (GHG) emissions but have remained poorly quantified. The purpose of this analysis was to investigate the impacts that meeting Sustainable Development Goal (SDG) 6.2 (i.e., ending open defecation by 2030) would have on SDG 13 (i.e., combatting climate impacts). The current Intergovernmental Panel on Climate Change GHG estimation methodology was used as the basis for calculations in this analysis, augmented with improved emission factors from collected data sets for all types of on-site sanitation infrastructure. Specifically, this assessment focused on the three different service levels of sanitation (i.e., improved, unimproved and no service) as defined by UNICEF and WHO as they pertain to three Shared Socioeconomic Pathways. This analysis considered the 100-year global warming potential values in carbon dioxide equivalents of methane and nitrous oxide that can be emitted for each scenario and decentralized sanitation technology. Ultimately, six scenarios were developed for various combinations of pathways and sanitation technologies. There was significant variability between the scenarios, with results ranging from 68 Tg CO_2eq/year to 7 TgCO_2eq/year. The main contributors of GHG emissions in each scenario were demonstrated to be septic tank systems and pit latrines, although in scenarios that utilized improved emission factors (EFs) these emissions were significantly reduced compared with those using only standard IPCC EFs. This analysis demonstrated that using improved EFs reduced estimated GHG emissions within each SSP scenario by 53% on average. The results indicate that achieving SDG sanitation targets will ultimately increase GHG emissions from the current state but with a relatively small impact on total anthropogenic emissions. There is a need for the continued improvement and collection of field-based emission estimations to refine coarse scale emissions models as well as a better characterization of relevant biodegradation mechanisms in popular forms of on-site sanitation systems. An increase in the understanding of sanitation and climate change linkages among stakeholders will ultimately lead to a better inclusion of sanitation, and other basic human rights, in climate action goals.

Keywords: open defecation; on-site; pit latrine; septic tank; Greenhouse Gas Emission Analysis; decentralized sanitation systems; sustainable development goals

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1. Introduction

Sanitation systems are a fundamental human right that provide an essential health-related service and can promote sustainable development; however, limited focus has been placed on their contributions to climate mitigation and adaptation. Climate change threatens existing sanitation systems, as well as efforts to increase services for over 2 billion people who lack even a basic sanitation service [1,2]. At the same time, the sanitation (i.e., decentralized non-sewered) and wastewater (i.e., centralized sewered) sector directly produces emissions associated with the breakdown of organic matter, and many treatment processes require large energy inputs [2,3].

The sustainable development goals (SDGs), as set in 2016 by the United Nations (UN) for the 2030 agenda, can be used to provide a multidimensional perspective on development and are useful in highlighting that there are synergies and trade-offs in the interactions among the different SDGs [4–7]. Currently, there is a conflict between SDG 6, specifically SDG 6.2, and SDG 13 [2,8]. SDG 6.2 states: "By 2030, achieve access to adequate and equitable sanitation and hygiene for all and end open defecation" [9]. This is closely linked to SDG 6.3, which addresses the need to reduce current untreated wastewater discharges through widespread treatment [9]. SDG 13 states: "there must be urgent action taken to combat climate change and its impacts" [9]. Not only are there trade-offs between the SGDs but conflict also exists between the 17 SDGs and the nine planetary boundaries as the ability to achieve these SDGs could increase the human ecological footprint and thereby intensify pressure on the planetary boundaries [6,10].

Climate change impacts existing sanitation systems and impedes progress to achieving these targets by increasing variability in natural climatic cycles and events. These impacts also exacerbate existing challenges in the sector, such as sustainability concerns related to infrastructure breakdowns. The effort required to achieve sanitation targets is significant, as approximately 5.6 billion more people will need to use safely managed services, of which approximately 1.3 billion will need to shift from open defecation to the use of a sanitation system by 2030 in order to achieve SDG 6.2 [1,11]. Additionally, as nations move towards urbanization, there will be an increasing importance for functional and properly managed sanitation services [7]. The emphasis on integration throughout the SDG agenda has highlighted that targets for sanitation and increased wastewater treatment must be achieved in order to attain a number of other outcomes, including improved water quality, healthy ecosystems, eliminating inequities (i.e., gender, socio-economic and geographical) and improving the overall health and well-being of the global population [2,8]. In this context, it is important to note that 'safely managed services', although defined and a part of the SDG agenda [12], refers primarily to a reduction of microbial risks and not resource recovery and environmental pollution, although these are also important factors that should be considered in any truly sustainable sanitation solution.

Decentralized (on-site) sanitation technologies are the focus of this assessment as they are generally the most scalable, effective and equitable adaptation measure within the sanitation sector and are typically the first accessible improved sanitation option for those that currently have no access to sanitation [2,13]. They have a lower economic burden on the household user [14,15], some forms have been proven to be effective in reducing negative climate impacts [16–19], and most importantly, they can provide access to improved sanitation for the most vulnerable populations [13,15,17]. Specifically, this assessment focused on the three different service levels of sanitation (i.e., improved, unimproved and no service), as defined by the Joint Monitoring Programme (JMP) [20], as they pertain to three Shared Socioeconomic Pathways (SSPs), as described in the framework presented by O'Neill et al. (2014). Many of the most resource-constrained populations are still facing major sanitation challenges, including widespread open defecation; as such, the climate impacts of the elimination of open defecation is the main focus of this assessment.

Discharge of untreated waste into the environment and the use of on-site technologies, such as septic tanks, pit latrines and ecological sanitation (i.e., container-based sanitation, composting toilets, etc.) contribute to greenhouse gas (GHG) emissions but have remained poorly quantified [2,13,15,19]. This analysis explored scenarios for global future GHG emissions from households implementing different forms of decentralized sanitation technologies to end open defecation practices. The specific objectives were as follows:

1. Model and compare scenarios for global future GHG emissions that would allow SDG 6.2 to be met in 2030 from household decentralized sanitation infrastructure given differences in demography, urbanization and economic growth as represented by three different SSPs (i.e., SSP1, SSP2 and SSP3).

2. Complete a sensitivity analysis to determine the relative impact each individual on-site sanitation system (e.g., septic tanks, pit latrines, composting toilets, etc.)—since they relate to the service level in the sanitation management ladder (i.e., improved, unimproved and no service), as defined by the JMP—has on climate change mitigation in the form of GHG emissions.
3. Expand upon the existing IPCC GHG estimation methodology using improved emission factors for each non-sewered sanitation form through augmentation with published measured data sets.

This model aims to increase the understanding of sanitation and climate change linkages among stakeholders and determine how the SDG and planetary boundary agendas can complement each other to more effectively include sanitation in climate action.

2. Materials and Methods

2.1. Model Description

The analysis presented here has considered the 100-year global warming potential (GWP) values of methane (CH_4) and nitrous oxide (N_2O) that can be emitted (in carbon dioxide equivalents, CO_2 eq.) for each scenario and decentralized sanitation technology [21,22]. It should be noted that CH_4 and N_2O were considered the most important GHGs directly produced from excreta in decentralized on-site sanitation systems [19,23] since a large fraction of decentralized sanitation systems are assumed to digest waste anaerobically [13]. and the two gases have a 100-year GWP of 21 and 310, respectively [22]. Typically, CO_2 emissions from wastewater are not considered in GHG estimations because they are considered to be solely from biogenic organic matter in human excreta and food waste [17,24–26]. However, discussions have arisen recently that considered the possibility of non-biogenic carbon (fossil) CO_2 emissions from wastewater treatment and discharge [26]. For this analysis, there was a lack of available and reliable data. As a result, CO_2 emissions were not accounted for.

The current IPCC GHG estimation methodology has been used as the basis for calculations in this analysis [26]. However, this methodology has significant limitations as GHG emissions vary widely among waste treatment technologies, especially among decentralized sanitation, depending on the biogeochemical conditions, operating conditions and associated collection and discharge systems [2,13,19,27]. As such, this analysis made provisions for refinement and comparison of the current IPCC model with improved and experimentally verified emission factors (EFs). GHG emissions from non-sewered sanitation systems are poorly constrained due to their decentralized locations and high level of operational variability. For example, direct measurements from septic systems are few and are proven to differ from modelled emission factors [17,19]. This analysis has been developed to quantify the impact of eliminating open defecation in addition to ranking on-site systems relative to their GHG emissions. Additionally, it can highlight potential measures to reduce GHG emissions resulting from the breakdown of excreta (i.e., regular emptying of septic tanks) and good wastewater management.

This model quantifies the climate change impacts of meeting SDG 6.2: ending open defecation by 2030. Global GHG emissions (i.e., CH_4 and N_2O) from decentralized sanitation technology, as defined by the JMP service ladder [1], expressed as CO_2eq converted into 100-year GWP [22], were estimated from countries currently still practicing open defecation. Representative alternatives (i.e., best-case, status-quo and worst-case) based on selected SSPs [21] were evaluated by integrating and comparing EFs from quantitative sampling programs and studies with the methodology from the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas inventories [26].

2.2. Scenario Description

2.2.1. Socioeconomic Pathways

The scenarios in this analysis are based on the shared socio-economic pathways (SSPs), as described in O'Neill et al. (2014) [21,28]. SSPs are reference pathways that describe plausible alternative trends in the evolution of society and ecosystems and include assumptions about future demographics, economic development and the degree of global integration [21,29]. These pathways have been developed over the previous year's teams consisting of interdisciplinary professionals including climate scientists, economists and energy modelers to capture the spectrum of socio-economic factors and provide comprehensive baseline scenarios that can be used by climate modelers. For this analysis, the goal was to use multiple scenarios to compare mitigation outcomes to a range of more realistic baseline future worlds. This analysis used three contrasting scenarios: SSP1, SSP2 and SSP3. These three scenarios were selected because they describe most favorable (i.e., best-case), average (i.e., status-quo), and least favorable (i.e., worst-case) developments in population, economic growth, environmental policy and technology development and transfer, respectively. Table 1, based on O 'Neill et al. (2012, 2014), summarizes the key elements of these pathways as they pertain to decentralized sanitation and this analysis.

Table 1. Key elements of SSP1, SSP2 and SSP3 as they pertain to decentralized sanitation [1].

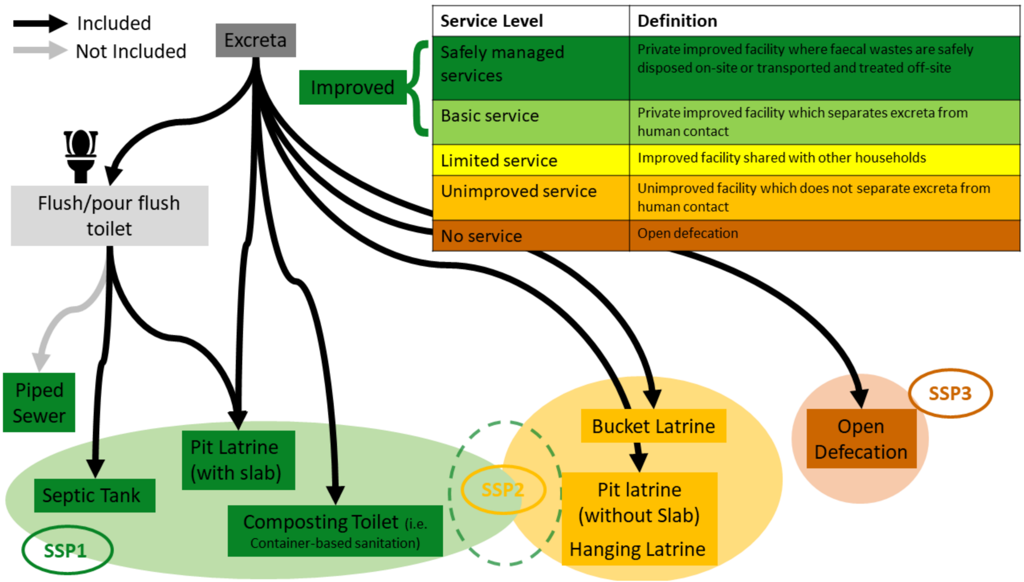
SSP Element	SSP Sub-Element	SSP1-Sustainability	SSP2-Current Trends Continue	SSP3-Fragmentation
Demographics	Population	Low	Medium	High
	Urbanization	Planned	Mixed	Unplanned
Economy & Lifestyle	Growth per Capita	Fast	Slow	Slow
	Inequality across regions	Convergence of incomes, but retaining diversity	Status-quo	Large
	Inequality within countries	Becoming more equitable, less stratification	Status-quo	Large
Policies & Institutions	Policy Orientation	Toward sustainable development	Status-quo	Toward security
Technology	Development	Rapid	Medium	Slow
	Transfer	Rapid	Status-quo	Slow
Environment & Natural Resources	Environment	Move towards sustainable management	Medium	Serious Degradation
	Land-Use	Move toward sustainable use	Medium	High

[1] Based on O 'Neill et al. (2012, 2014) [21,28].

The SSP database [30] provided country-level data for population for SSP1, SSP2 and SSP3, respectively, and was supplemented by JMP population data where gaps existed [20]. In addition to varying population growth, these scenarios were used to define alternatives in decentralized sanitation use and open defecation rate elimination.

2.2.2. Sanitation Technology Ladder

The JMP service ladder for sanitation has been developed by the World Health Organization (WHO) and the United Nations International Children's Emergency Fund (UNICEF) to be used to compare service levels across regions and countries [1]. The most recent version (i.e., 2017) provides definitions for service levels and facility types that are aligned with achieving SDG 6.2 and maintaining enhanced and continuous global monitoring. The sanitation ladder has three main categories that describe service levels: improved, unimproved and no service. These categories, specifically 'improved', are further divided to provide a total of five classifications. Figure 1 provides definitions for each rung of the sanitation service ladder. It should be noted that 'Safely Managed Sanitation' is defined as the use of an improved facility that is not shared with other households and where excreta are either safely disposed of in situ or transported and treated off-site [20]. This model was solely concerned with the "safely managed sanitation services" framework established by the JMP [20] with the definition of infrastructure that constituted an 'improved facility' from a technology perspective and did not account for social structure related issues such as community-led total sanitation (CLTS). This limitation is discussed further in Section 4.1. For the purposes of this analysis, each of the three main service levels was matched to one of the three selected SSPs (i.e., SSP1, SSP2 or SSP3) based on projected future conditions. Additionally, projected usages of each type of decentralized sanitation technology, as they pertain to each JMP service ladder rung and SSP, were determined. Table 2 presents the six scenarios used in this analysis and the corresponding service level, type of decentralized sanitation technology and emission factor. This served as the basis for the analysis presented.



Service Level	Definition
Safely managed services	Private improved facility where faecal wastes are safely disposed on-site or transported and treated off-site
Basic service	Private improved facility which separates excreta from human contact
Limited service	Improved facility shared with other households
Unimproved service	Unimproved facility which does not separate excreta from human contact
No service	Open defecation

Figure 1. Decentralized Sanitation Technology Scenario Development Schematic. Based on the JMP Sanitation Service Ladder [20].

Table 2. Scenario Definition and Characteristics.

Scenario ID	**Emission Factors**	**SDG 6.2 Target**	**Decentralized Sanitation Technology Usage**	
	IPCC vs. Improved	**Service Level**	**Proportion of the Population that is Openly Defecating**	**Proportion of the Population Using Improved Sanitation Facilities**
1a 1b	IPCC Improved	SSP1	0%	100%
2a 2b	IPCC Improved	SSP2	Current rates of reduction continue [3] (declining at a median rate of 0.5% per year)	Current rates of utilization continue [3] (increasing at a rate of 0.4% per year).
3a 3b	IPCC Improved	SPP3	No change from current proportion.[3] (Median of 9.5%).	No change from current proportion [3]. (Median of 47%).

[3] Based on global WASH data trends from 2000–2017, openly available data from the JMP database [31].

In this analysis, composting toilets, as an improved form of sanitation, refer to infrastructure such as container-based sanitation (CBS), which consists of an end-to-end service in which toilets collect excreta in sealable, removable containers that are regularly collected and transported to treatment facilities [32]. Piped sewer networks (i.e., centralized sanitation) were not included as part of this analysis (Figure 1). In each scenario described above (Table 2), the proportion of the population that was originally openly defecating in the present (i.e., the population for which GHG emission have been calculated) was diverted to solely decentralized forms of sanitation in either the unimproved or improved forms, or in the case of SSP3a and SSP3b remained as openly defecating. The implications of inherent assumptions are discussed in Section 4.1.

2.3. Emission Model Parameters

2.3.1. Activity Data

In order to investigate the impacts of sanitation and climate change as they relate to the SDGs, the inventory year used for all scenarios was 2030. This year is specified in the 2030 agenda for sustainable development, which is integral to the development of the SDGs and provides the goals and targets that were developed with the intended purpose to stimulate action in less than two decades in areas of critical importance for humanity and the planet [9].

The focus of this analysis is the target set out in SDG 6.2, which is ending open defecation by 2030 [9]. Therefore, the JMP database [20] was used to determine which countries were still practicing open defection. Of a total of 206 countries, it was determined that 96 (47%) had a percentage of their population (i.e., rate of open defecation > 0 as reported by the JMP in 2017 [20]) that was affected by open defecation (Figure 2); these are the countries that have been considered in this analysis. It should be noted that the figures reported in the JMP database have inherent inaccuracies, discussed in further detail in Section 4.1.

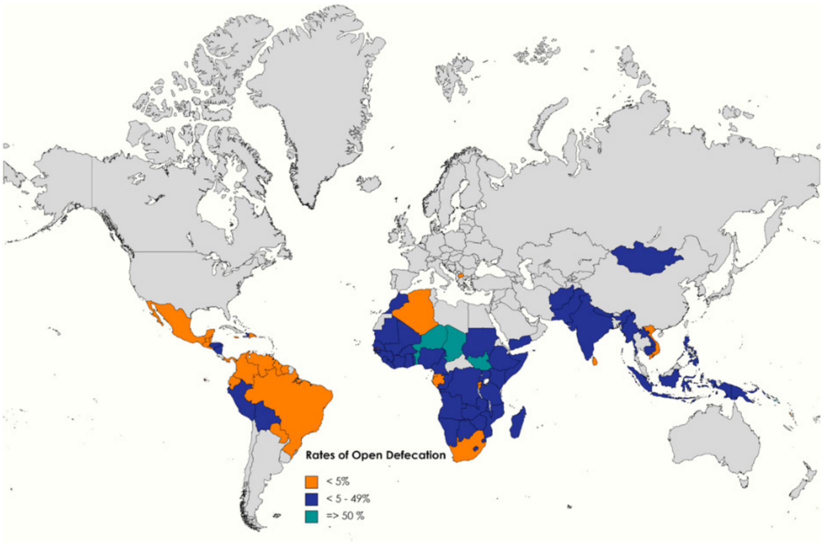


Figure 2. Map of Countries with a Proportion of their Population practicing Open Defecation [20].

Typically, estimations begin with the identification of nationally representative data sources that contain information on the use of water and sanitation services (WHO/UNICEF Joint Monitoring Programme (JMP) for Water Supply, Sanitation and Hygiene, 2018). For most countries, this information is collected from households during interviews conducted by national statistical offices [33].

The fraction of the population openly defecating that was reported [20] was then applied to the population projections provided by the SSP database [30] for each SSP scenario (i.e., SSP1, 2 and 3). As depicted in Table 2 in SSP1 (i.e., best-case scenario), it was assumed that 0% of the projected population would be openly defecating, with the portion of the population that would have been openly defecating (based on the 2017 JMP percent coverage rates [20]) now using improved sanitation facilities. In SSP2 (i.e., status-quo scenario), it was also assumed that the current rates of reduction of open defecation in the counties identified as still practicing open defecation would continue to decline at the rate experienced in the previous 17 years (2000–2017), projected to 2030. Similarly, the rates of utilization of the population using improved forms of sanitation would increase at the same rate experienced in the previous 17 years (2000–2017). In SSP3 (i.e., worst-case scenario), it was assumed that the proportion of the population that was openly defecating in 2017 would remain the same for the projected population increase for each affected country as well as the rates of utilization of improved forms of sanitation. Where SSP population data was not available, it was supplemented with World Bank projected populations [34]. It should be noted that for many countries it is expected that a proportion of the population will transfer to the utilization of centralized sewer networks in addition to increasing their use of improved decentralized sanitation facilities. This was not accounted for in this analysis as the focus of this assessment was on quantifying the impact of eliminating open defecation through the use of decentralized and on-site sanitation services alone.

2.3.2. Emission Factors

Currently, the IPCC guidelines provide emission factors (EFs) for various sanitation technologies (i.e., anaerobic treatment plants, reactors, lagoons, septic systems and latrines) for estimation of GHG emissions [26]. It should be noted that the IPCC guidelines only consider CH_4 and N_2O emissions in its calculations for total GHG emissions from the above-mentioned technologies. The 2006 IPCC guidelines assume that organic carbon present in wastewater from decentralized sanitation technologies is biogenic and therefore considered in GHG inventories [26]. The 2019 refinement, however, suggests that non-biogenic carbon (i.e., fossil wastewater organic carbon) could exist in a fraction estimated at 4-14 percent [26]. EFs and methodology to account for biogenic carbon were not available in the 2019 refinement. Additional studies have also discounted any contributions from carbon as CO_2 emissions in decentralized sanitation infrastructure [17,24,25]. Given the overall lack of data and the relative weight (i.e., 100-year GWP CO_2 equivalency factors), this analysis has focused on CH_4 and N_2O emissions exclusively. These emission factors are based on a combination of peer-reviewed references in addition to expert judgement. One of the main objectives of this work was to provide revised EFs based on data from experimental field studies for each safely managed decentralized sanitation technology for both CH_4 and N_2O. Recent studies (i.e., past 30 years) that included measured data for septic tank systems, pit latrines of varying types (i.e., VIP, twin chamber, etc.) and composting toilets (i.e., CBS) operating in the field were assessed for inclusion in this analysis. Studies that only considered a portion of the decentralized treatment technology pathway (i.e., leach field emissions only) or were solely lab or bench scale variants were not included as a part of this analysis. The calculation boundary of this analysis is concerned only with the on-site treatment component of the fecal sludge management chain; emissions from the collection system and off-site fecal sludge treatment are outside of the scope of this analysis. Additionally, where data did not exist, this analysis proved useful in the identification of the need for further experimental-based research in these areas. For each sanitation technology identified in scenarios 1a–3b, Table 3 summarizes the IPCC EF [26] for each GHG, as well as the revised values and corresponding study [15,17–19,23,35–43] that have been used in this analysis. Supplementary data that further support this work are available.

Table 3. Sanitation Service Ladder Technologies IPCC and Average Improved GHG Emission Factors. Number of Studies used in Improved Average Values in square brackets [15,17–19,23,35–43]. Where NR = Not Reported.

Sanitation Service Ladder Grouping	**CO_2 [gCO_2/Capita/Day]**		**CH_4 [gCH_4/Capita/Day]**		**N_2O [gN_2O/Capita/Day]**	
	IPCC	**Improved**	**IPCC**	**Improved**	**IPCC**	**Improved**
Septic Tank	NR	NR	15.7	11.2 [4]	0.01	0.12 [5]
Pit Latrine (with Slab)	NR	NR	13.6	5.3 [2]	NR	0.28 [1]
Composting Toilet	NR	NR	0.5	0.1 [2]	0.0004	0.00002 [2]
Pit Latrine [1] (without Slab)	NR	NR	13.6	5.3 [2]	NR	0.28 [1]
Hanging Latrine [2]	NR	NR	3.1	1.1 [1]	0.000009	
Bucket Latrine [3]	NR	NR	0.5	0.1 [2]	0.0004	0.00002 [2]
Open Defecation	NR	NR	3.1	1.1 [1]	0.000009	

[1] Considered to have the same emissions as a Pit Latrine (with Slab). [2] Considered to have the same emissions as open defecation. [3] Considered to have the same emissions as a composting toilet.

2.4. GHG Emissions

In order to calculate the GHG emissions for each scenario, as summarized in Table 2, the methodology outlined in the 2019 Refinement of the IPCC Guidelines was used [26]. This methodology specified a number of equations and parameters that are necessary to calculate total emission for each gas and each technology, which were then aggregated for the appropriate scenario in the year 2030 to define the 100-year CO_2eq. Table 4 summarizes each equation and associated parameters used in the applicable scenarios. All additional material pertaining to model development is available in Supplementary Materials.

Table 4. IPCC Equations, Input Parameters and Outputs.

IPCC Equation	GHG	Input Parameter(s)	Output
Equation (6.3)	CH_4	Country Population Country-specific per capita BOD	Total organics in wastewater in inventory year [kg BOD/yr]
Equation (6.3a)		Equation (6.3) Output Degree of utilization of each treatment/discharge pathway	Total organics in wastewater for each treatment system/pathway [kg BOD/yr]
Equation (6.3d)		Equation (6.3) Output Degree of utilization of each treatment/discharge pathway Fraction of total wastewater organics removed during wastewater treatment per treatment type	Total organics in the treated wastewater effluent discharged to aquatic environments in inventory year [kg BOD/yr]
Equation (6.3c)		Equation (6.3a) Output (Septic Tank Systems) Fraction of the population managing their septic tank in compliance with sludge removal instructions	Organic component removed from wastewater (i.e sludge) in septic systems [kg BOD/yr]
Equation (6.1)		Equation (6.3a) Output Equation (6.3c) Output Emission factor for each treatment/discharge pathway Amount of CH_4 recovered from treatment system	CH_4 Emissions from treatment/discharge system in inventory year [kg CH_4/yr]
Equation (6.10)	N_2O	Country population Annual per capita protein consumption Additional nitrogen from household products added to wastewater	Total annual amount of nitrogen in wastewater treatment pathway [kg N/yr]
Equation (6.8)		Equation (6.10) Output Degree of utilization of each treatment/discharge pathway Fraction of total wastewater nitrogen removed during wastewater treatment per treatment type	Total N discharged to the environment [kg N/yr]
Equation (6.7)		Equation (6.8) Output Emission factor for N_2O emissions from wastewater discharged to aquatic environments	N_2O Emissions from treatment/discharge system in inventory year [kg N/yr]

2.5. Model Uncertainties

Uncertainties associated with the various input parameters were compared to uncertainties accounted for in the comparison of the IPCC EFs to the improved EFs. There was a 53% average decrease in total GHG emissions as a result of this improvement. As such, there were no cases where input parameter uncertainties were greater than this comparison of EFs, and it was therefore determined that there would be little to no value of conducting additional uncertainly analyses.

3. Results

Based on the defined scenarios, CO_2eq, accounting for CH_4 and N_2O emissions, were estimated for various combinations of pathways and sanitation technologies, including a comparison between IPCC and improved EFs for the specified on-site sanitation technologies assessed.

3.1. Comparision across Shared Socioeconomic Pathways

Results were characterized by variability between SSP scenarios, with SSP3 producing estimations significantly lower than SSP1 and SSP2. For the 100-year GWP, the results ranged from 68 Tg CO_2eq/year (SSP1—Scenario 1a) to 7 TgCO_2eq/year (SSP3—Scenario 3b) in 2030. Figure 3 depicts the results of each SSP scenario with SSP1 representing best-case, SSP2 characterizing status-quo and SSP3 describing worst-case scenarios, respectively.

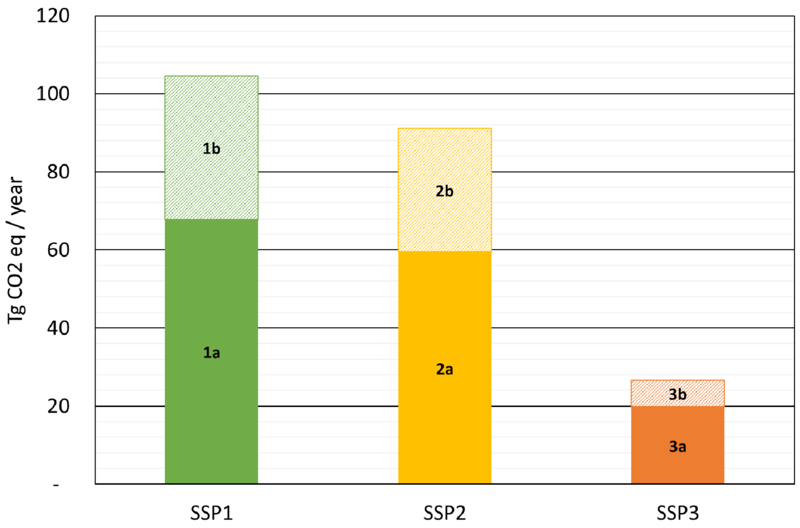


Figure 3. Estimated annual 100-year Global Warming Potential in CO_2eq for each Shared Socio-Economic Pathway (SSP1, SSP2 and SSP3) Scenario in 2030.

3.2. Comparision between Emission Factors (EFs)

Using the IPCC methodology without the improved EFs indicates a 436% increase in CO_2eq from SSP3a to SSP1b (i.e., worst case to best case scenario). However, using improved experimental EFs improves this to only an 84% increase and lowers these estimations within each respective SSP scenario on average by 53%. Table 5 compares the estimated annual 100-year GWP CO_2eq results for each scenario in 2030 using the IPCC default EF values to the results that used the improved, experimentally collected, averaged values from literature [15,17–19,23,35–43].

Table 5. Comparison of estimated 100-year Global Warming Potential CO_2eq for each Scenario using IPCC Default and Improved Emission Factors (EFs) in 2030.

Scenario ID	**SDG 6.2 Target Service Level**	**Emission Factors IPCC vs. Improved**	**100 Year GWP in 2030**	
			Tg CO_2/year	**Percent Decrease Using 'Improved' EFs**
1a	SSP1	IPCC	68	46%
1b		Improved	37	
2a	SSP2	IPCC	59	47%
2b		Improved	32	
3a	SSP3	IPCC	20	66%
3b		Improved	7	

3.3. Comparision across On-Site Sanitation Technologies

Figure 4 differentiates between the different categories of on-site sanitation technologies and their contributions to the total estimated amounts of GWP CO_2eq in 2030 for each scenario. Results were characterized by generally equal contributions to total estimated GWP CO_2eq from both septic tank systems and pit latrines for scenarios 1a through 2b. Notably, in scenarios 1b and 2b, the improved EFs lessened the relative contribution from septic tank systems by an average of 15%. Although only a small proportion of the population in these scenarios is predicted to shift from open defecation towards bucket latrines and composting toilets (0.2–0.5%), their value should not be understated. Contributions for scenarios 3a and 3b were not included in Figure 4 as SSP3 is characterized as having no change from current proportions of the population openly defecating. Since this analysis is specifically concerned with the estimation of emissions from the change in the proportion of the population openly defecating this meant that there were no changes in the proportion of emissions being contributed from unimproved and improved forms of sanitation facilities.

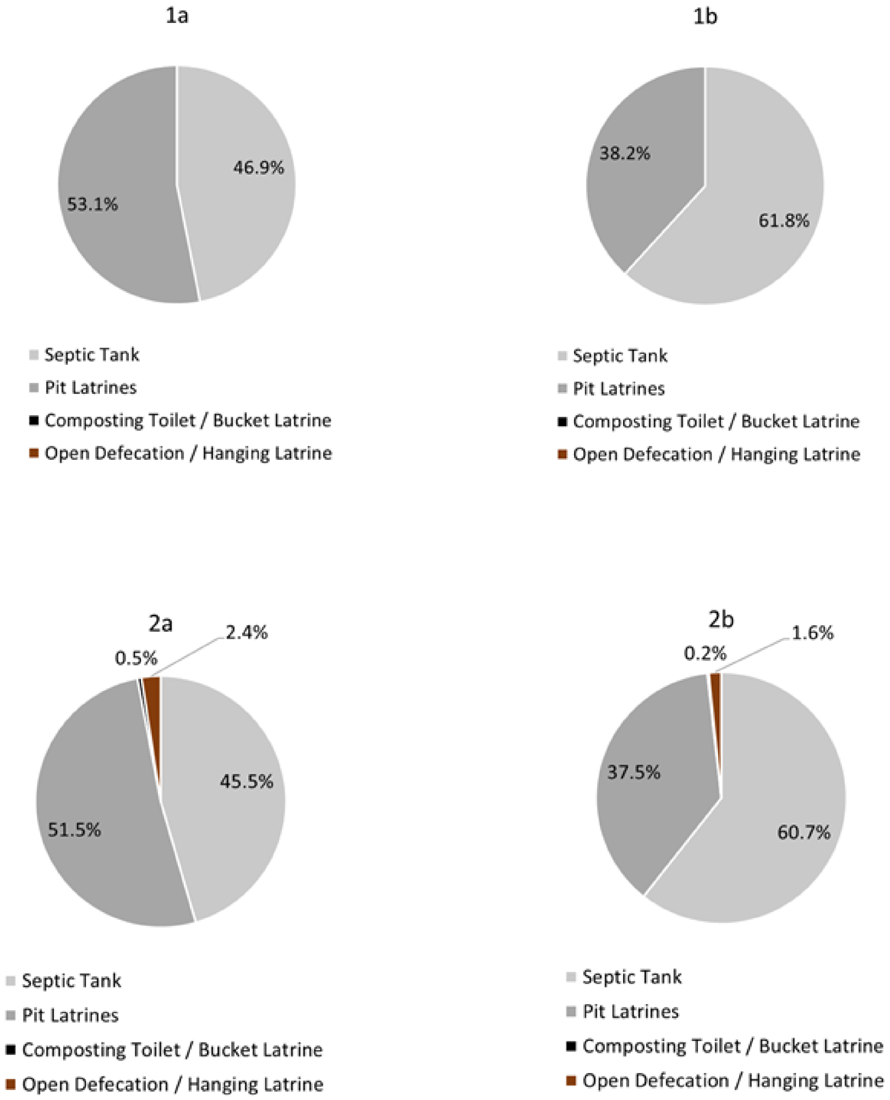


Figure 4. Estimated annual 100-year Global Warming Potential contributions in CO_2eq for each on-site sanitation technology grouping for SSP1 and SSP2 scenarios in 2030.

4. Discussion

The results indicate that achieving the SDGs sanitation targets can significantly affect environmental impacts in the form of global GHG emissions. Additionally, this study demonstrated that there is a need for the continued improvement and collection of field-based emission estimations to refine coarse scale emissions models such as this.

The GHG emissions represented as 100-year GWP CO_2eq in 2030 are in general agreement with estimates from experimentally based studies that considered on-site sanitation variants [15,17,23], although the estimates in this study are specific to the changes due to the elimination of open defecation and consider all types of on-site sanitation technologies. These studies also found that estimates obtained using the theoretical methods described by the IPCC GHG Estimation methodology [26] are approximately one to two times larger than estimates established from field-based data [13,17,23]. The results from this analysis could provide the basis for revised methane correction factors (MCFs) and EFs in future iterations of IPCC GHG emission guidelines.

It is clear that in order to eliminate open defecation using improved and accessible forms of on-site sanitation, total GHG emissions will increase from current levels in both SSP2 (status-quo) and SSP1 (best-case) scenarios. However, it is important to contextualize this through the lens of what it means to achieve sustainable development; as Kate Raworth stated in her book "Doughnut Economics", the goal is to arrive and stay in a "safe and just space for humanity" [44]. This space, in the context of sanitation, is one where every person's basic needs are met while at the same time safeguarding the natural world on which humanity depends (i.e., there will always be a balance between transgressing biophysical boundaries and achieving high social thresholds) [44,45]. For example, in scenario 1b, which is the best-case scenario where open defecation is eliminated by 2030 using only improved forms of sanitation, a total of 37 Tg CO_2eq/year in 2030 is yielded, which is only 0.2% of total global anthropogenic CO_2 emissions [46] and only 3% of total global emissions from wastewater [46,47]. Although emissions will likely increase, they are comparatively very small and will allow for the elimination of open defecation through the means of on-site sanitation (a basic human right) [9]. This analysis was based on the theory that empirical evidence exists that satisfying a basic need, such as ending open defection, is a precondition for well-being, which in turn can help propel the global population into an area that meets climate goals and maintains natural boundaries, and this is supported by the results obtained. This study provides evidence that on-site sanitation systems are a solution that is in-line with the Living Well Within Limits (LiLi) analytic framework [48] developed by Dr. Julia Steinberger and colleagues, whereby these technologies are a type of provisioning system that links biophysical resource use and social outcomes (Figure 5).

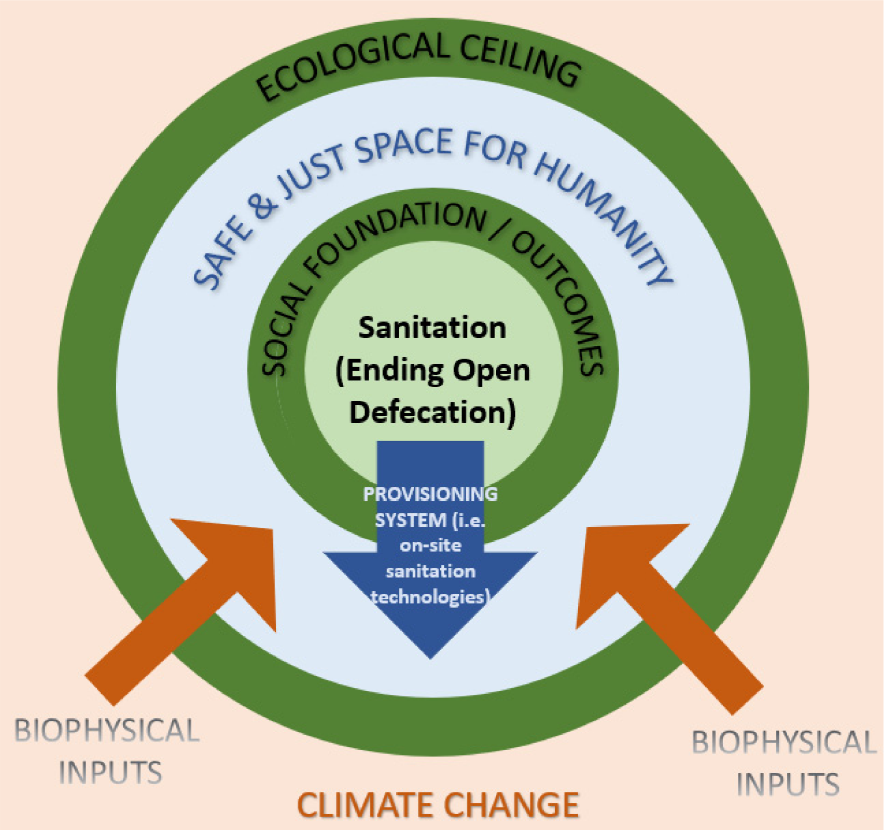


Figure 5. How Ending Open Defecation Aligns with Sustainable Development Perspectives (based on [44,45]).

This analysis also highlights the impacts that different levels of service that on-site sanitation could have on GHG emissions. Specifically, when looking at two of the most popular forms of improved on-site sanitation, septic tanks and pit latrines, it can be seen that they are relatively equal in terms of contributions to emissions in all scenarios but contribute significantly less overall when considering the results of improved EFs (i.e., scenarios 1b, 2b and 3b). Although outside the scope of this analysis it should be noted that septic tank systems, and to a lesser extent pit latrines, yield the potential for energy capture and reuse (i.e., lower emission potential) in the form of CH_4 capture. Additionally, although not as widespread, ecological sanitation variants (i.e., CBS) have the potential to not only act as an important rung on the ladder to obtaining access to safely managed sanitation but also provide simple examples of climate mitigation potential as a form of furthering the treatment and reuse portion of the fecal sludge management value chain (Strande et al., 2014; Ryals et al., 2019; McNicol et al., 2020). It is especially important to note that this analysis provides evidence that the IPCC National GHG Methodology [26] is likely overestimating GHG contributions from these basic, affordable and extremely scalable forms of sanitation and further emphasizes the need for continued efforts in field-based and experimental work focused on the quantification of gas emissions. This analysis is selective and from a perspective that is focused on ending open defecation. Currently, many sanitation solutions approach this issue from a linear perspective as opposed to a circular one. In order to further this type of emissions analysis, a circular-based approach is one that will allow for the identification of which process efficiencies need to be improved [49].

Ultimately, this type of analysis would be an integrated approach [50] that would expand to the entire collection chain (i.e., on-site, transport and off-site treatment), an expansive and in-depth process including an analysis of the integration of planning, management, and technology. A feasible next step for this work would be to integrate these results into the work that is currently ongoing surrounding sustainability indexes of sanitation variants. These indices aim to provide, through an evaluation framework, sustainable sanitation for a community, by understanding the technical, economic, and social characteristics of that community [51]. Several indices like this have already been designed [51–53]. Although many of these indices are fairly comprehensive, there have been limited case studies, especially when it comes to the spectrum of costs and benefits of implementing these systems in developing and resource-constrained contexts [51]. This model, in combination with additional field-based results, would be able to strengthen these types of frameworks, which would allow communities access to relevant databases with the information they need to make informed choices regarding sustainable sanitation.

4.1. Limitations

As mentioned previously, this analysis did not fully consider the impacts that social and community constraints and motivations, such as programs like community-led total sanitation (CLTS), could have on the usage of improved sanitation technologies. This analysis focused mainly on the substitution of different technologies and their resulting impacts; however, moving forward the societal, behavioral, and cultural implications involved with fully eliminating open defecation should be considered as any sustainable solution will need to be a combined effort between individuals, communities, public health agencies and local governments.

As with most community-based data collection, despite rigorous procedures to produce reliable data, inaccuracies can occur. For example, there is known open defecation that has not been reported on or included in the data available from the JMP database. This is apparent in many high-income countries that claim a total eradication of open defecation, such as in Canada, where the federal government estimates that there are approximately five thousand homes in rural and primarily indigenous communities that lack access to basic water and sewage [54]. However, it should be noted that this type of data is hard to come across, and analyses such as this must rely on sources such as Multiple Indicator Cluster Surveys (MICS), Living Standards Measurement Study (LSMS), and Demographic and Health Surveys (DHS) [55,56]. Additionally, many sources like nationwide household surveys rely on self-reported data with inherent biases. There can be stigma associated with admitting to openly defecating, and therefore it is likely under-reported [57]. Although this would have a comparatively small impact to the totals obtained in this analysis, it is worth mentioning that there is room for improvement in robustness and clarity in the included country dataset, should this analysis continue to be used and enhanced in the future.

Additionally, it is worth noting that the deliberate exclusion of piped sewer networks from this analysis could be viewed as a barrier to robustness. However, it was reasonable to assume that in order to fully eliminate open defecation, the majority of this shift will be taken up by decentralized sanitation technologies as either final or intermediate solutions leading to piped sewer networks [49,58]. As sewered service chains have been shown to be significantly more expensive than fecal sludge management chains [59], this would make adequately managed on-site technologies a long-term, sustainable and viable alternative. Additionally, in contrast to centralized sewer networks and treatment plants, decentralized on-site sanitation presents a current gap in literature and data to support its impacts and usefulness in terms of reaching climate focused goals. This analysis, at its core, was designed to highlight the role these technologies can play at bridging the sanitation gap realistically and sustainably.

As explained previously, the combination of lack of evidence to support non-biogenic carbon and relevant data led to the exclusion of direct CO_2 emissions from this analysis, with the focus instead being on higher impacting gases: CH_4 and N_2O. However, as the amount of information and data increases in the field of major non-biogenic organic carbon petroleum-based products (i.e., cosmetics, pharmaceuticals, surfactants, detergents and food additives) [60], so too should the re-evaluation of inclusion of direct CO_2 emissions in this type of analysis.

Further sensitivity analysis with improved emission factors would be beneficial as work in this field progresses. It is clear that this field suffers from a relative scarcity of data, and this study goes to highlight the need for further improvement of data collection, aggregation and distillation into such models on sustainable sanitation technologies.

Finally, the analysis in this paper does not cast a wide enough net to capture the expected benefits of climate change mitigation in terms of the avoided impacts on water resources and consequently the performance of energy technologies that rely on water availability. Nor does it have the resolution to consider specifics such as temperature effects on decentralized wastewater treatment systems. Significant geographic diversity is anticipated, and there is an opportunity for future work that could develop temperature-dependent emission factors as well as other global benefits that fell outside of the scope of this particular analysis.

5. Conclusions

This paper has analyzed the interaction between SDG 6 and SDG 13 and estimated the GHG emissions of meeting sanitation targets using different forms of decentralized sanitation technologies through the lens of sustainable development. It has been shown that in order to end open defecation by 2030 and meet the targets set out in SDG 6, GHG emissions will increase. This is a small price to pay given the relatively small contribution these emissions make to global anthropogenic CO_2 (less than 0.2%), as highlighted previously, coupled with the ability to provide a basic human right. It has also provided evidence to support the continued refinement of GHG emission methodologies with field-based and experimental data to refine coarse scale emissions models as well as better characterize the relevant biodegradation mechanisms in popular forms of on-site sanitation systems. The impacts from providing a more comprehensive evidence base, such as this, could be significant for sanitation policies, technology options and carbon intensity changes and will support the planning of locally appropriate sanitation and wastewater systems that consider a broader range of climate impacts. It can provide a wider vision and platform for the communications between sanitation experts, urban planners and development agencies to forge a new, developing nation leadership in sustainable governance and a clear path towards equity and inclusion globally.

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