Water Science & Technology

Water Science & Technology Vol 90 No 10, 2842 doi: 10.2166/wst.2024.377

Comparative life cycle assessment of on-site sanitation systems using lagoons or drying beds for fecal sludge treatment in low-income tropical countries

Davidson Jean-Baptiste * and Frédéric Monette

École de technologie supérieure, Montréal, QC, Canada
*Corresponding author. E-mail: davidson.jean-baptiste.1@ens.etsmtl.ca

DJ, 0000-0002-7935-7883; FM, 0000-0002-0952-1924

ABSTRACT

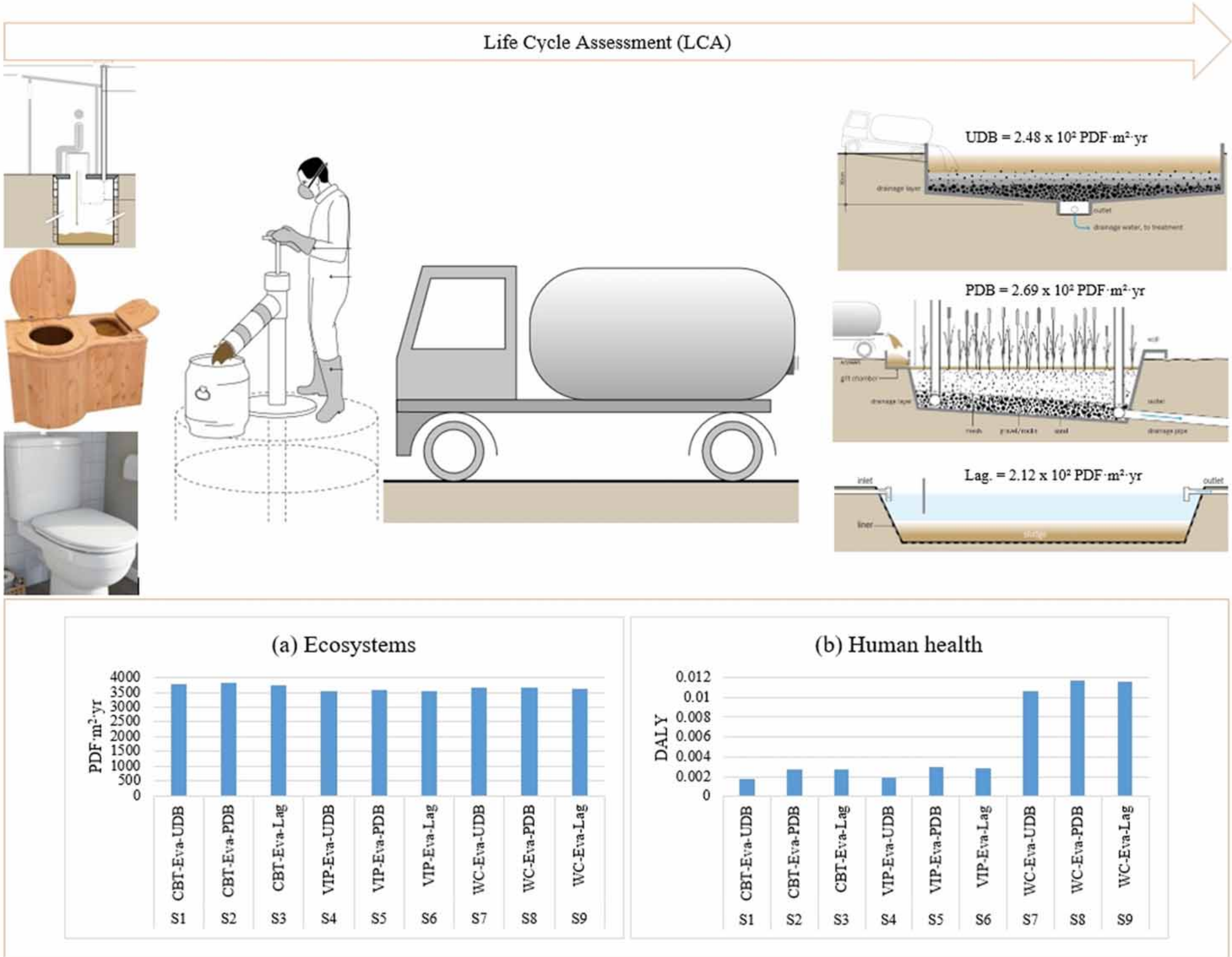
Environmental challenges in low-income countries, such as Haiti, persist due to inadequate sanitation infrastructure. This study assesses the environmental impacts of nine on-site sanitation systems to identify those with the least environmental impacts and explore improvement options. Nine scenarios were developed, each representing different systems for managing 1 ton of fecal sludge over 1 year. The 'Impact World + ' and 'IPCC 2013 GWP 100a' methods evaluated impacts on ecosystems, human health, and climate change. Data sources included interviews, weighing records, and scientific publications. Results show that Scenario 8 (Flush Toilet – Evacuation – Planted Drying Beds) is most impactful on health (1.17×10^{-2} DALY), while Scenario 1 (Composting Toilet – Evacuation – Unplanted Drying Beds) is least impactful (1.77×10^{-3} DALY). For ecosystem impacts, Scenario 2 (Container-based Toilet – Evacuation – Planted Drying Beds) is most impactful (3.81×10^3 PDF·m^2·year), while Scenario 6 (VIP latrine – Evacuation – Lagoons) is least impactful (3.52×10^3 PDF·m^2·year). Key hotspots include toilet paper, wood shavings, GHG emissions, and water use. The study recommends an integrated approach combining environmental life cycle assessment (LCA) with life cycle cost assessment and social LCA for sustainable decision-making on sanitation systems in low-income countries.

Key words: environment, GHG, human health, LCA, sanitation, sustainable

HIGHLIGHTS

- This study evaluates the entire on-site sanitation system, including toilet access, sludge emptying and evacuation, and treatment via lagoons or drying beds (planted or unplanted).
- Unlike earlier studies that focused primarily on fecal sludge treatment technologies, this research assesses potential health and environmental impacts across the complete sanitation chain, from initial access to final treatment (of sludge).

GRAPHICAL ABSTRACT



1. INTRODUCTION

Low-income countries frequently face sanitary and environmental challenges, one of the most concerning being fecal pollution (Hyun *et al.* 2019). The multiple health and environmental issues resulting from this pollution have been documented in the scientific literature (Mara 2004; Strande *et al.* 2014; Odey *et al.* 2017; Jean-Baptiste *et al.* 2023). This situation often stems from the lack of adequate sanitation infrastructure to manage blackwater or human excreta.

Low-income countries have often attempted to replicate the conventional sanitation systems employed in developed countries (Aguilar *et al.* 2014; Jha & Bajracharya 2014; Egloso *et al.* 2015; Mng'ombe *et al.* 2023), without considering that their socio-economic and geoclimatic contexts generally differ from those of developed countries. Indeed, these countries often do not have the same level of sanitation infrastructure, frequently face water availability constraints, and, in most cases, they have a tropical climate (Koottatep *et al.* 2005; Bouquet 2013). Consequently, the conventional sanitation system used in developed countries is not necessarily adapted to low-income tropical countries. This situation suggests that these countries should instead develop their own sanitation systems, capitalizing on the advantages that the tropical climate offers in terms of drying, stabilization, and hygienization of fecal sludge. These climatic advantages are, moreover, widely demonstrated in the literature (Koottatep *et al.* 2005; Strande *et al.* 2014; Pocock *et al.* 2022; Samal *et al.* 2022; Sorrenti *et al.* 2022).

Extensive sanitation technologies, which mimic natural sanitation processes, could prove beneficial for low-income countries due to their generally low cost, low energy and water consumption, and adaptation to tropical regions (Sasse 1998; Monvois *et al.* 2010; Uggetti *et al.* 2011; Strande *et al.* 2014; Tilley *et al.* 2016). Currently, three sanitation technologies stand out: lagoons, unplanted drying beds (UDBs), and planted drying beds (PDBs). However, from these three sanitation technologies, it is essential to objectively identify the one most suited to the environmental context of low-income countries, as well as those that can be improved.

Life cycle assessment (LCA), as a multicriteria environmental assessment method (Jolliet *et al.* 2015), is the most appropriate tool to address this question. LCA allows the identification of the stages, activities, and materials responsible for the environmental impact of a system or product throughout its life cycle, from the extraction of raw materials necessary for its manufacture to its end-of-life management (Jolliet *et al.* 2015, 2017). As an ecodesign tool, it also facilitates the identification of improvement levers by highlighting critical variables.

Despite the numerous scientific studies devoted to the LCA of sludge treatment processes, no research has been reported in the scientific literature on the LCA of complete on-site sanitation systems, including downstream treatment by lagoons or drying beds, whether planted or unplanted. Existing studies focus primarily on fecal sludge treatment technologies, representing the final link in an on-site sanitation system. A study conducted in Brazil by Moni Silva *et al.* (2023) investigated the potential environmental impacts of three scenarios for the treatment of sludge from UDBs, namely landfilling, anaerobic digestion, and incineration. The results showed that the use of sludge to produce energy through anaerobic digestion can reduce environmental impacts, although greenhouse gas (GHG) emissions and heavy metals must be considered.

In Spain, Uggetti *et al.* (2011) compared four sludge treatment scenarios: (S1) drying reed beds followed by biosolids application in fields, (S2) drying reed beds followed by biosolids composting, (S3) centrifugation followed by composting, and (S4) treatment in a conventional wastewater treatment plant (activated sludge). The scenario of drying reed beds followed by biosolids land application (S1) was identified as the least environmentally impactful and most economically beneficial for the following reasons: (i) it does not require transporting sludge to a post-treatment site, thus eliminating transportation-related impacts, (ii) it does not require additional treatment such as composting, avoiding impacts associated with these additional processes, (iii) the raw materials required for the construction of the system in question are responsible for most of the impact in this scenario, but this impact remains low compared to other scenarios involving transportation, and (iv) the contribution to impacts from direct GHG emissions as well as indirect emissions related to energy consumption and transportation is minor compared to other scenarios.

Other studies have compared lagoons to conventional sanitation systems. In a study conducted in Iran, Mohammadi & Fataei (2019) compared a lagoon system with an activated sludge plant. They concluded that the lagoon system was more impactful overall than activated sludge, mainly due to significantly higher methane (CH_4) production (29,090 kg/day versus 7,527 kg/day for activated sludge) and its lower performance in terms of reducing levels of nitrogen and phosphorus, which are responsible for water eutrophication. In contrast, Thompson *et al.* (2022) in Nebraska (USA) found opposite results, concluding that the lagoon system is less impactful because it requires less operational energy and leads to fewer emissions into water and air. These divergences can be attributed to differences in the environmental indicators studied.

Finally, Flores *et al.* (2019) compared drying reed beds to activated sludge systems in Spain, demonstrating that drying reed beds are less harmful to the environment due to the avoidance of wastewater and sludge transportation, as they are treated on-site, as well as reduced electricity and chemical consumption, compared to the activated sludge system.

These studies highlight the need for further research to more comprehensively assess the LCA of autonomous sanitation systems, considering the three components in the system: access to toilets, fecal sludge evacuation, and fecal sludge treatment. This is particularly crucial for systems integrating lagoons or drying bed links in order to better understand the factors influencing their environmental performance. The present study aims to fill these gaps in the scientific literature by providing new data on the LCA of sanitation systems used in low-income tropical countries.

2. METHODOLOGY

2.1. Geophysical framework of the study

The Republic of Haiti occupies the western portion of the island of Hispaniola, which it shares with the Dominican Republic (World Population Review 2024). Situated in the Caribbean basin at approximate geographical coordinates of 19°00′N and 72°25′W, Haiti is characterized by a tropical climate (Singh & Cohen 2014; World Population Review 2024). The climate is generally warm and humid, with variations depending on altitude (World Bank 2021). The mean annual temperature ranges between 24 and 27 °C (Jean-Baptiste 2019).

The average annual precipitation for the period 1981–2020 was 118 cm, with a value of 115.3 cm recorded in 2020 (UNDP 2021). The mean potential evapotranspiration for the same period amounted to 155.9 cm *per annum*, reaching 158 cm in 2020 (UNDP 2021). This evapotranspiration exceeding precipitation indicates a generally arid climate. Haiti is a mountainous country, with 60% of its area presenting slopes greater than 20% (Pierre 2020). The country is frequently exposed to natural disasters such as hurricanes, floods, and earthquakes, phenomena exacerbated by extensive deforestation (Singh & Cohen 2014; Pierre 2020; Preux 2022).

2.2. Objective and scope of the study

The main objective of this study is to compare, through LCA, the autonomous sanitation systems used in low-income tropical countries such as Haiti (a tropical climate country), focusing on the following on-site sanitation technologies as downstream links: PDB, UDB, and lagoons. This analysis is part of a broader research project aimed at identifying sanitation technologies and systems with the least environmental impact, while considering the socio-economic and climatic context of low-income countries, particularly Haiti. Furthermore, this study will pinpoint opportunities for improving the examined sanitation systems. This study is addressed to policymakers, donors funding sanitation projects in developing countries, as well as academics and researchers interested in the issue of on-site sanitation.

2.2.1. Description of the systems studied

As indicated in the introduction of the study, each studied system consists of three distinct links. Data related to the 'toilet' and 'fecal sludge evacuation' links are detailed by Jean-Baptiste & Monette (2024). Therefore, this section focuses on the description of the technologies comprising the 'sludge treatment' link.

2.2.1.1. Unplanted drying bed. The UDB (Figure 1) has an area of 300 m^2. It is designed on an annual basis of dry sludge (DS) mass loading per unit area of 200 kg DS/m^2/year (Strande *et al.* 2014). In accordance with Cofie *et al.* (2006), Strande *et al.* (2014) and Chandana & Rao (2022), the UDB consists of three superimposed layers with different grain sizes: (i) a 20-cm-thick surface layer of sand (grain size of 0.20–0.60 mm), (ii) a 10-cm-thick layer of fine gravel (grain size of 10 mm) located directly below the sand layer, and (iii) at the bottom, a 15-cm-thick layer of coarse gravel (grain size of 19 mm). Under the gravel layer, drainage pipes collect the leachate resulting from the drying of the fecal sludge. This leachate is then recirculated into the UDB to sustain microbial activity. The system can accumulate a layer of sludge up to 30 cm thick on the surface (Tilley *et al.* 2016). The infrastructure has a lifespan of 25 years.

2.2.1.2. Planted drying bed. This drying bed (Figure 2) is similar in composition to the one described above, with the addition of macrophyte plants, specifically reeds (*Phragmites australis*), which facilitate evapotranspiration, reduce clogging, and promote the development of purifying microorganisms (Strande *et al.* 2014; Tilley *et al.* 2016). However, the system is fed sequentially with volumes of sludge distributed on the surface of the bed (batches), and the beds are cyclically rested to ensure biodegradation of the sludge layer. The PDB also differs from the UDB in terms of the amount of greenhouse gases emitted into the atmosphere during the utilization phase, and the fact that it needs to be desludged every 3–5 years, unlike the UDB, which is desludged every 5–10 drying cycles (Strande *et al.* 2014).

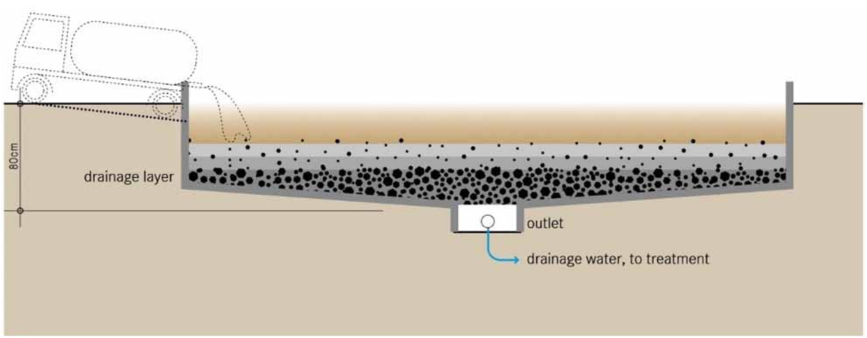


Figure 1 | Overview of an unplanted drying bed design (Tilley *et al.* 2016).

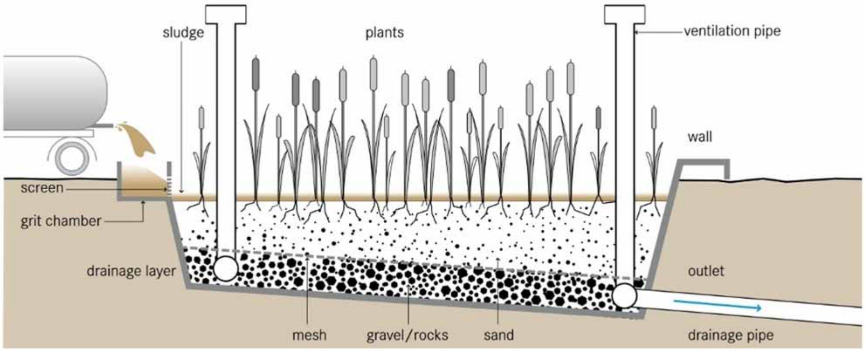


Figure 2 | Schematic of a planted drying bed (Tilley *et al.* 2016).

2.2.1.3. Lagoon systems. The lagoon system considered in the present study (Figure 3) is a complete retention lagoon system based on the adaptation of 'Lagoon A' modeled by Thompson *et al.* (2022) in a study conducted in Nebraska (USA). It covers an area of approximately 12,900 m^2, with a treatment capacity of 49 m^3/day and an evaporation rate of 109 cm/year. Lagoon lifespan is estimated at 20 years (Thompson *et al.* 2022). Additional information on the lagoons and other treatment technologies is available in Supplementary data, Table SD-10.

2.2.2. Function and functional unit

The primary function of the studied sanitation systems is to treat human excreta in order to preserve the environment and human health from potential contamination and nuisances generated by these sludges. Furthermore, these systems fulfill a secondary function by producing biosolids (dried sludge) that can be used as fertilizer in agriculture. The functional unit chosen for this study is the management of 1 ton of fecal sludge (wet basis) over 1 year in Haiti.

The analyzed fecal sludges exhibit the following characteristics, in accordance with Jean-Baptiste & Monette (2024): (i) 23.4% dry solids (DS), equivalent to 234 kg of dry solids per ton (sludges from composting toilets contain 40.0% DS due to the addition of litter), (ii) 25.5 kg/t of total nitrogen, (iii) 3.68 kg/t of total phosphorus, (iv) 8.00 kg/t of potassium, and (v) a chemical oxygen demand (COD) of 635 kg/t. These data are based on the average of information provided by Strande *et al.* (2014) and Andriani *et al.* (2015). Information regarding annual feces production per person comes from the study by Jean *et al.* (2017), which estimates that a Haitian produces an average of between 120 and 130 g of feces (wet mass) per day. Thus, an average of 125 g of feces per person per day was used.

2.2.3. Scenarios considered

The studied system consists of the three links of on-site sanitation: toilet, evacuation, and sludge treatment. To achieve the objectives of the study, nine sanitation system scenarios were developed in accordance with these three links, which are listed in Table 1. Scenario 6 (VIP latrine – Evacuation – Lagoon) corresponds to the system most widely used in urban areas with a sludge treatment plant in Haiti, followed by Scenario 9 (Flush toilet – Evacuation – Lagoon), which is primarily used in relatively affluent areas.

2.2.4. System boundaries and impact assessment methods

This study considers the complete life cycle of the sanitation technologies examined, from their construction to their end-of-life management. Figures 4 and 5 illustrate the system boundaries. The 'Impact World + ' method (Damage 1.47) as described

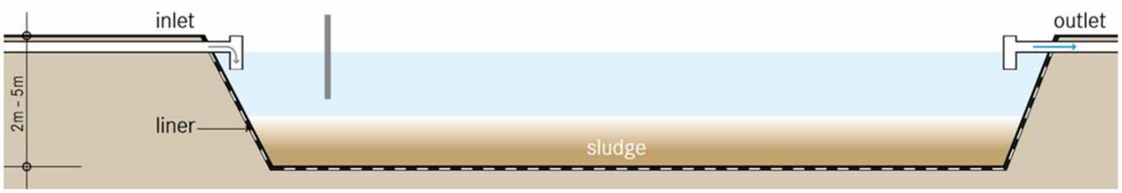


Figure 3 | Diagram of a lagoon (Tilley *et al.* 2016).

Table 1 | Scenarios considered in the study

Scenario	First component	Second component	Third component
Scenario 1	Container-based toilet (CBT)	Evacuation	Unplanted drying bed (UDB)
Scenario 2			Planted drying bed (PDB)
Scenario 3			Lagoon
Scenario 4	Ventilated improved pit (VIP) latrine		Unplanted drying bed
Scenario 5			Planted drying bed
Scenario 6			Lagoon
Scenario 7	Flush toilet (W.C.)		Unplanted drying bed
Scenario 8			Planted drying bed
Scenario 9			Lagoon

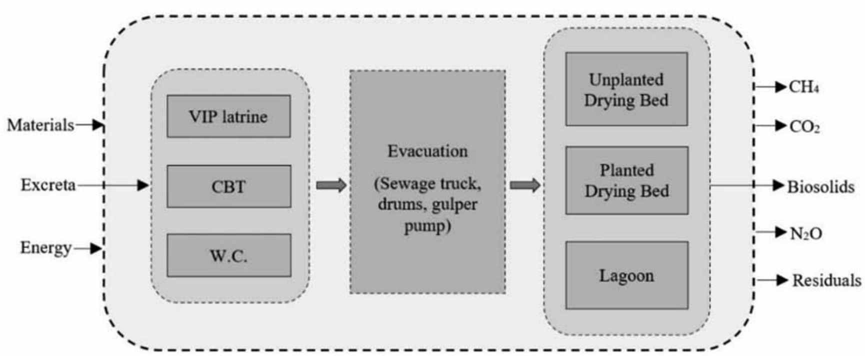


Figure 4 | System boundaries.

by Bulle *et al.* (2019) has been combined with the 'IPCC 2013 GWP 100a' method to assess potential impacts on ecosystems, human health, and climate, respectively.

2.3. Life cycle inventory assessment

The necessary data for modeling the systems studied were collected using a life cycle inventory (LCI) in accordance with ISO 14040 (2006). In this process, the ecoinvent database version 3.7, integrated into the OpenLCA application version 1.11.0, was utilized for background data. The data sources collected during this inventory and the quality of these data are referenced in Table 2. The data quality was assessed according to the criteria of Weidema *et al.* (2013) and Bicalho *et al.* (2017). These criteria are defined in Supplementary data, Table SD-12.

Equations (1) and (2) were used to estimate the GHG fluxes emitted into the atmosphere by the examined toilets and drying beds, respectively. Table 3 lists the data related to the emission factors used for each technology studied. To achieve the functional unit, a total of 22 people per year is required. The surface area of each drying bed is 300 m^2, as mentioned previously.

$$\text{Emission(toilets)} = \text{Emission rate} \times \text{Number of people/year} \tag{1}$$

$$\text{Emission (drying beds)} = \text{Emission rate} \times \text{surface area} \times 365\ \text{days} \tag{2}$$

The information regarding the inputs and outputs used in modeling the studied systems is available in Supplementary material.

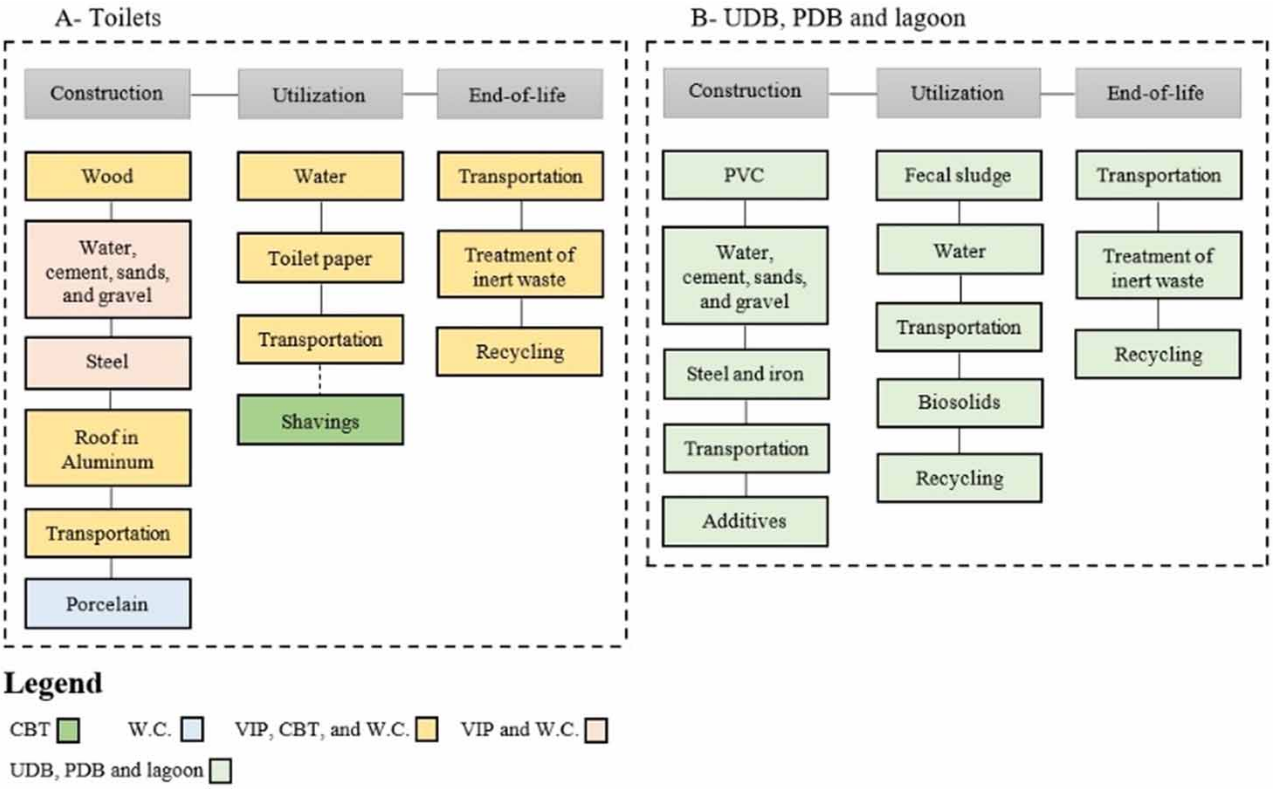


Figure 5 | Main components of the upstream and downstream links (adapted from Jean-Baptiste & Monette (2024)).

Table 2 | Sources of life cycle inventory data used in the study (adapted from Jean-Baptiste & Monette (2024))

Types of data	Data quality	References
Container-based toilet (CBT)	Good quality (1, 4, 5, 1, 1)	Julien Boyer, manager of Lécopot, manufacturer of CBT (Fabulous toilettes 2016)
VIP latrine	Good quality (2, 4, 5, 3, 1)	(Mara 1984; DINEPA *et al.* 2013; Tilley *et al.* 2016)
Flush toilet (W.C.)	Good quality (1, 4, 5, 1, 2)	Direct measurements
Gulper pump	Good quality (3, 4, 4, 2, 1)	(Strande *et al.* (2014); Gabert *et al.* 2018)
Fecal sludge	Good quality (2, 2, 5, 1, 1)	(Strande *et al.* (2014); Andriani *et al.* 2015)
Sewage truck	Good quality (1, 2, 5, 2, 3)	Ecoinvent version 3.7
Planted drying bed (PDB)	Good quality (2, 3, 4, 1, 2)	EAWAG – SANDEC
Unplanted drying bed (UDB)	Good quality (2, 3, 4, 1, 2)	EAWAG – SANDEC
Lagoon	Good quality (2, 3, 3, 1, 2)	Adapted from Thompson *et al.* (2022))

Table 3 | Information about the GHG emission rates used in the modeling of toilets and treatment systems for the study (adapted from Jean-Baptiste & Monette (2024))

Technology	Emission rate (ER)	References
CBT	0.454 kg CH_4/capita/year 0.0661 kg N_2O/capita/year	Johnson *et al.* (2022)
VIP latrine	1.134 kg CH_4/capita/year 0.0661 kg N_2O/capita/year	
W.C.	1.804 kg CH_4/capita/year 0.0441 kg N_2O/capita/year	
UDB	13.3 g CO_2 eq./m^2/day or 0.532 g CH_4/m^2/day	Adapted from Cui *et al.* (2015)
PDB	1,653 mg CH_4/m^2/day 485 mg N_2O/m^2/day	Adapted from Uggetti *et al.* (2012) and Cui *et al.* (2015) Adapted from Uggetti *et al.* (2012)
Lagoons	0.0018 kg CH_4/m^3 0.000629 kg N_2O/m^3 0.000608 kg NH_3/m^3	Adapted from Thompson *et al.* (2022)

3. RESULTS AND DISCUSSION

3.1. Potential impact assessment of the sanitation systems analyzed

Table 4 presents the endpoint results concerning the potential impacts of the different examined sanitation systems on climate, ecosystems, and human health. The midpoint results are presented in Figures 6 and 7. Regarding potential climate impacts, the scenarios are ranked in descending order as follows: S8 > S5 > S2 > S7 > S4 > S1 > S9 > S6 > S3. The scenarios equipped with a PDB are consistently the most impactful in each category for the same type of toilet, followed by scenarios with an UDB, and finally, those with a lagoon. Overall, the climate impact of scenarios equipped with a PDB is on average 2.37 times higher than those with a UDB, and 6.87 times higher than those with a lagoon. Thus, the PDB proves to be the most impactful sludge treatment technology (5.53×10^3 kg CO_2 eq.), followed by the UDB (1.78×10^3 kg CO_2 eq.) and the lagoon (3.13×10^{-1} kg CO_2 eq.). Regarding toilet types, scenarios with a flush toilet (WC) are on average 1.12 times more impactful than those with a VIP latrine, and 1.26 times more impactful than those with a container-based toilet (CBT). This confirms that the flush toilet is the most impactful toilet (1.32×10^3 kg CO_2 eq.), followed by the VIP latrine (9.11×10^2 kg CO_2 eq.) and the CBT (5.51×10^2 kg CO_2 eq.).

Regarding potential ecosystem impacts, the scenarios (S) are ranked in descending order of impact as follows: S2 > S1 > S3 > S8 > S7 > S9 > S5 > S4 > S6. The analysis of results also reveals that systems equipped with a CBT are, on average, 1.04 times more impactful than those equipped with a flush toilet (WC), and 1.07 times more impactful than those equipped with a VIP latrine. Consequently, CBT emerges as the most impactful technology in terms of ecosystem impact (3.48×10^3 PDF·m²·year), followed by W.C. (3.31×10^3 PDF·m²·year) and VIP latrine (3.21×10^3 PDF·m²·year). Regarding treatment

Table 4 | Potential impacts of the analyzed sanitation systems

Scenario	Climate change (kg CO_2 eq.)	Ecosystems (PDF·m^2·year)	Human health (DALY)
S1 (CBT-Eva-UDB)	2.35×10^3	2.79×10^3	1.76×10^{-3}
S2 (CBT-Eva-PDB)	6.09×10^3	3.81×10^3	2.76×10^{-3}
S3 (CBT-Eva-Lag)	5.64×10^2	3.76×10^3	2.71×10^{-3}
S4 (VIP-Eva-UDB)	2.71×10^3	3.56×10^3	1.93×10^{-3}
S5 (VIP-Eva-PDB)	6.45×10^3	3.58×10^3	2.93×10^{-3}
S6 (VIP-Eva-Lag)	9.28×10^2	3.52×10^3	2.88×10^{-3}
S7 (WC-Eva-UDB)	3.12×10^3	3.66×10^3	1.07×10^{-2}
S8 (WC-Eva-PDB)	6.86×10^3	3.68×10^3	1.17×10^{-2}
S9 (WC-Eva-Lag)	1.33×10^3	3.62×10^3	1.16×10^{-2}

CBT, container-based toilet; VIP, ventilated improved pit latrine; WC, flush toilet; UDB, unplanted drying bed; PDB, planted drying bed; Lag, lagoon.

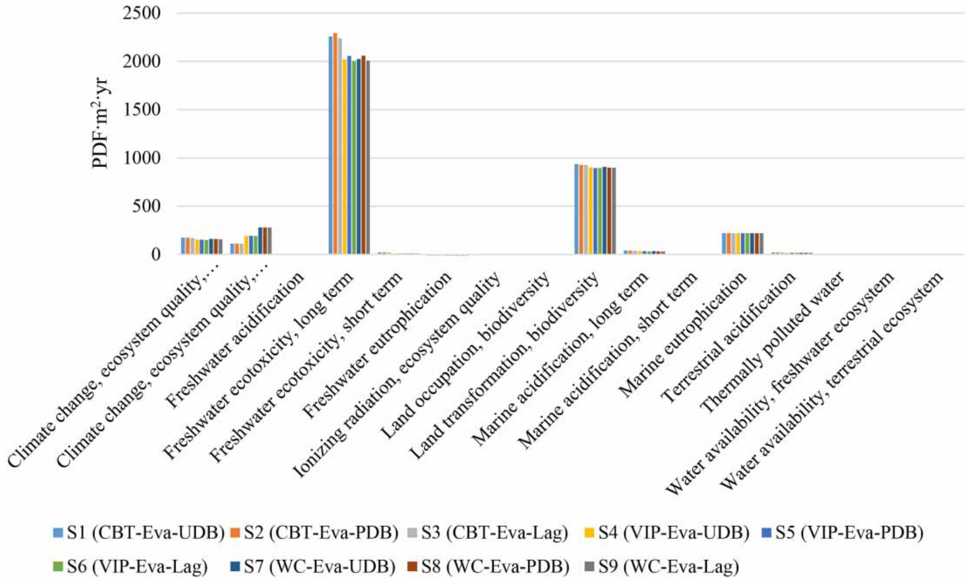


Figure 6 | Potential ecosystem impacts of the examined systems at the midpoint level.

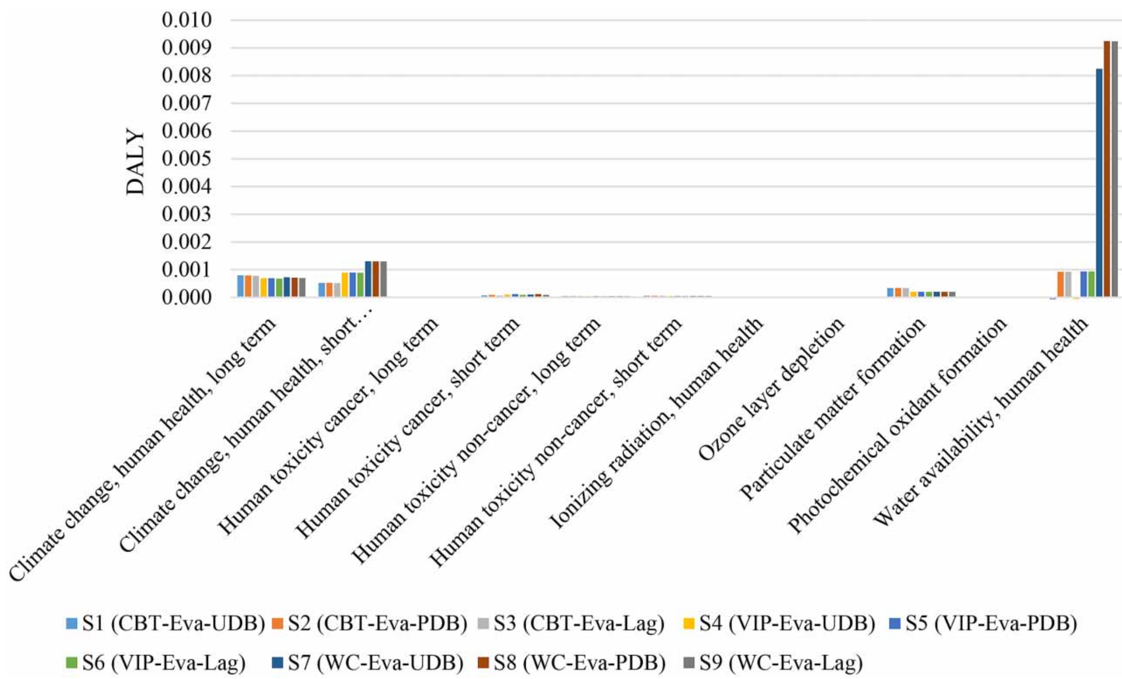


Figure 7 | Potential sanitary impacts of the examined systems at the midpoint level.

technologies, scenarios incorporating a PDB are 1.02 times more impactful than those with a lagoon, and 1.01 times more impactful than those with an UDB. Therefore, PDB emerges as the most impactful treatment technology in terms of ecosystem impact (2.69×10^2 PDF·m²·year), followed by UDB (2.48×10^2 PDF·m²·year) and lagoon (2.12×10^2 PDF·m² year). These data suggest that both the examined sanitation systems and treatment technologies show relatively insignificant differences in terms of ecosystem impact.

Regarding potential impacts on human health, the ranking in descending order is as follows: S8 > S9 > S7 > S5 > S6 > S2 > S3 > S4 > S1. The results have also highlighted that, in terms of health impacts, systems equipped with a flush toilet are on average 4.51 times more impactful than those equipped with a VIP latrine and 4.85 times more impactful than those equipped with a CBT. Thus, the flush toilet appears as the most impactful toilet in terms of health impact (1.15×10^{-2} DALY), followed by the VIP latrine (2.74×10^{-3} DALY) and the CBT (2.64×10^{-3} DALY). Regarding treatment technologies, systems equipped with a PDB are on average 1.21 times more impactful than those equipped with an UDB and 1.01 times more impactful than those equipped with a lagoon. This suggests that the PDB is the most impactful treatment technology in terms of health impact (5.15×10^{-5} DALY), followed by the lagoon (1.62×10^{-6} DALY) and the UDB (-9.51×10^{-4} DALY).

3.2. Contribution analysis

A contribution analysis was carried out to identify the technologies and life cycle phases with the most impact, as well as the critical variables (hotspots). Three impact categories were selected: climate change, ecosystem quality, and human health. For ecosystems and human health, aquatic ecotoxicity and water availability were chosen respectively, as Figures 6 and 7 show that these indicators have the highest impact scores for these two impact categories.

3.2.1. Contribution to climate change

Table 5 presents the results of the contribution analysis related to climate change. The data indicate that, in scenarios including a drying bed (i.e., 66.7% of scenarios), it is the treatment technologies, particularly their utilization phase, that have the greatest impact on climate. Indeed, in these scenarios, the utilization phase of the drying bed is responsible for 57.1–90.7% of the total impact, depending on the scenario considered. This is mainly explained by GHG emissions resulting from the degradation process of fecal sludge in these technologies.

The utilization phase of toilets comes second, with a contribution of 9.00–42.1% in scenarios involving a drying bed, and first in scenarios equipped with a lagoon (97.7–98.6% of the overall impact). The impact of toilets is mainly due to GHG emissions resulting from the degradation of fecal sludge (4.50–82.0%), the use of toilet paper (3.41–39.0%), and the use of wood shavings in scenarios involving a CBT (0.90–9.71%).

The sludge evacuation phase ranks third, with an impact ranging from 0.20 to 1.78%. However, in scenarios equipped with a lagoon (i.e., 33.3% of scenarios), it is the utilization phase of toilets that proves to be the most impactful, with a contribution ranging from 97.7 to 98.6% depending on the scenario considered, followed by the sludge evacuation process, which contributes 1.24–2.19% of the overall climate impact of the system.

As indicated in the work of Jean-Baptiste & Monette (2024), the adoption of practices such as the use of locally manufactured recycled paper, wood residues from carpentry and joinery workshops, and the use of ash as litter could mitigate the environmental impact of sanitation systems on climate change.

Table 5 | Contribution to climate change

Elements evaluated	S1 CBT-Eva-UDB	S2 CBT-Eva-PDB	S3 CBT-Eva-Lag	S4 VIP-Eva-UDB	S5 VIP-Eva-PDB	S6 VIP-Eva-Lag	S7 WC-Eva-UDB	S8 WC-Eva-PDB	S9 WC-Eva-Lag
Toilet construction	0.04%	0.02%	0.17%	0.08%	0.03%	0.24%	0.09%	0.04%	0.21%
Toilet utilization	23.4%	9.01%	97.7%	33.5%	14.1%	98.0%	42.1%	19.2%	98.6%
– GHG emission	11.8%	4.5%	49.0%	25.4%	10.7%	74.3%	35.0%	16.0%	82.0%
– Toilet paper	9.37%	3.61%	39.0%	8.11%	3.41%	23.7%	7.09%	3.22%	16.6%
– Wood shavings	2.33%	0.90%	9.71%	N/A	N/A	N/A	N/A	N/A	N/A
Toilet end-of-life	−0.02%	−0.01%	−0.08%	0.00%	0.00%	0.00%	0.00%	0.00%	−0.01%
Evacuation	0.53%	0.20%	2.19%	0.61%	0.26%	1.78%	0.53%	0.24%	1.24%
Treatment tech. construction	0.29%	0.11%	0.02%	0.25%	0.10%	0.01%	0.22%	0.09%	0.01%
Treatment tech. utilization	75.8%	90.7%	0.00%	65.6%	85.5%	0.00%	57.1%	80.5%	0.00%
– GHG emission	75.7%	90.7%	0.00%	65.5%	85.5%	0.0%	57.0%	80.5%	0.00%
– Sands extraction	0.12%	N/A	0.00%	0.10%	N/A	0.00%	0.09%	N/A	0.00%
Treatment tech. end-of-life	−0.06%	−0.02%	0.00%	−0.05%	−0.02%	0.00%	−0.05%	−0.02%	0.00%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

3.2.2. Ecosystem impact: contribution to long-term aquatic ecotoxicity

Table 6 presents the contribution to long-term aquatic ecotoxicity. The analysis of the results reveals that the utilization phase of toilets represents 92.5–97.9% of the total impact. Again, toilet paper is the main contributor, representing 83.8–95.8% of the impact, followed by litter, responsible for 12.0–12.2%. In second position, the evacuation link contributes 1.84–4.00% to the total impact. Treatment remains, once again, the least impactful link of the system, with an impact ranging from 0.06 to 2.53%.

3.2.3. Human health impact: contribution to water availability

Table 7 presents the contribution to water availability. These data indicate that the toilet utilization phase is the most impactful (except in Scenarios 1 and 4), ranging from 98.8 to 112%. This predominance is primarily attributed to water used for handwashing and toilet flushing in Scenarios 7–9. Toilet paper ranks second, contributing from 2.67 to 26.7% depending on the scenario considered, and litter wood shavings third, contributing from −2.00 to 26.4%.

The evacuation phase comes after the utilization phase and represents −11.9 to 0.92% of the overall impact. Finally, the treatment phase ranks third, responsible for −12.1 to 0.32%. However, Scenarios 1 and 4 have particularly high values compared to the other seven scenarios, reaching 1,394 and 1,705%, respectively. These high values are associated with the process of extracting sand from riverbeds for the utilization phase of the UDB, which seems to strongly affect river ecosystems, particularly by reducing water availability. These high values are mainly offset by the utilization phase of the CBT (−1,282%) and the VIP toilet (−1,600%), as these systems save water by not requiring flushing water.

The design and use of water-efficient toilets, requiring a smaller volume of water for flushing and handwashing, represents an effective solution to reduce the environmental impact associated with water consumption. Furthermore, previous

Table 6 | Contribution to long-term aquatic ecotoxicity

Elements evaluated	S1 CBT-Eva-UDB	S2 CBT-Eva-PDB	S3 CBT-Eva-Lag	S4 VIP-Eva-UDB	S5 VIP-Eva-PDB	S6 VIP-Eva-Lag	S7 WC-Eva-UDB	S8 WC-Eva-PDB	S9 WC-Eva-Lag
Toilet construction	0.50%	0.49%	0.50%	0.64%	0.63%	0.64%	1.65%	1.62%	1.66%
Toilet utilization	97.1%	95.8%	97.9%	95.0%	93.5%	95.8%	94.0%	92.5%	94.8%
– Toilet paper	85.0%	83.8%	85.7%	95.0%	93.5%	95.8%	94.0%	92.5%	94.8%
– Wood shavings	12.1%	12.0%	12.2%	N/A	N/A	N/A	N/A	N/A	N/A
End-of-life	−0.38%	−0.37%	−0.38%	−0.53%	−0.52%	−0.53%	−0.54%	−0.53%	−0.54%
Evacuation	1.87%	1.84%	1.89%	3.96%	3.90%	4.00%	3.96%	3.89%	4.00%
Treatment	0.87%	2.27%	0.06%	0.97%	2.53%	0.07%	0.97%	2.52%	0.07%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Table 7 | Contribution to water availability

Elements evaluated	S1 CBT-Eva-UDB	S2 CBT-Eva-PDB	S3 CBT-Eva-Lag	S4 VIP-Eva-UDB	S5 VIP-Eva-PDB	S6 VIP-Eva-Lag	S7 WC-Eva-UDB	S8 WC-Eva-PDB	S9 WC-Eva-Lag
Toilet construction	−0.24%	0.02%	0.02%	−0.92%	0.06%	0.06%	0.01%	0.01%	0.01%
Toilet utilization	−1,282%	98.8%	99.1%	−1,600%	99.4%	99.7%	112%	99.9%	100%
– Toilet paper	−345%	26.6%	26.7%	−422%	26.2%	26.3%	2.99%	2.67%	2.70%
– Wood shavings	26.4%	−2.00%	−2.00%	N/A	N/A	N/A	N/A	N/A	N/A
– Water	−964%	74.2%	74.4%	−1,178%	73.2%	73.4%	109%	97.2%	97.3%
End-of-life	0.08%	−0.01%	−0.01%	0.30%	−0.02%	−0.02%	0.00%	0.00%	0.00%
Evacuation	−11.9%	0.91%	0.92%	−4.11%	0.26%	0.26%	0.03%	0.03%	0.00%
Treatment	1,394%	0.32%	0.01%	1,705%	0.32%	0.01%	−12.1%	0.03%	0.00%
Total	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 8 | Sensitivity of the study to the amount of wood shavings used for (a) ecosystem impacts and (b) human health impacts.

recommendations on the use of recycled paper as well as sawdust or ash as alternatives to toilet paper and wood shavings remain relevant to mitigate this impact.

3.3. Sensitivity analysis

A sensitivity analysis was conducted to assess the influence of the mass of wood shavings used on the study results, given that litter is one of the two main critical variables identified. To do this, the mass of wood shavings used (1,170 kg) was increased, and then decreased by 33.3% ($\pm$390 kg). Figure 8(a) and 8(b) presents the results of the sensitivity analysis for both potential ecosystem and human health impacts. The results show that the mass of litter used does not affect the study results for health impacts. On the other hand, for ecosystem impacts, there is a slight change in results when the mass of litter decreases by 33.3%, particularly for Scenarios 1 and 3, which move from second and third place to third and fifth place, respectively.

4. CONCLUSION

This study aimed to compare different on-site sanitation systems using drying beds or lagoons for the treatment of human excreta in Haiti, by applying the environmental LCA. Nine scenarios were developed, comprising three successive stages: toilet, evacuation, and treatment of fecal sludge, with the functional unit being the management of 1 ton of fecal sludge (wet basis) over 1 year.

The results indicate that toilets, particularly their utilization phase, are the most impactful component, while the treatment phase is the least impactful. The critical variables identified include the use of toilet paper, wood shavings, GHG emissions, water usage, and the transportation of fecal sludge. The use of recycled paper, sawdust, or ash as litter, as well as water-efficient toilets, could reduce health and environmental impacts.

To better guide decisions on sanitation systems to be prioritized in low-income tropical countries, the study suggests combining LCA with Life Cycle Cost Assessment (LCCA) and Social Life Cycle Assessment (SLCA). This integrated approach will allow for the consideration of environmental, economic, and social aspects, thus promoting more informed and sustainable decisions regarding on-site sanitation.

ACKNOWLEDGEMENTS

The lead author expresses gratitude to Lécopot for providing the necessary data for modeling the container-based toilet and to EAWAG-SANDEC for providing the data related to drying beds.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information

CONFLICT OF INTEREST

The authors declare there is no conflict.

REFERENCES

Aguilar, Y., Tadiosa, E. & Tondo, J. (2014) A comparative study on wastewater treatment methods of selected multinational and local beverage companies in the Philippines and their effects on the environment, *IJESD*, **5**, 570–574. https://doi.org/10.7763/IJESD.2014.V5.548.

Andriani, D., Wresta, A., Saepudin, A. & Prawara, B. (2015) A review of recycling of human excreta to energy through biogas generation: Indonesia case, *Energy Procedia*, **68**, 219–225. https://doi.org/10.1016/j.egypro.2015.03.250.

Bicalho, T., Sauer, I., Rambaud, A. & Altukhova, Y. (2017) LCA data quality: A management science perspective, *Journal of Cleaner Production*, **156**, 888–898. https://doi.org/10.1016/j.jclepro.2017.03.229.

Bouquet, C., (2013) La pauvreté, entre l'eau et le profit (Poverty, Between Water and Profit). In: Ayeb, H. & Ruf, T. (eds.) *Eaux, Pauvreté et Crises Sociales, Colloques et Séminaires*. Marseille: IRD Éditions, pp. 63–69. https://doi.org/10.4000/books.irdeditions.4812.

Bulle, C., Margni, M., Patouillard, L., Boulay, A.-M., Bourgault, G., Bruille, V., Cao, V., Hauschild, M., Henderson, A., Humbert, S., Kashef, S., Kounina, A., Laurent, A., Levasseur, A., Liard, G., Rosenbaum, R., Roy, P.-O., Shaked, S., Fantke, P. & Jolliet, O. (2019) IMPACT world+: A globally regionalized life cycle impact assessment method, *The International Journal of Life Cycle Assessment*, **24**, 1653–1674. https://doi.org/10.1007/s11367-019-01583-0.

Chandana, N. & Rao, B. (2022) A critical review on sludge management from onsite sanitation systems: A knowledge to be revised in the current situation, *Environmental Research*, **203**, 111812. https://doi.org/10.1016/j.envres.2021.111812.

Cofie, O. O., Agbottah, S., Strauss, M., Esseku, H., Montangero, A., Awuah, E. & Kone, D. (2006) Solid–liquid separation of faecal sludge using drying beds in Ghana: Implications for nutrient recycling in urban agriculture, *Water Research*, **40**, 75–82. https://doi.org/10.1016/j.watres.2005.10.023.

Cui, Y., Zhang, S., Chen, Z., Chen, R. & Deng, X. (2015) Greenhouse gas emissions from sludge treatment reed beds, *Water Science and Technology*, **71**, 1011–1018. https://doi.org/10.2166/wst.2015.018.

DINEPA, , OIEau & UNICEF (2013) Fiche technique – Dispositions constructives pour une toilette à fosse simple ventilée: exemple de dispositif réalisé en Haïti (Technical Sheet – Construction Guidelines for a Ventilated Single-Pit Latrine: Example of a Device Implemented in Haiti), in: Référentiel technique national EPA, République d'Haïti : Fascicule technique. DINEPA, Haïti, pp. 1–7.

Egloso, N. L., Seville, J. S. O. & Icay, C. L. (2015) Wastewater treatment facility of HIDECO sugar milling company (HISUMCO) In Kananga, Leyte Philippines: A Key to environmental management, *IJARCS*, **2**, 33–40.

Fabulous toilettes (2016) Fabrication d'une toilette sèche (Manufacturing of a dry toilet). Fabulous Toilettes. Available at: https://www.fabuloustoilettes.com/wp-content/uploads/plan-toilette-seche.pdf (Accessed 3.6.23).

Flores, L., García, J., Pena, R. & Garfí, M. (2019) Constructed wetlands for winery wastewater treatment: A comparative life cycle assessment, *Science of The Total Environment*, **659**, 1567–1576. https://doi.org/10.1016/j.scitotenv.2018.12.348.

Gabert, J., Santi, M., Oddo, S., Ily, J.-M. & LeJeune, T. (2018) *Mémento de L'assainissement (The Sanitation Handbook)*, 1st ed. France: GRET & Quæ.

Hyun, C., Burt, Z., Crider, Y., Nelson, K. L., Sharada Prasad, C. S., Rayasam, S. D. G., Tarpeh, W. & Ray, I. (2019) Sanitation for Low-Income regions: A cross-Disciplinary review, *Annual Review of Environment and Resources*, **44**, 287–318. https://doi.org/10.1146/annurev-environ-101718-033327.

ISO 14040 (2006) *Environmental Management – Life Cycle Assessment – Principles and Framework*. Geneva, Switzerland: International Organization for Standardization.

Jean, G., Bayard, R., Lacour, J. & Naquin, P. (2017) Assainissement par toilettes sèches à litière biomaîtrisée : Premiers résultats d'une expérimentation menée en milieu rural (Sanitation by dry toilets with biocontrolled litter: First results of an experiment carried out in a rural environment). *Déchets, Sciences et Techniques*, **74**, 1–9. https://doi.org/10.4267/dechets-sciences-techniques.3618.

Jean-Baptiste, D. (2019) *Diagnostic de l'organisation et de la gouvernance du secteur de l'Eau Potable et de l'Assainissement Haïtien (Diagnostic of the Organization and Governance of the Haitian Drinking Water and Sanitation Sector)*. *Master's thesis*. Port-au-Prince, Haiti: Université d'État d'Haïti.

Jean-Baptiste, D. & Monette, F. (2024) Comparative life cycle assessment of excreta management systems through composting and biomethanization: Case of a low-income tropical country, *Water Science and Technology wst*, **89**, 2024184. https://doi.org/10.2166/wst.2024.184.

Jean-Baptiste, D., De Giudici, P. & Monette, F. (2023) Quantitative microbial risk assessment associated with the use of container-based toilets in Haiti, *Water Science and Technology wst*, **88**, 2023274. https://doi.org/10.2166/wst.2023.274.

Jha, A. K. & Bajracharya, T. R. (2014). 'Wastewater Treatment Technologies in Nepal', Presented at the *Proceedings of IOE Graduate Conference*. Department of Mechanical Engineering, Central Campus, Pulchowk. Nepal: Institute of Engineering, Kathmandu, pp. 76–81.

Johnson, J., Zakaria, F., Nkurunziza, A. G., Way, C., Camargo-Valero, M. A. & Evans, B. (2022) Whole-system analysis reveals high greenhouse-gas emissions from citywide sanitation in Kampala, Uganda, *Communications Earth & Environment*, **3**, 1–10. https://doi.org/10.1038/s43247-022-00413-w.

Jolliet, O., Saadé-Sbeith, M., Shaked, S., Jolliet, A. & Crettaz, P. (2015) *Environmental Life Cycle Assessment*, 1st ed. Boca Raton: CRC Press, Taylor & Francis Group.

Jolliet, O., Saadé, M., Crettaz, P., Jolliet-Gavin, N. & Shaked, S. (2017) *Analyse du cycle de vie: Comprendre et réaliser un écobilan (Life Cycle Assessment: Understanding and Conducting Environmental Life Cycle Assessment)*, 3rd ed, Science & ingéniérie de l'environnement. Suisse: PPUR Presses polytechniques.

Koottatep, T., Surinkul, N., Polprasert, C., Kamal, A., Koné, D., Montangero, A., Heinss, U. & Strauss, M. (2005) Treatment of septage in constructed wetlands in tropical climate: Lessons learnt from seven years of operation, *Water Science and Technology : A Journal of the International Association on Water Pollution Research*, **51**, 119–126. https://doi.org/10.2166/wst.2005.0301.

Mara, D. (1984) *The design of ventilated improved pit latrines (Technical Note No. TAG13)*. Washington, DC: World Bank Group.

Mara, D. (2004) *Domestic Wastewater Treatment in Developing Countries*. London: Routledge. https://doi.org/10.4324/9781849771023.

Mng'ombe, M. H., Chunga, B. A., Mtonga, E. W., Chidya, R. C. G. & Malota, M. (2023) Infilling missing data and outliers for a conventional sewage treatment plant using a self-organizing map: A case study of kauma sewage treatment plant in Lilongwe, Malawi, *H2Open Journal*, **6**, 280–296. https://doi.org/10.2166/h2oj.2023.013.

Mohammadi, M. & Fataei, E. (2019) Comparative life cycle assessment of municipal wastewater treatment systems: Lagoon and activated sludge, *Caspian Journal of Environmental Sciences*, **17**, 327–336. https://doi.org/10.22124/cjes.2019.3806.

Moni Silva, A. P., Barros, R. M., Silva Lora, E. E., Díaz Flórez, C. A., Silva dos Santos, I. F., Cassia Crispim, A. M. d. & Grillo Renó, M. L. (2023) Characterization and evaluation of the life cycle of energy use from drying bed sludge, *Energy*, **263**, 125630. https://doi.org/10.1016/j.energy.2022.125630.

Monvois, J., Gabert, J., Frenoux, C. & Guillaume, M. (2010) *How to Select Appropriate Technical Solutions for Sanitation, Methodological Guides*. France: GRET & PS-Eau

Odey, E. A., Li, Z., Zhou, X. & Kalakodio, L. (2017) Faecal sludge management in developing urban centers: A review on the collection, treatment, and composting, *Environmental Science and Pollution Research*, **24**, 23441–23452. https://doi.org/10.1007/s11356-017-0151-7.

Pierre, C. E. D. (2020) La Colonisation et le désastre écologique d'Haïti (Colonization and the ecological disaster of Haiti). Concepts-Clés de la Communication environnementale et du développement durable 128–134.

Pocock, J., Septien, S., Makununika, B. S. N., Velkushanova, K. V. & Buckley, C. A. (2022) Convective drying kinetics of faecal sludge from VIP latrines, *Heliyon*, **8**, 09221. https://doi.org/10.1016/j.heliyon.2022.e09221.

Preux, J. F. S. (2022) *Water Security in Haiti: Do National Stakeholders Consider Water and Sanitation as a Priority in Development*. *Master's thesis*. Alabama, United States: Auburn University

Samal, K., Moulick, S., Mohapatra, B. G., Samanta, S., Sasidharan, S., Prakash, B. & Sarangi, S. (2022) Design of faecal sludge treatment plant (FSTP) and availability of its treatment technologies, *Energy Nexus*, **7**, 100091. https://doi.org/10.1016/j.nexus.2022.100091.

Sasse, L. (1998) *Decentralised Wastewater Treatment in Developing Countries, BORDA*. ed. Bremen, Germany.

Singh, B. & Cohen, M. J. (2014) *Climate Change Resilience: The Case of Haiti (Oxfam Research Reports)*. Oxford, United Kingdom: Oxfam.

Sorrenti, A., Corsino, S. F., Traina, F., Viviani, G. & Torregrossa, M. (2022) Enhanced sewage sludge drying with a modified solar greenhouse, *Clean Technologies*, **4**, 407–419. https://doi.org/10.3390/cleantechnol4020025.

Strande, L., Ronteltap, M. & Brdjanovic, D. (2014) *Faecal Sludge Management: Systems Approach for Implementation and Operation*, 1st ed. London, United Kingdom: IWA Publishing.

Thompson, M., Moussavi, S., Li, S., Barutha, P. & Dvorak, B. (2022) Environmental life cycle assessment of small water resource recovery facilities: Comparison of mechanical and lagoon systems, *Water Research*, **215**, 118234. https://doi.org/10.1016/j.watres.2022.118234.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, P. & Zurbrügg, C. & SIA ingénierie-conseil (2016) *Compendium of Sanitation Systems and Technologies*, 2nd ed. Dubendorf, Suisse: Eawag.

Uggetti, E., Ferrer, I., Molist, J. & García, J. (2011) Technical, economic and environmental assessment of sludge treatment wetlands, *Water Research*, **45**, 573–582. https://doi.org/10.1016/j.watres.2010.09.019.

Uggetti, E., García, J., Lind, S. E., Martikainen, P. J. & Ferrer, I. (2012) Quantification of greenhouse gas emissions from sludge treatment wetlands, *Water Research*, **46**, 1755–1762. https://doi.org/10.1016/j.watres.2011.12.049.

UNDP (2021) *Rapport sur l̂état de lieux des ressources en eau : Évaluation de l'impact des changements climatiques (cc) sur les ressources en eau et l'appui au développement des solutions novatrices (Report on the State of Water Resources: Assessment of the Impact of Climate Change (CC) on Water Resources and Support for the Development of Innovative Solutions)*. UNDP.

Weidema, B. P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Vadenbo, C. O. & Wernet, G. (2013) *Overview and Methodology. Data Quality Guideline for the Ecoinvent Database Version 3* (Ecoinvent Report No. 1 v3). St. Gallen, Switzerland: Swiss Centre for Life Cycle Inventories.

World Bank (2021) Climate Change Knowledge Portal [WWW Document]. Available at: https://climateknowledgeportal.worldbank.org/ (Accessed 9.13.24).

World Population Review (2024) Where is Haiti in the World? [WWW Document]. Available at: https://worldpopulationreview.com/countries/haiti/location (Accessed 9.14.24).

First received 28 June 2024; accepted in revised form 2 October 2024. Available online 13 November 2024