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Comparative life cycle assessment of excreta management systems through composting and biomethanization: Case of a low-income tropical country

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ABSTRACT

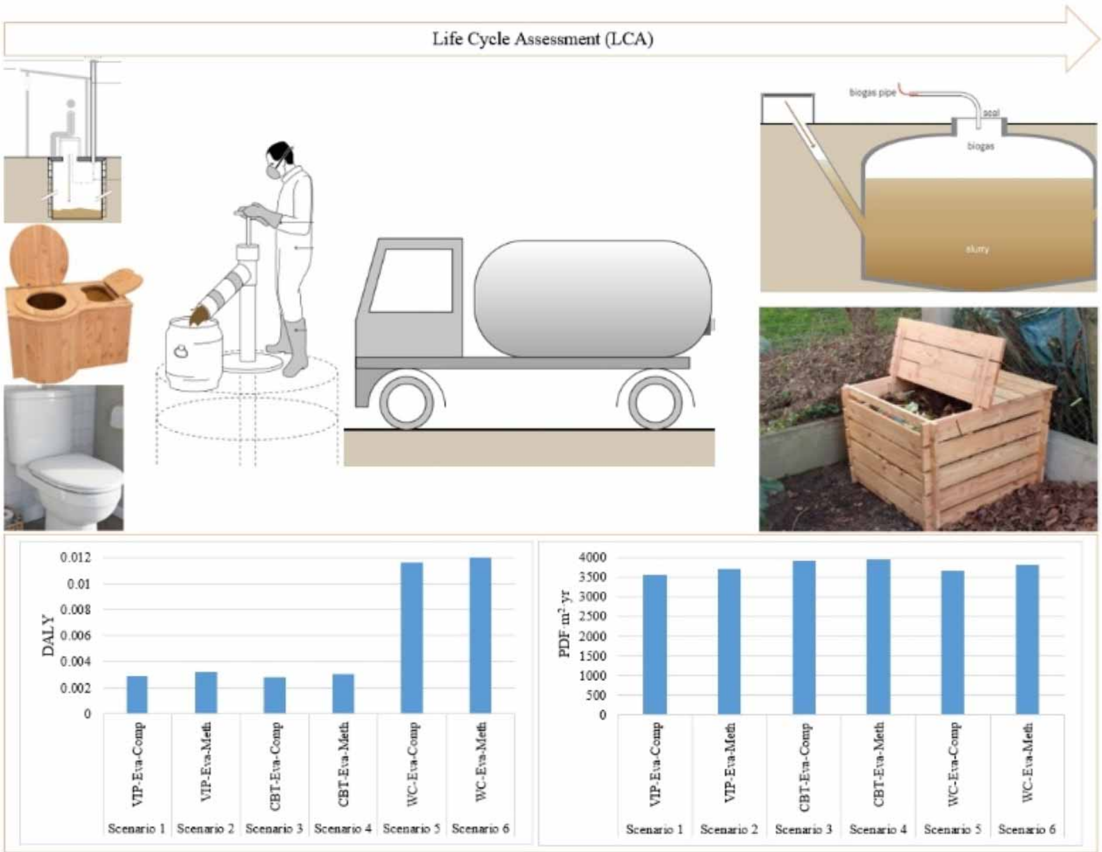
Low-income tropical regions, such as Haiti, grapple with environmental issues stemming from inadequate sanitation infrastructure for fecal sludge management. This study scrutinizes on-site sanitation systems in these regions, evaluating their environmental impacts and pinpointing improvement opportunities. The focus is specifically on systems integrating excreta valorization through composting and/or anaerobic digestion. Each system encompasses toilet access, evacuation, and sludge treatment. A comparative life cycle assessment was undertaken, with the functional unit managing one ton of excreta in Haiti over a year. Six scenarios representing autonomous sanitation systems were devised by combining three toilet types (container-based toilets (CBTs), ventilated improved pit (VIP) latrines, and flush toilets (WC)) with two sludge treatment processes (composting and biomethanization). Biodigester-based systems exhibited 1.05 times higher sanitary impacts and 1.03 times higher ecosystem impacts than those with composters. Among toilet types, CBTs had the lowest impacts, followed by VIP latrines, with WCs having the highest impacts. On average, WC scenarios were 3.85 times more impactful than VIP latrines and 4.04 times more impactful than those with CBTs regarding human health impact. Critical variables identified include the use of toilet paper, wood shavings, greenhouse gas emissions, and construction materials.

Key words: environment, excreta, Haiti, health, LCA, sanitation

HIGHLIGHTS

- This study analyzes the on-site sanitation chain components throughout their life cycle, assessing three types of toilets in Haiti and two sludge valorization scenarios, resulting in six scenarios.
- Scenario 6 had the highest sanitary impact, while Scenario 3 had the lowest.
- Scenario 4 showed the highest ecosystem impacts, with Scenario 1 displaying the lowest impact.
- Key hotspots identified: toilet paper, wood shavings and GHG emissions.

GRAPHICAL ABSTRACT



INTRODUCTION

The planet Earth is currently facing unprecedented population growth, leading to an increase in the consumption of natural resources and, consequently, a growing production of solid and liquid waste, as well as gas emissions, particularly in urban areas (Maja & Ayano 2021; Voukkali *et al.* 2023). These residues exert increasing pressure on ecosystems, contributing to a growing environmental pollution that could have a negative impact on both the environment and human health.

Among these residues are wastewater and fecal sludge. Wastewater is typically managed by centralized sanitation systems, which are commonly used in industrialized countries (Gabert *et al.* 2018), with sewage sludge resulting from treatment processes. Fecal sludge, on the other hand, falls under on-site sanitation, which is primarily used in low-income countries (Strande *et al.* 2014; Gabert *et al.* 2018; Penn *et al.* 2018). The untreated discharge of these residues into the environment can lead to health problems, including oro-fecal infections and diseases, as well as environmental issues such as eutrophication of aquatic ecosystems (Mara 2004; Strande *et al.* 2014; Gabert *et al.* 2018). The implementation of effective and sustainable sanitation technologies and systems to address this situation is, therefore, a necessity. However, ensuring that these solutions result in real environmental benefits becomes crucial to avoid simply shifting the problem from one place to another and/or from one form to another. Life cycle assessment (LCA) allows for the quantification of environmental impacts associated with various sanitation systems and technologies and facilitates their comparison. This ensures better decision-making and, consequently, the implementation of more sustainable sanitation systems by minimizing negative effects on the environment and human health.

While numerous LCA studies have been conducted on centralized sanitation systems (Renou 2006; Reverdy & Pradel 2010; Butin *et al.* 2011; Thibodeau *et al.* 2014; Risch *et al.* 2021; Rodrigues *et al.* 2021), there has been limited research dedicated to on-site systems. Furthermore, existing studies have primarily focused on specific components of the system rather than the entire on-site sanitation system. Some studies have addressed toilets (Anastasopoulou *et al.* 2018a, 2018b), while others have explored technologies for the treatment and/or valorization of excreta (Gallego-Schmid & Tarpani 2019; Imansyah & Karnaningroem 2020). A few studies have examined all components of the system (Benetto *et al.* 2009; Anand & Apul 2011; Gao *et al.* 2017; Shi *et al.* 2018; Risch *et al.* 2021); however, they generally focused on centralized systems, occasionally incorporating scenarios based on on-site sanitation systems. This research aims to contribute to filling this gap in scientific literature by focusing exclusively on on-site sanitation systems.

The main objective of this study is to compare the main on-site sanitation systems that have been implemented in low-income tropical countries using LCA, which is based on a case study in Haiti. Specifically, this approach aims to identify: (i) the systems most suitable for the sanitary and environmental context of these countries and (ii) the sensitive variables within each system considered, thereby identifying areas for improvement. The study also seeks to provide a decision support tool for on-site sanitation, offering key information on the environmental performance of the various systems considered. The results of this research are primarily targeted at policymakers, the scientific community, and anyone interested in the research and implementation of sustainable and inclusive on-site sanitation technologies/systems. By enhancing the understanding of on-site sanitation systems and their impacts, this study will contribute to the continuous improvement of these systems and the promotion of more sustainable solutions in low-income tropical countries.

METHODOLOGY

Scope of the study

Description of the systems assessed

The sanitation systems studied each consist of three successive components: (i) toilet access, (ii) evacuation (excreta disposal), and (iii) fecal sludge treatment (Gabert *et al.* 2018). The 'evacuation' component encompasses toilet emptying and the transport of fecal sludge to a treatment site. The 'treatment' component includes the processing and valorization of the sludge. Three toilet technologies were considered: container-based toilet (CBT), ventilated improved pit (VIP) latrine, and flush toilet (WC). An adaptation of data from DINEPA *et al.* (2013) was conducted to model the toilets, particularly the VIP latrine. Specifically, each examined toilet is constructed on an area of 1.70 m^2, with dimensions of 1.70 m in length, 1.00 m in width, and 1.80 m in height. The VIP and WCs are connected to a pit with a capacity of 1.92 m^3. The foundation of these toilets is made of concrete, while the superstructure and roofing are constructed of wood and aluminum, respectively.

Regarding the emptying of excreta from VIP latrines and WCs, this is carried out by manual emptiers, known as '*bayakous*' in Haiti, followed by transportation using sewage trucks. The use of a manual pump such as the Gulper pump is recommended for extracting sludge from the pit to prevent direct contact between *bayakous* and excreta. This pump can be locally manufactured using available materials (Oxfam 2007; Strande *et al.* 2014; Gabert *et al.* 2018).

As for CBT, the sludge management process begins with users voluntarily bringing their excreta, which contains wood shavings, to a collection point. Once collected, the fecal sludge, totaling 1 ton (1,000 kg), is stored in five 208 L (55 gal.) drums. Subsequently, these drums are transported by truck to a treatment station that is located 10 km away from the initial extraction point. The treatment and/or valorization of excreta are then carried out using anaerobic digestion and/or composting processes. These methods allow for the valorization of sludge by producing biogas intended for use as cooking fuel instead of charcoal or natural gas, or compost that can be used as organic fertilizer, replacing chemical fertilizers. The considered scenarios are listed in Table 1.

Table 1 | Presentation of the six scenarios considered in the study

Scenarios	First component	Second component	Third component
Scenario 1	VIP latrine	Evacuation	Composting
Scenario 2			Biomethanization
Scenario 3	CBT		Composting
Scenario 4			Biomethanization
Scenario 5	WC		Composting
Scenario 6			Biomethanization

Function and functional unit

The studied sanitation systems have the primary function of managing human excreta to protect human health and the environment from the potential hazards of fecal pollution. Multifunctional in nature, these systems also serve the following co-functions: (i) compost production through composting and/or (ii) biogas production through anaerobic digestion. The functional unit of the study is defined as follows: 'manage 1 ton of fecal sludge (wet basis) in Port-au-Prince (Haiti) over one year'.

The fecal sludge being considered contains (i) 23.4% dry matter (DM), which is equivalent to 234 kg of DM per ton (those from CBT are composed of 40.0% DM due to the addition of wood shavings), (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 of 635 kg/t. These data were obtained from the arithmetic average of the values presented by Strande *et al.* (2014) and Andriani *et al.* (2015). The data concerning the amount of feces produced per person per year come from the study conducted by Jean *et al.* (2017), which estimates that an average Haitian produces between 120 and 130 g of feces (wet basis) per day. An arithmetic average of 125 g of feces per person per day was therefore applied.

System boundaries

The studied system is characterized by a holistic approach that considers the entire life cycle of the analyzed systems and technologies. The Gulper pump is not used during the evacuation of sludge from CBT, as it does not have a pit. Figures 1 and 2 illustrate the system boundaries, delineating the elements included in the life cycle analysis of the evaluated systems. This approach allows for more relevant results on the environmental impacts of each technology throughout its life cycle, from manufacturing to use, including transportation and waste disposal.

Impact assessment method and allocation rule

To assess the potential environmental impacts of the studied systems, the Impact World+ method (Damage 1.47), as described by Bulle *et al.* (2019), was employed. Additionally, a sensitivity analysis was conducted using the Impact 2002+ method, comparing the results obtained with the Impact World+ method.

Given that these systems are multifunctional and generate co-products such as compost and/or biogas, the system expansion allocation method was applied in accordance with ISO 14044 (2006). This allocation approach assigns to co-products their share of the environmental burden, thereby highlighting the avoided impacts. It also enabled the consideration of recycling certain products (steel, plastics, wood, and aluminum) during the dismantling of the system at the end of its life cycle.

Life cycle inventory assessment

The data used to model the studied systems come from various sources, including (i) a manufacturer of CBT named Lécopot, (ii) direct measurements conducted in the laboratory using an Ohaus Explorer balance model EX6202/E for parts with a mass less than 6.20 kg and a GKF 165aH balance for parts exceeding 6.20 kg, (iii) the technical reference developed by the National Directorate of Drinking Water and Sanitation in Haiti (DINEPA *et al.* 2013), (iv) the ecoinvent version 3.7 database, and (vi) scientific literature. Table 2 lists the specific sources of data used in the study, along with an evaluation of the data quality, adhering to the criteria outlined by Weidema *et al.* (2013) and Bicalho *et al.* (2017).

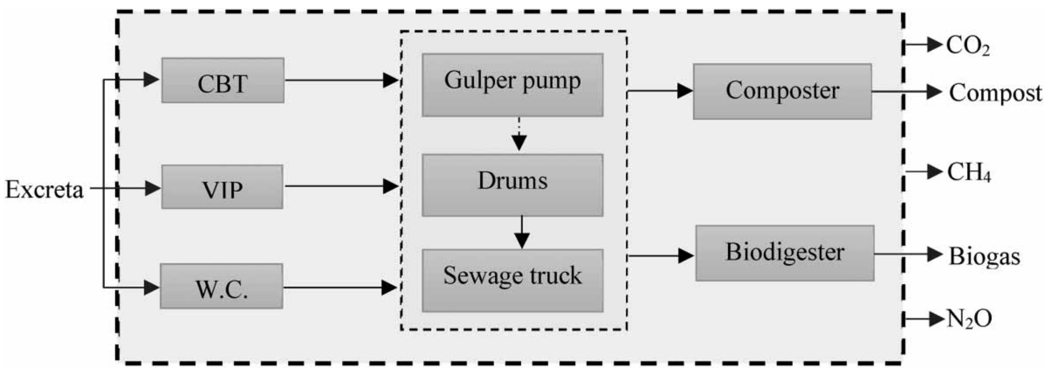


Figure 1 | System boundaries.

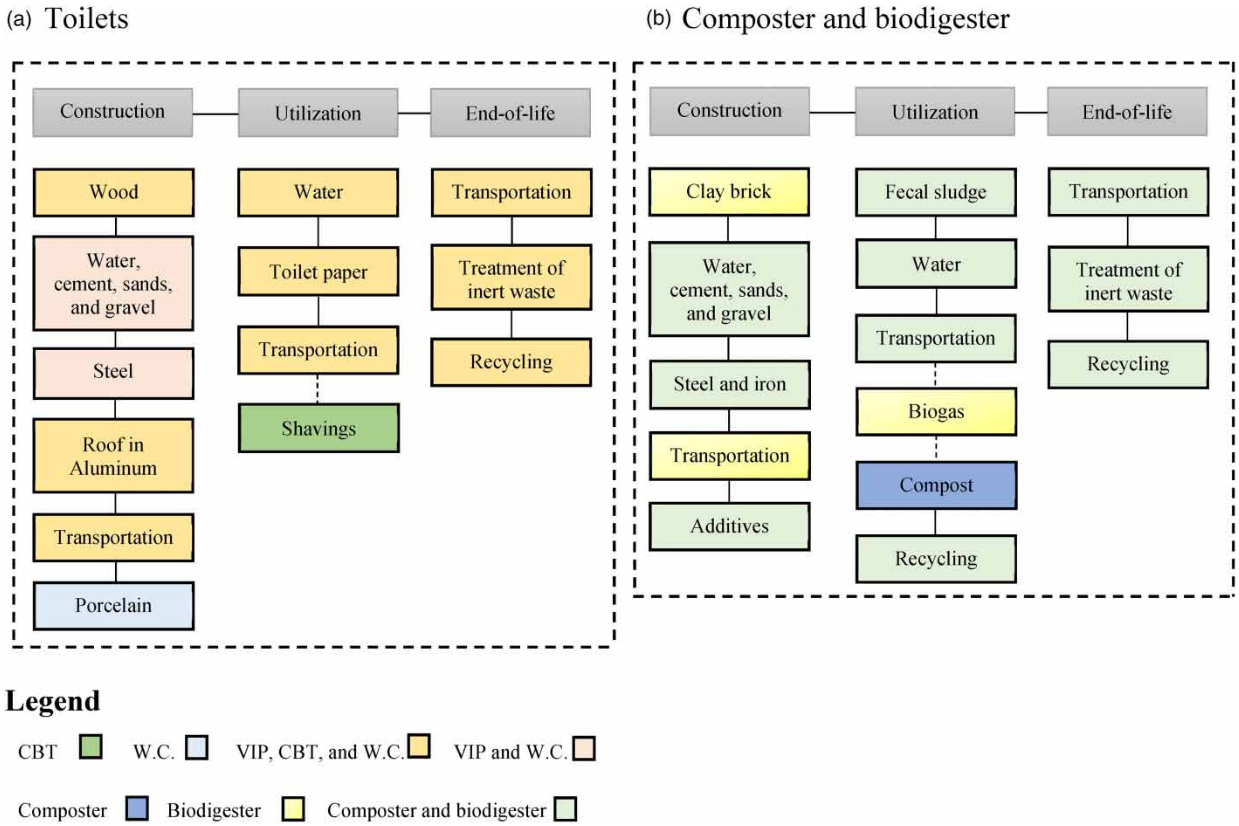


Figure 2 | Main components of the upstream and downstream links. (a) Toilets and (b) composter and biodigester.

Table 2 | Sources of life cycle inventory data used in the study

Types of data	Data quality	References
CBT	Good quality (1, 4, 5, 1, 1)	Julien BOYER, manager of Lécopot, and Fabulous toilettes (2016)
VIP latrine	Good quality (2, 4, 5, 3, 1)	DINEPA *et al.* (2013); Mara (1984); Tilley *et al.* (2014)
WC	Good quality (1, 4, 5, 1, 2)	Direct measurements in the laboratory, and DINEPA *et al.* (2013)
Gulper pump	Good quality (3, 4, 4, 2, 1)	Gabert *et al.* (2018); Strande *et al.* (2014)
Fecal sludge	Good quality (2, 2, 5, 1, 1)	Andriani *et al.* (2015); Strande *et al.* (2014)
Sewage truck	Good quality (1, 2, 5, 2, 3)	Ecoinvent database version 3.7
Composter	Good quality (2, 2, 4, 2, 3)	Ecoinvent database version 3.7
Biodigester	Good quality (3, 3, 4, 1, 2)	Andriani *et al.* (2015); Ioannou-Ttofa *et al.* (2021)

Equation (1) was used to estimate the amount of greenhouse gases (GHGs) emitted by the toilets examined. To reach the defined functional unit, 22 people per year are required. Regarding biomethanization, the gas emission data are based on an adaptation of the data provided by Ioannou-Ttofa *et al.* (2021). Table 3 presents detailed information on the emission factors used:

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

These data have been analyzed and normalized to correspond to the scale of the functional unit. Subsequently, they were modeled using the LCA software OpenLCA version 1.11.0. All information regarding inputs and outputs used in the modeling of the studied systems is accessible in the 'Supplementary Data'.

Table 3 | Information about the GHG emission factors used in the modeling of toilets and composting for the study

Technology	Emission rate (ER) and/or emission factor (EF)	References
CBT	ER = 0.454 kg CH_4/capita/year ER = 0.0661 kg N_2O/capita/year	Johnson *et al.* (2022)
VIP latrine	ER = 1.134 kg CH_4/capita/year ER = 0.0661 kg N_2O/capita/year	
WC	ER = 1.804 kg CH_4/capita/year ER = 0.0441 kg N_2O/ capita/year	
Composting	EF = 4.0 g CH_4/kg (or 4.0 kg CH_4/t) EF = 0.24 g N_2O/kg (or 0.24 kg de N_2O/t)	IPCC (2006)

RESULTS AND DISCUSSION

Assessment of the potential impacts of sanitation systems on human health

Table 4 and Figure 3 present the results of the health impact assessment of the studied sanitation systems. Each scenario value has been normalized by dividing it by the value of Scenario 6, and the corresponding ratio is indicated above the histogram bars in Figure 3. Thus, Figure 3 illustrates both the overall and relative impact of each scenario. The analysis of the results reveals the descending order of scenarios with the most impact on human health. Scenario 6 has the highest impact, followed by Scenario 5, Scenario 4, Scenario 2, Scenario 1, and Scenario 3. These results indicate that systems with WCs (Scenarios 5 and 6) are, on average, 3.85 times more impactful than those with VIP latrines (Scenarios 1 and 2) and 4.04 times more impactful than those with CBT (Scenarios 3 and 4). Moreover, when comparing two systems equipped with the same type of toilets, those incorporating a biodigester were found to be, on average, 1.05 times more impactful than those equipped

Table 4 | Impacts on human health, in DALYs, and impact rate, in percentage

Indicator	Scenario 1 VIP-Eva-Comp	Scenario 2 VIP-Eva-Meth	Scenario 3 CBT-Eva-Comp	Scenario 4 CBT-Eva-Meth	Scenario 5 WC-Eva-Comp	Scenario 6 WC-Eva-Meth
Climate change, human health, long term	6.84×10^{-4} (23.5%)	8.49×10^{-4} (26.3%)	8.10×10^{-4} (29.0%)	9.42×10^{-4} (30.9%)	7.07×10^{-4} (6.07%)	8.72×10^{-4} (7.29%)
Climate change, human health, short term	8.91×10^{-4} (30.7%)	9.39×10^{-4} (29.1%)	5.29×10^{-4} (18.9%)	5.64×10^{-4} (18.5%)	1.30×10^{-3} (11.1%)	1.35×10^{-3} (11.2%)
Human to × icity cancer, long term	1.42×10^{-6} (0.05%)	1.54×10^{-6} (0.05%)	1.75×10^{-6} (0.06%)	1.80×10^{-6} (0.06%)	1.42×10^{-6} (0.01%)	1.54×10^{-6} (0.01%)
Human toxicity cancer, short term	1.00×10^{-4} (3.45%)	1.00×10^{-4} (3.11%)	7.84×10^{-5} (2.81%)	7.14×10^{-5} (2.34%)	1.00×10^{-4} (0.86%)	1.00×10^{-4} (0.84%)
Human toxicity non–cancer, long term	4.50×10^{-5} (1.55%)	4.85×10^{-5} (1.50%)	5.47×10^{-5} (1.9%)	5.63×10^{-5} (1.84%)	4.50×10^{-5} (0.39%)	4.85×10^{-5} (0.41%)
Human toxicity non-cancer, short term	4.62×10^{-5} (1.59%)	4.85×10^{-5} (1.50%)	5.41×10^{-5} (1.94%)	5.46×10^{-5} (1.79%)	4.62×10^{-5} (0.40%)	4.85×10^{-5} (0.41%)
Ionizing radiation, human health	3.83×10^{-7} (0.01%)	4.26×10^{-7} (0.01%)	5.27×10^{-7} (0.02%)	5.59×10^{-7} (0.02%)	3.80×10^{-7} (0.00%)	4.24×10^{-7} (0.00%)
Ozone layer depletion	4.35×10^{-8} (0.00%)	5.31×10^{-8} (0.00%)	5.71×10^{-8} (0.00%)	6.50×10^{-8} (0.00%)	4.34×10^{-8} (0.00%)	5.30×10^{-8} (0.00%)
Particulate matter formation	2.00×10^{-4} (6.88%)	2.20×10^{-4} (6.80%)	3.48×10^{-4} (12.4%)	3.55×10^{-4} (11.6%)	1.99×10^{-4} (1.71%)	2.18×10^{-4} (1.83%)
Photochemical oxidant formation	3.46×10^{-8} (0.00%)	4.25×10^{-8} (0.00%)	5.49×10^{-8} (0.00%)	6.12×10^{-8} (0.00%)	3.44×10^{-8} (0.00%)	4.24×10^{-8} (0.00%)
Water availability, human health	9.39×10^{-4} (32.3%)	1.02×10^{-3} (31.6%)	9.19×10^{-4} (32.9%)	1.01×10^{-3} (33.0%)	9.24×10^{-3} (79.4%)	9.33×10^{-3} (78.0%)

VIP: VIP latrine; CBT: Container-based toilet; WC: Flush toilet; Eva: Evacuation; Comp: composting; Meth: methanization.

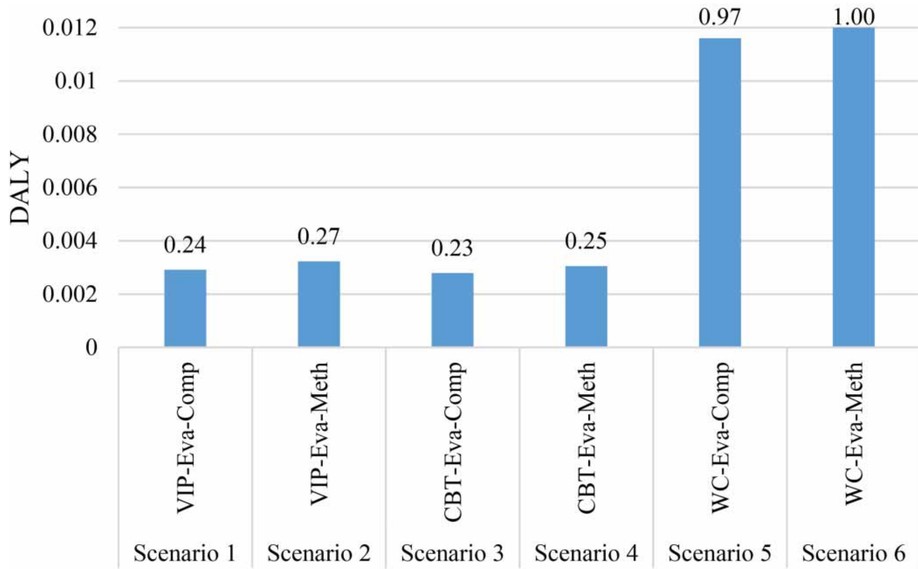


Figure 3 | Classification of scenarios in terms of health impact, with ratios compared to Scenario 6 overlaid on the bars.

with a composter, depending on the scenario considered. However, the health impact of the biodigester (3.62×10^{-4} DALY) is 10.4 times higher than the impact of the composter (3.47×10^{-5} DALY).

The data presented as percentages in Table 4 indicate the contribution of impact indicators to the global impact. Analyzing this data reveals that the indicators with the greatest impact on the global result are water availability (responsible for 31.6–79.4% of the overall impact depending on the scenario considered), short- and long-term climate change (responsible for 6.07–30.9% of the overall impact), particulate matter formation ($PM_{2.5}$, responsible for 1.71–12.4% of the overall impact), and short-term cancer (responsible for 0.84–3.45% of the overall impact). Conversely, the indicators with the lowest percentages are human toxicity cancer, long-term, photochemical oxidant formation, ozone layer depletion, and ionizing radiation, each responsible for less than 0.10% of the overall impact.

Assessment of impacts on ecosystems

Table 5 and Figure 4 present the results of the ecosystem impact on the sanitation systems examined. The ratio, representing the relationship of each scenario to Scenario 6, is indicated above the histogram bars in Figure 4, which illustrates both the overall and relative impact of each scenario. The results reveal a decreasing order of impacts on ecosystems, starting with Scenario 4 having the highest impact, followed by Scenario 3, Scenario 6, Scenario 2, Scenario 5, and finally Scenario 1, which has the least impact among all evaluated scenarios.

These results emphasize once again that scenarios incorporating a biodigester have, on average, an impact of 1.03 times higher than those incorporating a composter. However, the ecosystem impact of the biodigester (4.26×10^2 PDF·m^2·year) is 1.72 times higher than the impact of the composter (2.48×10^2 PDF·m^2·year). Scenarios with a CBT have the highest impact, while those with a VIP latrine have the lowest impact. Indeed, scenarios equipped with a CBT are, on average, 1.05 times more impactful than those equipped with a WC and 1.08 times more impactful than those containing a VIP latrine.

The percentages in Table 5 represent the respective contribution of each impact indicator to the global impact. These data reveal that, among the impact indicators, long-term freshwater ecotoxicity (responsible for 55.7–61.0% of the overall impact depending on the scenario considered), land transformation (responsible for 23.6–25.2% of the overall impact), marine eutrophication (responsible for 5.63–6.23% of the overall impact), and short- and long-term climate change (responsible for 2.91–7.66% of the overall impact) are contributing the most to the overall impact. Conversely, indicators such as freshwater eutrophication, ionizing radiation, 'water availability, terrestrial and freshwater ecosystems,' and thermally polluted water contribute the least, each responsible for less than 0.01% of the overall impact. Negative values for freshwater eutrophication have been identified for all scenarios, indicating that ecosystem impacts have been avoided.

Table 5 | Impacts on ecosystems, in PDF·m^2·year, and impact rate, in percentage

Indicator	Scenario 1 VIP-Eva-Comp	Scenario 2 VIP-Eva-Meth	Scenario 3 CBT-Eva-Comp	Scenario 4 CBT-Eva-Meth	Scenario 5 WC-Eva-Comp	Scenario 6 WC-Eva-Meth
Climate change, ecosystem quality, long term	1.52×10^2 (4.28%)	1.88×10^2 (5.06%)	1.79×10^2 (4.55%)	2.08×10^2 (5.27%)	1.58×10^2 (4.33%)	1.95×10^2 (5.09%)
Climate change, ecosystem quality, short term	1.93×10^2 (5.42%)	2.03×10^2 (5.45%)	1.14×10^2 (2.91%)	1.22×10^2 (3.09%)	2.80×10^2 (7.66%)	2.90×10^2 (7.60%)
Freshwater acidification	2.68 (0.08%)	2.91 (0.08%)	3.21 (0.08%)	3.34 (0.08%)	2.66 (0.07%)	2.90 (0.08%)
Freshwater ecotoxicity, long term	2.03×10^3 (57.2%)	2.14×10^3 (57.5%)	2.39×10^3 (61.0%)	2.37×10^3 (60.0%)	2.04×10^3 (55.7%)	2.14×10^3 (56.1%)
Freshwater ecotoxicity, short term	10.4 (0.29%)	10.8 (0.29%)	20.5 (0.52%)	20.2 (0.51%)	10.3 (0.28%)	10.7 (0.28%)
Freshwater eutrophication	−9.18 (−0.25%)	−9.17 (−0.25%)	−9.11 (−0.23%)	−9.11 (−0.23%)	−9.17 (−0.25%)	−9.17 (−0.24%)
Ionizing radiation, ecosystem quality	3.48×10^{-8} (0.00%)	4.04×10^{-8} (0.00%)	5.07×10^{-8} (0.00%)	5.51×10^{-8} (0.00%)	3.46×10^{-8} (0.00%)	4.01×10^{-8} (0.00%)
Land occupation, biodiversity	1.85 (0.05%)	2.39 (0.06%)	4.77 (0.12%)	5.19 (0.13%)	1.84 (0.05%)	2.38 (0.06%)
Land transformation, biodiversity	8.96×10^2 (25.2%)	8.96×10^2 (24.1%)	9.30×10^2 (23.7%)	9.30×10^2 (23.6%)	9.00×10^2 (24.6%)	9.00×10^2 (23.6%)
Marine acidification, long term	33.4 (0.94%)	42.1 (1.13%)	41.6 (1.06%)	48.6 (1.23%)	33.0 (0.90%)	41.7 (1.09%)
Marine acidification, short term	3.62 (0.10%)	4.57 (0.12%)	4.51 (0.12%)	5.28 (0.13%)	3.58 (0.01%)	4.53 (0.12%)
Marine eutrophication	2.22×10^2 (6.23%)	2.22×10^2 (5.97%)	2.22×10^2 (5.64%)	2.22×10^2 (5.63%)	2.21×10^2 (6.06%)	2.22×10^2 (5.81%)
Terrestrial acidification	17.6 (0.50%)	19.3 (0.52%)	21.4 (0.55%)	22.4 (0.57%)	17.5 (0.48%)	19.2 (0.50%)
Thermally polluted water	2.44×10^{-4} (0.00%)	2.53×10^{-4} (0.00%)	3.02×10^{-4} (0.00%)	2.96×10^{-4} (0.00%)	2.37×10^{-4} (0.00%)	2.46×10^{-4} (0.00%)
Water availability, freshwater ecosystem	2.13×10^{-3} (0.00%)	2.33×10^{-3} (0.00%)	2.12×10^{-3} (0.00%)	2.43×10^{-3} (0.00%)	2.44×10^{-2} (0.00)	2.46×10^{-2} (0.00%)
Water availability, terrestrial ecosystem	3.04×10^{-2} (0.00%)	3.07×10^{-2} (0.00%)	3.23×10^{-2} (0.00%)	3.23×10^{-2} (0.00%)	3.04×10^{-2} (0.00%)	3.07×10^{-2} (0.00%)

Contribution analysis

In order to identify critical variables and life cycle stages that are improvable, a contribution analysis was conducted for four significant impact indicators: (i) the short-term impact of climate change on human health, (ii) water availability and human health, (iii) long-term freshwater ecotoxicity, and (iv) land transformation and biodiversity. This selection was made based on the findings from Tables 4 and 5, which reveal that these impact indicators have the highest values.

Health impacts: Contributions to short-term climate change, water availability, and human health

Table 6 presents the contribution of the evaluated sanitation systems to the impact of short-term climate change on human health. In 100% of scenarios, toilet utilization proves to be the most impactful phase, following the emission of GHGs from the toilet pit. It accounts for a substantial proportion, ranging between 89.6 and 98.6%, of the overall impact of these systems, depending on the specific scenario under consideration. This environmental impact is primarily attributable to the use of toilet paper and/or wood shavings. Indeed, toilet paper is responsible for 13.6–35.4% of the global impact, depending on the scenario considered. As for the wood shavings, they are only used in scenarios involving a CBT, namely, Scenarios 3 and 4, where they account for 8.77 and 8.06% of the respective overall impact of each scenario. To reduce the environmental impact of systems with CBT, various alternatives can be considered. For example, the use of local materials such as ash or sawdust from carpentry and joinery workshops could advantageously replace wood shavings. Regarding toilet paper, improvements in the production process and the use of locally manufactured recycled paper could be considered to reduce associated impacts.

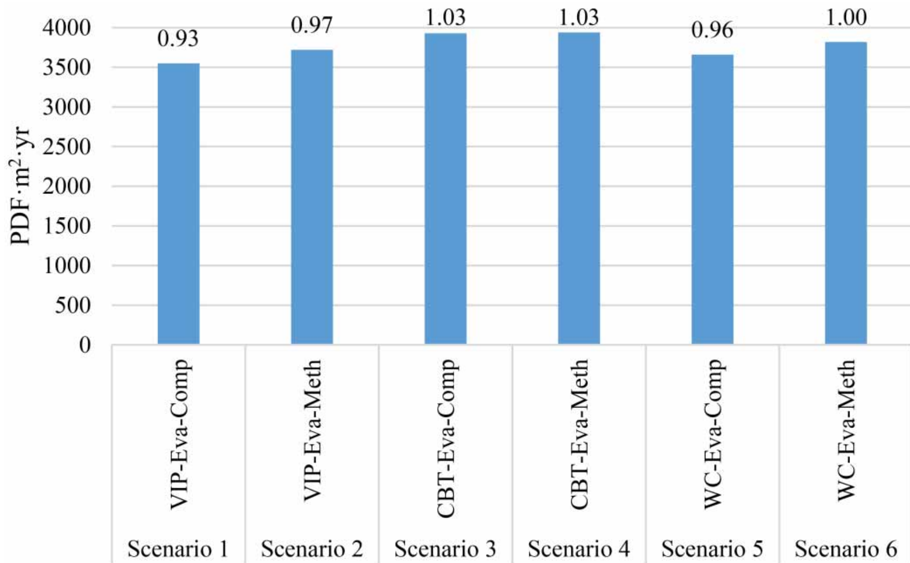


Figure 4 | Classification of scenarios in terms of ecosystem impact, with ratios compared to Scenario 6 overlaid on the bars.

Table 6 | Contribution to short-term climate change and human health

Evaluated elements	Scenario 1 VIP-Eva-Comp	Scenario 2 VIP-Eva-Meth	Scenario 3 CBT-Eva-Comp	Scenario 4 CBT-Eva-Meth	Scenario 5 WC-Eva-Comp	Scenario 6 WC-Eva-Meth
Toilet construction	0.20%	0.19%	0.15%	0.14%	0.18%	0.17%
Toilet utilization	98.0%	93.0%	97.5%	89.6%	98.6%	95.1%
– GHG emission	77.4%	73.5%	53.3%	49.0%	84.6%	81.4%
– Toilet paper	20.6%	19.5%	35.4%	32.5%	14.0%	13.7%
– Wood shavings	N/A[a]	N/A	8.77%	8.06%	N/A	N/A
Toilet end of life	0.00%	0.00%	−0.07%	−0.06%	−0.01%	−0.01%
Evacuation	1.52%	1.44%	2.00%	1.83%	1.04%	1.01%
Treatment	0.37%	5.69%	0.63%	9.47%	0.25%	3.97%
Compost or biogas	−0.10%	−0.34%	−0.17%	−0.96%	−0.07%	−0.24%
Total	100%	100%	100%	100%	100%	100%

[a]Non-applicable.

After the toilet utilization phase, the treatment phase has the next biggest environmental impact. This impact is mainly attributed to the construction of the composter or biodigester and varies from 0.25 to 9.47% depending on the scenario considered. The evacuation link, focused on the transport of fecal sludge, represents approximately 1.01–2.00% of the overall impact, depending on the specific scenario being considered. An effective strategy to minimize these impacts would be to reduce the transportation distance by implementing decentralized treatment stations. In the case of households using the CBT, a practice already in place in Haiti and many other countries is to provide them with a composter located near the house, which can significantly contribute to reducing the impact associated with transport.

Furthermore, the valorization of fecal sludge remains the least impactful step (from −0.10 to −0.96%), thanks to the environmental credit generated by the composting and/or biomethanization of these sludges. Taking into account the avoided impacts, such as the production of 5.62 m^3 of biogas for Scenarios 2 and 6, as well as 9.60 m^3 of biogas for Scenario 4, and/or 350 kg of compost, the valorization of fecal sludge could prove to be a crucial solution to reduce the overall environmental impact of the on-site sanitation systems. This underscores the importance of considering waste management approaches that promote valorization to reduce environmental impact.

In terms of short-term climate change-related health impacts, the WC is slightly more impactful, followed by the VIP latrine and the CBT. The ratio of the WC to the VIP latrine and the CBT is less than 1.05. However, the biodigester is, on average, 15.3 times more impactful than the composter for this indicator.

Regarding water availability and human health, Table 7 highlights that the toilet utilization phase is responsible for the majority of the overall impact of the examined systems, ranging from 92.8 to 97.3% depending on the scenario. Toilet paper is the main contributor to this impact, with a range from 97.0 to 108.9%. In Scenarios 3 and 4, the bedding contributes positively by avoiding the impact related to water availability, representing −16.1 and −16.0%, respectively. The evacuation of sludge is the third contributor, with an impact ranging from 1.22 to 5.60% of the overall impact. The VIP latrine is slightly the most impactful, followed by the WC and the CBT, with a ratio to the other two toilets not exceeding 1.05.

Ecosystem impacts: Contribution to long-term freshwater ecotoxicity and land transformation

Regarding impacts on long-term freshwater ecotoxicity, the data in Table 8 reveal certain long-term trends. The toilet usage phase generally remains the most impactful, being responsible for approximately 88.9–96.8% of the total impact. The manufacturing of toilet paper and the use of wood shavings are the main contributors to the global impact. Indeed, toilet paper accounts for 78.1–87.2% of the total impact. In scenarios involving a CBT (Scenarios 3 and 4), the use of wood shavings as bedding contributes to approximately 12.1 and 11.6% of the respective global impact.

Table 7 | Contribution to water availability and human health

Evaluated elements	Scenario 1 VIP-Eva-Comp	Scenario 2 VIP-Eva-Meth	Scenario 3 CBT-Eva-Comp	Scenario 4 CBT-Eva-Meth	Scenario 5 WC-Eva-Comp	Scenario 6 WC-Eva-Meth
Toilet construction	0.19%	0.19%	0.04%	0.04%	0.39%	0.39%
Toilet utilization	97.3%	97.4%	92.8%	92.8%	97.0%	97.1%
– Toilet paper	97.3%	97.4%	108.9%	108.8%	97.0%	97.1%
– Wood shavings	N/A	N/A	−16.1%	−16.0%	N/A	N/A
Toilet end of life	−0.07%	−0.07%	0.00%	0.00%	−0.09%	−0.09%
Evacuation	1.22%	1.22%	5.60%	5.59%	1.29%	1.29%
Treatment	1.34%	1.04%	1.51%	1.17%	1.43%	1.11%
Compost or biogas	0.03%	0.24%	0.03%	0.45%	0.03%	0.25%
Total	100%	100%	100%	100%	100%	100%

Table 8 | Long-term contribution to freshwater ecotoxicity

Evaluated elements	Scenario 1 VIP-Eva-Comp	Scenario 2 VIP-Eva-Meth	Scenario 3 CBT-Eva-Comp	Scenario 4 CBT-Eva-Meth	Scenario 5 WC-Eva-Comp	Scenario 6 WC-Eva-Meth
Toilet construction	0.63%	0.60%	0.50%	0.48%	1.64%	1.56%
Toilet utilization	94.6%	89.8%	96.8%	92.8%	93.6%	88.9%
– Toilet paper	94.6%	89.8%	84.7%	81.2%	93.6%	88.9%
– Wood shavings	N/A	N/A	12.1%	11.6%	N/A	N/A
Toilet end of life	−0.52%	−0.50%	−0.38%	−0.36%	−0.54%	−0.51%
Evacuation	3.95%	3.75%	1.86%	1.79%	3.94%	3.74%
Treatment	1.54%	6.92%	1.38%	6.25%	1.54%	6.90%
Compost or biogas	−0.14%	−0.61%	−0.13%	−0.94%	−0.14%	−0.61%
Total	100%	100%	100%	100%	100%	100%

The sludge treatment phase comes in second in terms of negative impact, representing approximately 1.38–6.92% of the overall impact of the studied systems, depending on the scenario being considered. The impact of this phase is mainly related to the materials used in the construction of the composter or biodigester, including clay bricks, cement, steel, and their transportation. Valorization through composting or anaerobic digestion is identified as the least impactful phase, taking into account the environmental credit generated by the production of compost or biogas, which will be used as agricultural fertilizer (compost) or cooking fuel (biogas). This emphasizes the importance of considering waste treatment solutions that valorize these resources rather than disposing of them, thereby the sustainable minimization of environmental impacts.

The sludge evacuation phase ranks third in terms of generated impacts, with an impact ranging from 1.79 to 3.95% of the total impact of the system. These impacts are mainly attributable to the use of high-density polyethylene in the manufacturing of drums used for sludge storage during collection and transport. Additionally, the Gulper pump is responsible for approximately 3.35% of the overall impact, primarily due to the steel used in its fabrication.

Regarding ecosystem impacts related to land transformation, the data from Table 9 reveal that the toilet use phase remains the most impactful (from 98.4 to 98.9%), mainly due to toilet paper, which represents 91.2–98.6% of the overall impact. Wood shavings are the second contributor for Scenarios 3 and 4, responsible for 7.60% of the overall impact. The treatment phase comes in second with an impact ranging from 0.74 to 0.91%. Evacuation is the least impactful phase of the pathway, ranging from 0.31 to 0.59%.

Sensitivity analysis

Assessment of the influence of the mass of wood shavings used on the results

A sensitivity analysis was conducted to assess the potential impact of the imprecision related to the quantity of wood shavings used in the CBT on the study results. To do this, the wood shavings mass used (1,170 kg/year) was modified by increasing and then decreasing by one-third (i.e., $\pm$ 390 kg). The results were then compared. Figure 5(a) and 5(b) illustrates that this variation did not influence the study results.

Assessment of the influence of the impact assessment method

A second sensitivity analysis was conducted to check whether the impact assessment method significantly influenced the study results. Figure 6(a) and 6(b) shows that impact levels vary depending on the impact assessment method used. Specifically, lower impacts are observed when the Impact 2002+ method is applied compared to Impact World+. Regarding health impacts, the results from the Impact World+ method are 3.77–22.9 times higher than those from Impact 2002 +, depending on the scenario considered (Figure 6(a)). Using the Impact World+ method, the scenarios are ranked in descending order of health impact as follows: $6 > 5 > 4 > 2 > 1 > 3$. In contrast, applying the Impact 2002+ method results in different rankings: $4 > 3 > 2 > 6 > 1 > 5$. However, in the Impact 2002+ method, Scenarios 1 and 5, as well as 2 and 6, are practically equivalent and interchangeable.

Regarding ecosystem impact, the results from the Impact World+ method are 4.72–7.29 times higher than those obtained with Impact 2002+ (Figure 6(b)). Furthermore, Figure 6b reveals a slight influence of the assessment method on the

Table 9 | Contribution to land transformation

Evaluated elements	Scenario 1 VIP-Eva-Comp	Scenario 2 VIP-Eva-Meth	Scenario 3 CBT-Eva-Comp	Scenario 4 CBT-Eva-Meth	Scenario 5 WC-Eva-Comp	Scenario 6 WC-Eva-Meth
Toilet construction	0.12%	0.12%	0.18%	0.18%	0.13%	0.13%
Toilet utilization	98.6%	98.4%	98.9%	98.8%	98.6%	98.4%
– Toilet paper	98.6%	98.4%	91.3%	91.2%	98.6%	98.4%
– Wood shavings	N/A	N/A	7.60%	7.60%	N/A	N/A
Toilet end of life	−0.04%	−0.04%	−0.08%	−0.08%	−0.04%	−0.04%
Evacuation	0.59%	0.58%	0.31%	0.31%	0.58%	0.58%
Treatment	0.79%	0.91%	0.74%	0.84%	0.79%	0.90%
Compost or biogas	−0.04%	−0.02%	−0.04%	−0.03%	−0.04%	−0.02%
Total	100%	100.0%	100.0%	100.0%	100.0%	100.0%

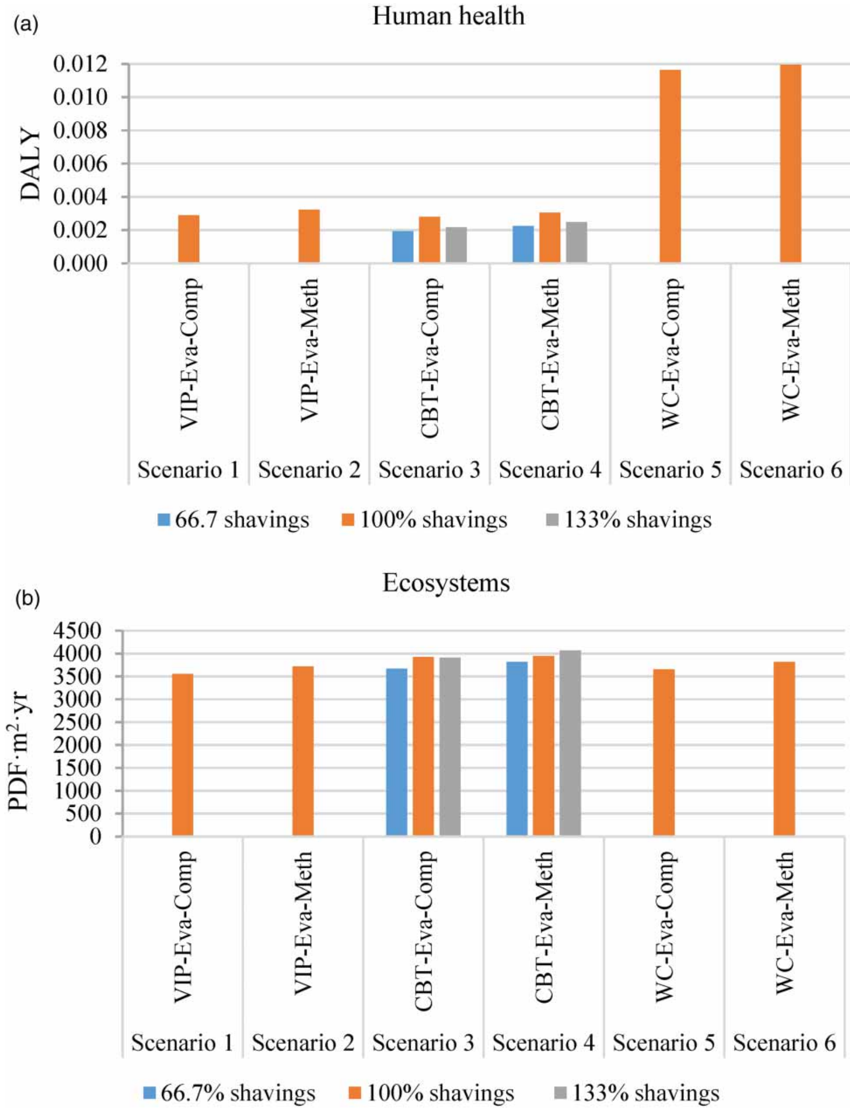


Figure 5 | Verification of the influence of the amount of wood shavings used on the results in terms of health impact (a) and ecosystem impact (b).

descending ranking order of scenarios, shifting from $4 > 3 > 6 > 2 > 5 > 1$ to $3 > 4 > 6 > 2 > 5 > 1$. However, as observed before, Scenarios 1 and 5, as well as 2 and 6, and 3 and 4 are interchangeable, showing practically identical values in the results obtained with the Impact 2002+ method.

Thus, the results are slightly sensitive to the chosen impact assessment method. This variation is not surprising, given that each of the two methods considered uses specific impact categories and indicators to assess environmental impacts. This highlights the need to harmonize the impact assessment methods used in LCA.

CONCLUSION

The main objective of this study was to compare stand-alone sanitation systems implemented in a low-income tropical country, specifically Haiti, using LCA. To achieve this goal, six scenarios representing different stand-alone sanitation systems were developed. Each scenario included three distinct stages: toilet access, fecal sludge evacuation, and sludge treatment. The results identified the systems, as well as sanitation technologies, with the most and least environmental impact. Additionally, the assessment highlighted key contributing elements and potential improvement opportunities.

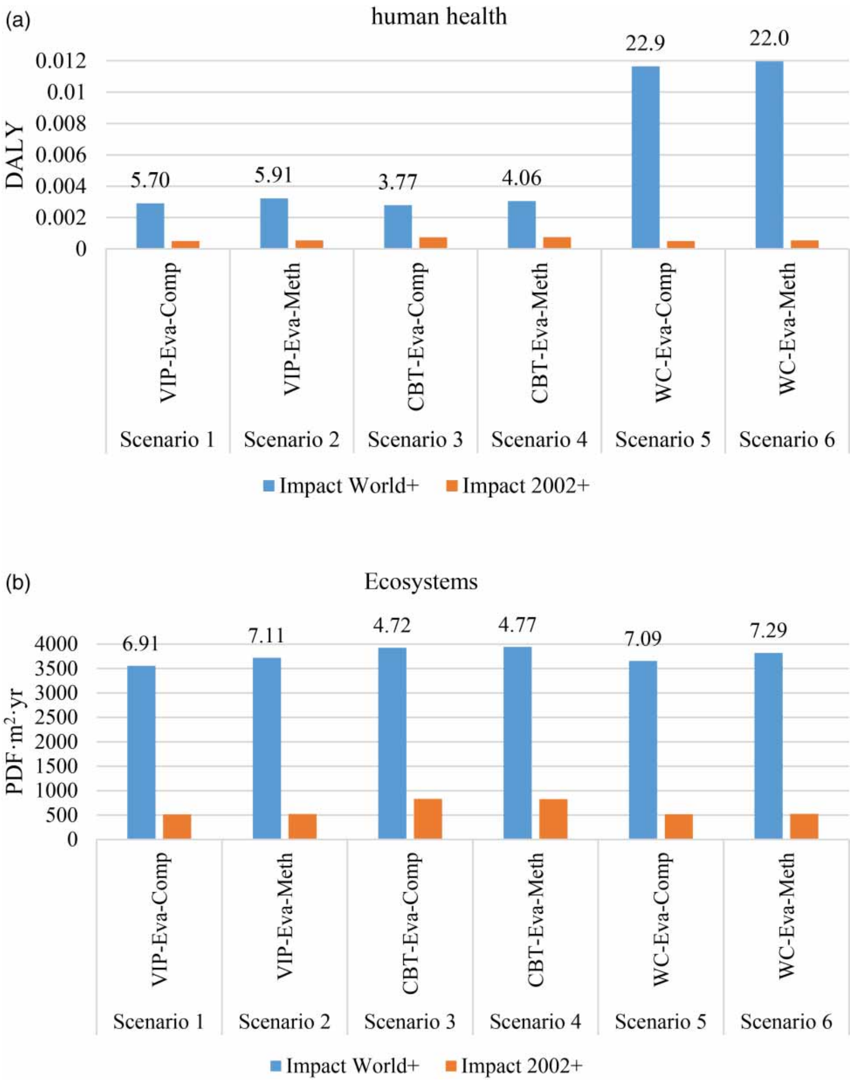


Figure 6 | Comparison of results between the Impact World+ and Impact 2002+ methods for impacts on (a) human health and (b) ecosystems. Numbers above the bars represent the ratio of Impact World+ results to Impact 2002+ results.

The three main areas for improvement identified for the sanitation systems examined are as follows: toilet paper, wood shavings in systems with CBT (Scenarios 3 and 4), and the production of bricks and cement, especially in systems equipped with biodigesters. Implementing measures such as using locally manufactured recycled toilet paper, replacing wood shavings with residual materials like sawdust and/or ash, and utilizing local materials in the construction of biodigesters instead of imported materials like cement, iron, and steel, should help reduce the environmental impact of the sanitation systems examined. However, this study is not exhaustive in terms of sustainability. A life cycle cost assessment as well as a social life cycle assessment (SLCA), including a study of social acceptability, could strengthen the conclusions and better guide decision-makers in the choice of sanitation treatment system.

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DATA AVAILABILITY STATEMENT

All relevant data are available from an online repository or repositories: https://etsmtl365-my.sharepoint.com/:w:/g/personal/davidson_jean-baptiste_1_ens_etsmtl_ca/EQR6sIyXGAlHlv_BnyEFTnAB7WuJXL0DBHuFOIwpTJqfUA?e=XqroaP.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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