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Quantitative microbial risk assessment associated with the use of container-based toilets in Haiti

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ABSTRACT

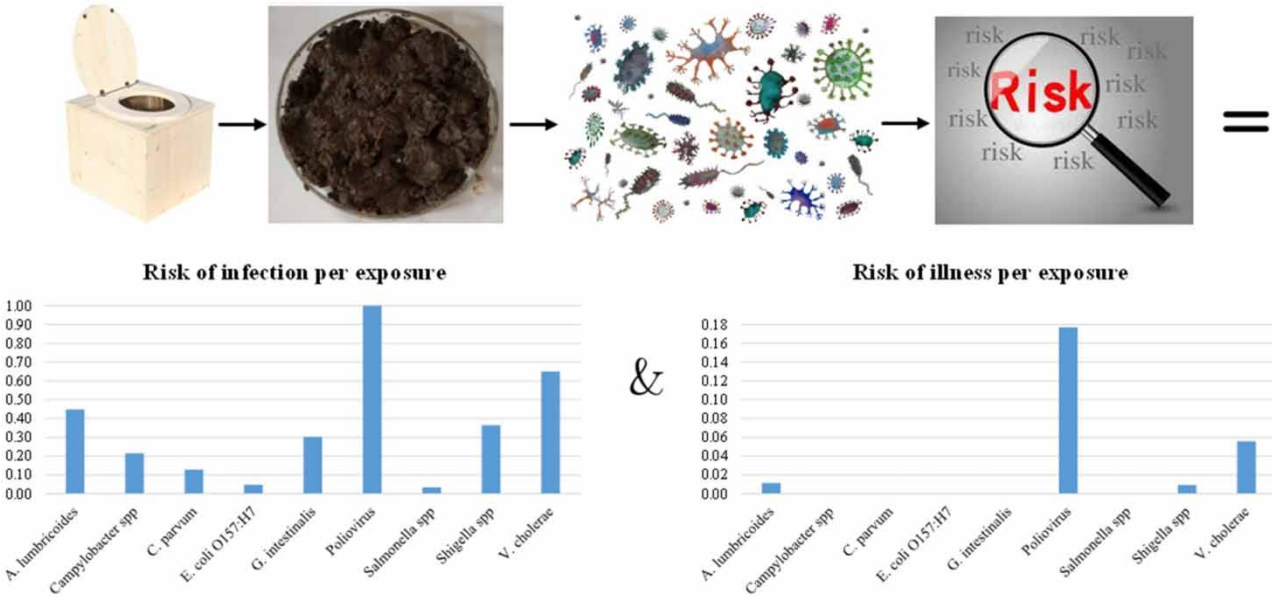
A container-based toilet (CBT) is a type of ecological toilet that allows users to compost their feces. During emptying, bucket washing, and composting operations, operators are exposed to microbial risks. This paper aims to evaluate these risks using the Quantitative Microbial Risk Assessment (QMRA) method. Nine pathogens prevalent in Haiti were targeted: *Ascaris lumbricoides*, *Campylobacter* spp., *Cryptosporidium parvum*, *Escherichia coli* O157:H7, *Giardia intestinalis*, poliovirus, *Salmonella* spp., *Shigella* spp., and *Vibrio cholerae*. Information regarding pathogens' concentration in feces came from scientific literature data. The exposure scenarios considered were those in which operators accidentally ingested a low dose of feces during the aforementioned operations. A Monte Carlo simulation was conducted to address uncertainties. The results showed that the probability of infection is highly elevated, while the probability of illness is generally moderate or minor, except for poliovirus and *Ascaris*. Preventive measures can be implemented to reduce these risks during various operations, such as wearing gloves, disposable protective masks, and appropriate clothing. It is up to the political authorities to develop guidelines in this regard and to organize awareness-raising activities with the help of local organizations mandated by the relevant authorities to ensure the safer use of technology by households.

Key words: CBT, composting, feces, illness, infection, QMRA

HIGHLIGHT

- Quantitative Microbial Risk Assessment related to container-based toilets (CBTs) in Haïti represents the first scientific QMRA study on composting toilets in the country. It considers nine pathogens, including some that have not been considered in previous studies. Results show the importance of precautions during emptying and composting operations.

GRAPHICAL ABSTRACT



INTRODUCTION

Although access to sanitation is now considered a fundamental human right, about 2.3 billion people worldwide still lack access to basic sanitation facilities (Dickin *et al.* 2020). This problem is particularly common in low-income countries and promotes inadequate sanitation practices such as open defecation and/or dumping untreated feces into the environment (Jean *et al.* 2017; Ufomba *et al.* 2021). These practices pose a threat to human health (Saleem *et al.* 2019; Ufomba *et al.* 2021). Pathogens present in feces can contaminate the environment and, subsequently, cause infectious diseases in humans (Feachem *et al.* 1983; Mara 2004), most of which are contagious (Cloeckaert & Kuchler 2020; Zhang 2022). In Haiti, due to fecal contamination of the Artibonite River in 2010 (Guimier 2011), cholera was responsible for nearly 9,800 deaths and more than 820,000 suspected cases from 2010 to 2019 (Griffiths *et al.* 2021).

Technological solutions, such as container-based toilets (CBTs), have been developed to help reduce fecal pollution around the world (Esrey *et al.* 1998; Jean 2018). This type of ecological toilet offers households the possibility of recycling their feces usually through composting (Figure 1). With the CBT, feces are collected in a 20-L bucket, and a quantity of litter – consisting of shavings and/or sawdust – is poured over the feces after each defecation (Jean *et al.* 2017; Jean 2018). The litter helps absorb moisture and limits odors (Jean *et al.* 2017). When the bucket is full, it is emptied manually, and the fecal sludge is deposited into a composter for agricultural recovery. This material recovery is aligned with the principles of the circular economy, which advocates recycling matter to preserve natural resources and avoid potential contamination (Stahel 2016). However, handling feces during manual emptying and composting operations carries microbial risks, since the feces contain pathogens that can have a negative impact on human health (Feachem *et al.* 1983; Mara 2004). In the current context, where national and international institutions are promoting the use of this type of toilet, the assessment of microbial health risks associated with CBTs is necessary to prevent risks to human health.

Quantitative Microbial Risk Assessment (QMRA) is an assessment method developed in the 1970s by the United States National Research Council, which is inspired by the chemical risk assessment method (De Giudici *et al.* 2011). It consists of four main steps: hazard identification, exposure assessment, hazard characterization (often reduced to dose-response assessment), and risk characterization (Haas *et al.* 1999; U.S. EPA 2012; WHO 2022). Studies relating to the QMRA have been carried out on composting toilets, but they have generally focused on the health risks associated with either the use of compost resulting from the recovery of feces (Nakagawa *et al.* 2006; Schonning *et al.* 2007; Darimani *et al.* 2015; Kumwenda *et al.* 2017) or spreading feces on gardens or agricultural fields (WHO 2006). The conclusions were divided in regard to the results of these studies. According to Nakagawa *et al.* (2006) and Schonning *et al.* (2007), the risk of infection is generally below the acceptable level of risk, whereas it is above the acceptable level of risk according to Kumwenda *et al.*

Figure 1 | Container-based toilet (Lécopot 2022).

(2017) and Darimani *et al.* (2015). The acceptable level of risk corresponds to 10^{-4} per person per year (Nakagawa *et al.* 2006; Schonning *et al.* 2007; Darimani *et al.* 2015). This disparity is mainly due to (i) the pathogens targeted, which differ between studies and/or regions, (ii) the different exposure scenarios developed by the authors, and (iii) the types of toilets considered. In addition, a semi-QMRA associated with the use of CBTs was carried out by Mackinnon *et al.* (2018) where *Escherichia coli* was considered as the target pathogen. The study revealed a high level of fecal contamination on toilet surfaces and a high risk of infection, through hand-to-mouth contact, in users and operators.

Unlike the aforementioned previous studies, the present paper aims to quantitatively assess the microbial risks faced by operators. It is not interested in the risk associated with the use of compost or feces as a fertilizer, as that subject has already been extensively studied in previous research. Furthermore, this study takes into consideration pathogens that have not been considered by other studies, such as *Campylobacter* spp., poliovirus, *Shigella* spp., and *Vibrio cholerae*.

METHODOLOGY

This section aims to present the methodological approach used to conduct the study. The main steps are schematically presented in Figure 2.

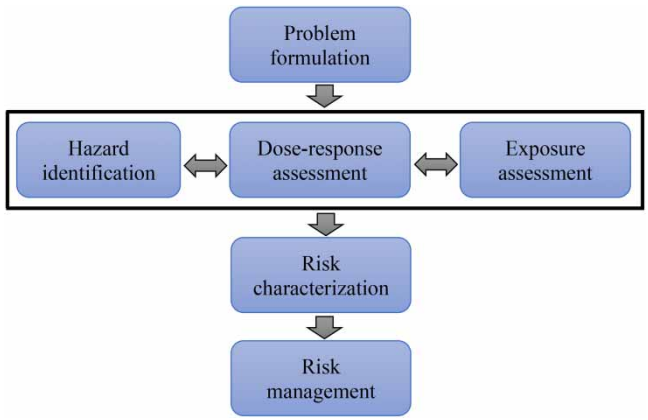


Figure 2 | Diagram illustrating the steps of the study.

Presentation of the study area

Grande Plaine was chosen as the study area because it is one of the two main areas in Haiti with a significant number of CBT users. This rural area is located in the municipality of Gros-Morne, Haiti, and has the following geographical coordinates: 18.52°N and 74.34°W (Google Earth 2022). The average annual temperature is 24.8 °C (Jean *et al.* 2017). Grande Plaine has nearly 2,000 inhabitants distributed across 192 households, 35 of which, i.e. 280 people, use the CBT (Association des Originaires de Grande Plaine 2022). The health centers and reference hospitals in the region mentioned by Jean *et al.* (2017) revealed that typhoid, gastroenteritis, and intestinal parasitosis are the most frequent diseases in the region (especially among children). In addition to these pathologies, cholera is a sporadic epidemic in the region.

Out of the 35 aforementioned households, 33 use a community composting platform to compost their feces and two use their own composter (Association des Originaires de Grande Plaine 2022). This composting platform consists of nine compost bins, including five community and four individual, which compost fecal sludge from CBT user households throughout the year (Association des Originaires de Grande Plaine 2022). The platform and the composting process are described by Jean *et al.* (2017) and Jean (2018).

Hazard identification

This study focuses on nine pathogens. These pathogens were selected based on the following criteria in accordance with Westrell (2004), Schonning *et al.* (2007), and WHO (2022): (i) prevalence in Haiti, (ii) presence in feces, (iii) pathogenicity, (iv) ability to survive in the environment after excretion, and (v) availability of data (especially those related to the dose-response model) to allow their integration into a QMRA study. The target pathogens are *Ascaris lumbricoides*, *Campylobacter* spp., *Cryptosporidium parvum*, *E. coli* O157:H7, *Giardia intestinalis*, poliovirus, *Salmonella* spp., *Shigella* spp., and *V. cholerae*. The health problems generated by this organism are ascariasis, campylobacteriosis, cryptosporidiosis, hemorrhagic diarrhea, giardiasis, poliomyelitis, salmonellosis, shigellosis, and cholera, respectively (Feachem *et al.* 1983; Mara 2004). For the purpose of this study, *Ascaris* eggs were considered (not the worms).

Exposure assessment

Concentration of pathogens in feces

The data on fecal pathogen content of feces are drawn from the scientific literature (Table 1). Most of these studies used the quantitative polymerase chain reaction (qPCR) method to quantify target pathogens in feces.

Exposure scenarios

CBT users collect feces in approximately 20-L buckets, which are usually emptied once a week. In each household, sludge is manually emptied by an adult from the household (referred to as 'emptier' in this study) who carries the bucket of sludge to a community composting platform located approximately 200 m from the house.

The population exposed to microbial risks mainly includes emptiers and master composters. Farmers, who spread compost on their fields, as well as the potential consumers of the products grown, were excluded from the scope of this study.

Table 1 | Concentration of target pathogens in feces

Pathogens	CFU/g for bacteria, NE/g for *Ascaris*, NO/g for protozoa, and $TCID_{50}$ /g for poliovirus	References
A. lumbricoides	10^4	(Feachem *et al.* 1983; WHO 2006)
Campylobacter spp.	10^3	(Misawa *et al.* 2001; LaGier *et al.* 2004)
C. parvum	10^3	(Valdez *et al.* 1997)
E. coli O157:H7	3.3×10^2	(Westrell 2004; Schonning *et al.* 2007)
G. intestinalis	10^2–10^3	(Straub *et al.* 1993)
Poliovirus	1.3×10^5	(Hovi *et al.* 2001; Lodder *et al.* 2012)
Salmonella spp.	10^4	(Yin Ngan *et al.* 2010; Teh *et al.* 2021)
Shigella spp.	10^4	(Yavzori *et al.* 1994; Mokhtari *et al.* 2012)
V. cholera	10^2–10^5	(Feachem *et al.* 1983)

CFU: colony-forming unit; NE: number of eggs; NO: number of oocysts/cysts; $TCID_{50}$: 50% tissue culture infectious dose.

Thermophilic (co)composting is supposed to sanitize fecal sludge because of the increase in temperature during the second phase (Berendes *et al.* 2015; Jean 2018), which implies that the health risk can be considered negligible. The main known exposure routes are accidental ingestion, inhalation of bioaerosols, and skin contact. However, due to the absence of a dose-response model for the latter two exposure routes, only ingestion was considered.

The exposure scenarios considered the most plausible were those where the operators' hands were contaminated and accidentally brought to the mouth either directly or indirectly through eating, drinking, hand-to-mouth contact, or nail-biting. Two scenarios were developed: (i) contamination of emptiers during transport, unloading, and washing of the feces bucket and (ii) contamination of master composters while handling sludge during the composting process.

Measurement of the ingestion dose

The ingestion dose (D) corresponds to the amount of pathogens ingested per exposure. Equation (1) was used to determine D from the concentration (C) of pathogens in the sludge and the accidental ingestion (I) of feces.

$$D = C \times I \tag{1}$$

Two hypotheses were formulated based on previous studies to estimate accidental ingestion of feces by emptiers and master composters. The following values were considered, in cases where the operators did not sufficiently use personal protective equipment (PPE) in the course of their work:

- emptiers inadvertently ingest about 0.033 g of feces per operation (Schonning *et al.* 2007), which usually occurs once a week;
- master composters accidentally ingest between 0.05 and 0.48 g of feces per operation (Gerba *et al.* 2002; Brooks *et al.* 2012; Gholipour *et al.* 2020; Sadeghi *et al.* 2022). These operations mainly consist of turning the piles approximately once a week throughout the year (i.e. 52 weeks).

Dose-response assessment

To model the behavior of pathogens within the host organism, two dose-response models were used: the exponential model represented by Equation (2) and the β-Poisson model represented by Equation (3).

$$P_{\text{inf}} = 1 - e^{-rD} \tag{2}$$

$$P_{\text{inf}} = 1 - \left(1 + \frac{D}{\beta}\right)^{-\alpha} \tag{3}$$

where P_{inf} is the probability of host infection following the ingestion of a given pathogen; r is the constant corresponding to the survival capacity of the pathogen in the host organism; D is the ingested dose (in CFU for bacteria, number of roundworm eggs for *A. lumbricoides*, number of oocysts (or cysts) for protozoa (*C. parvum* and *G. Intestinalis*) and $TCID_{50}$ for poliovirus); α and β are parameters of the β-Poisson model ($\alpha < \beta$). They describe the pathogen's ability to survive and cause host infection (Health Canada 2019).

The parameters α, β, and r are specific to each of the pathogens considered. The values chosen for each of these organisms are presented in Table 2.

Risk characterization

Uncertainty analysis through Monte Carlo simulation

The data demonstrate variability in the ingestion of feces by master composters, and the concentrations of *G. intestinalis* and *V. cholerae* in the feces were subjected to a Monte Carlo simulation to address the inherent uncertainties. The @RISK software, version 8.4.0 developed by Palisade Corporation, was used for this purpose. Log-normal distribution was chosen as the appropriate probability distribution, in accordance with Schonning *et al.* (2007). A total of 10,000 iterations were executed. The median (50th percentile) was utilized for result interpretation, representing the realistic scenario, while the 95th percentile was employed to represent the pessimistic scenario. The variables selected for uncertainty analysis are listed in Table 3.

Table 2 | Dose-response model applied to target pathogens

Pathogens	Model	Parameters	References
A. lumbricoides	β-Poisson	$\alpha = 0.104$ $\beta = 1.1$	(Navarro *et al.* 2009; O'Connor *et al.* 2017)
Campylobacter spp.	β-Poisson	$\alpha = 0.145$ $\beta = 7.59$	(Haas *et al.* 1999; Mara 2004; Health Canada 2019)
C. parvum	Exponential	$r = 0.0042$	(Haas *et al.* 1999; Mara 2004; U.S. EPA 2012)
E. coli O157:H7	β-Poisson	$\alpha = 0.248$ $\beta = 48.8$	(Teunis *et al.* 2008; U.S. EPA 2012)
G. intestinalis	Exponential	$r = 0.0199$	(Haas *et al.* 1999; U.S. EPA 2012; Health Canada 2019)
Poliovirus	Exponential	$r = 0.0091$	(Haas *et al.* 1999; U.S. EPA 2012)
Salmonella spp.	β-Poisson	$\alpha = 0.3126$ $\beta = 2{,}884$	(Haas *et al.* 1999; Westrell 2004; U.S. EPA 2012)
Shigella spp.	β-Poisson	$\alpha = 0.21$ $\beta = 42.86$	(Haas *et al.* 1999; Mara 2004; U.S. EPA 2012)
V. cholerae	β-Poisson	$\alpha = 0.25$ $\beta = 16.2$	(Haas *et al.* 1999; Mara 2004; U.S. EPA 2012)

Table 3 | Selected variables for uncertainty analysis in the Monte Carlo simulation

Variable	Units	Minimum	Likeliest	Maximum	SD
Giardia concentration in feces	Cyst/g	10^2	550	10^3	450
V. cholerae concentration in feces	CFU/g	10^2	50,050	10^5	49,950
Fecal ingestion by master composters	g	0.05	0.265	0.48	0.215

SD: standard deviation.

Determining the risk of infection and illness

The risk or probability of infection at each exposure was obtained from Equations (2) and (3). The annual probability of infection ($P_{\text{inf/year}}$) was calculated using Equation (4).

$$P_{\text{inf}/year} = 1 - (1 - P_{\text{inf}})^n \tag{4}$$

where n is the number of exposures per year.

In the context of this study, $n = 52$ for emptiers, since the bucket is emptied once a week on average. Similarly, for the master composters, $n = 52$, as they work throughout the year at a frequency of once a week.

To determine the probability of illness occurring following an infection, Equation (5) was used.

$$P_{\text{ill}} = P_{\text{inf}} \times P_{\text{ill}/\,\text{inf}} \tag{5}$$

where P_{ill} is the probability of illness and $P_{\text{ill/inf}}$ is the probability of illness by infection.

The term $P_{\text{ill/inf}}$ is defined by Equation (6) and is proposed by Havelaar & Swart (2014).

$$P_{\text{ill}/\,\text{inf}} = 1 - (1 + \eta D)^{-\rho} \tag{6}$$

where η and ρ are parameters of an underlying Gamma distribution for the duration of infection (Havelaar & Swart 2014). Values of 5.15×10^{-4} and 0.167 are suggested by Havelaar & Swart (2014) for η and ρ, respectively.

Risk classification

A risk classification model inspired by the work of Westrell *et al.* (2004) was used to facilitate the interpretation of the study results. This model classifies the risks as insignificant, minor, moderate, major, and highly elevated, in accordance with Table 4. Insignificant risk corresponds to the level of acceptable risk mentioned in the Introduction, which is equivalent to 10^{-4} per person per year (10^{-4} pppy).

RESULTS AND DISCUSSION

Probability of infection

Probability of infection per exposure

The calculations carried out using the selected dose-response functions and the ingestion doses per exposure made it possible to determine the probability of infection associated with each operation. These results are summarized in Table 5.

These results show that operators are highly exposed to a risk of infection if basic precautions are not taken. For emptiers, the highest risks are related to poliovirus (100%), *V. cholerae* (approximately 65%), *A. lumbricoides* (nearly 45%), *Shigella* spp. (nearly 37%), and *G. intestinalis* (nearly 28%). For master composters, in the realistic scenario, the highest risks are linked to poliovirus (100%), *G. intestinalis* (approximately 82%), *V. cholerae* (approximately 78%), and *C. parvum* (nearly 58%). In the pessimistic scenario (95th percentile), the highest risks were associated with poliovirus (100%), *G. intestinalis* (100%), *C. parvum* (nearly 94%), *V. cholerae* (approximately 86%), *Shigella* spp. (approximately 65%), and *A. lumbricoides* (nearly 60%).

The most likely pathogens to cause infection during an operation are ranked in descending order as follows: poliovirus > *V. cholerae* > *G. intestinalis* > *A. lumbricoides* > *Shigella* spp. This ranking is consistent with the information provided by Jean *et al.* (2017) on the most prevalent pathologies in the region, which are presented in the section 'Presentation of the Study Area'.

Table 4 | Proposed classification of microbial risks according to the probability of infection and/or illness (adapted from Westrell *et al.* (2004))

Risk level	Percentage (%)
Insignificant	0.01
Minor	0.02 to <1
Moderate	1 to <5
Major	5–25
Highly elevated	>25

Table 5 | Probability of infection per exposure

Pathogens	Emptiers	Master composters	
	50th percentile	50th percentile	95th percentile
A. lumbricoides	4.48×10^{-1}	5.43×10^{-1}	5.95×10^{-1}
Campylobacter spp.	2.16×10^{-1}	3.83×10^{-1}	4.77×10^{-1}
C. parvum	1.29×10^{-1}	5.78×10^{-1}	9.38×10^{-1}
E. coli O157:H7	4.87×10^{-2}	1.94×10^{-1}	3.44×10^{-1}
G. intestinalis	2.78×10^{-1}	8.23×10^{-1}	1.00
Poliovirus	1.00	1.00	1.00
Salmonella spp.	3.33×10^{-2}	1.66×10^{-1}	3.11×10^{-1}
Shigella spp.	3.65×10^{-1}	5.58×10^{-1}	6.53×10^{-1}
V. cholerae	6.51×10^{-1}	7.83×10^{-1}	8.61×10^{-1}

Annual probability of infection

The results show that the yearly probability of infection is, on average, two times higher than the probability of infection per operation, equal to 1.00 for all the pathogens considered, except for *E. coli* O157:H7 and *Salmonella* spp., where it is 9.25×10^{-1} and 8.28×10^{-1}, respectively, among emptiers.

The yearly risk of infection was 8,281.36–10,000 times higher than the acceptable level of risk (10^{-4} pppy) depending on the pathogen considered. However, it should be noted that infection does not necessarily lead to illness. The probability of illness following a given infection depends on a range of factors, including age, the host's immune system status, and previous exposure to other pathogens (De Giudici *et al.* 2011; U.S. EPA 2012).

Probability of illness

Probability of illness per exposure

The calculated values of the probability of illness per exposure are summarized in Table 6.

Analysis of these data revealed that the probability of illness per operation was 2.58–1,071.19 times lower than the probability of infection per operation. During each operation, the emptiers and the master composters were exposed to two major risks, namely those related to poliovirus and *V. cholerae*; other risks were considered moderate and/or minor. The pessimistic scenarios indicate that master composters were exposed to two highly elevated risks of illness, approximately 39% for poliovirus and 25% for *V. cholera*, and two major risks, almost 8% for *A. lumbricoides* and nearly 9% for *Shigella* spp. Therefore, the most likely pathogens to cause disease are ranked as follows: poliovirus > *V. cholerae* > *Shigella* spp. > *A. lumbricoides*.

Annual probability of illness

The results of the annual probability of illness presented in Table 7 show that the yearly probability of illness was 1.16–24.87 times higher than the probability of illness per operation and 2.58–1,071.19 times lower than the annual probability of infection. Emptiers and master composters were only exposed to two major risks, which were related to poliovirus and *V. cholerae*; the risks associated with the other target pathogens were, overall, classified as moderate and/or minor, ranging from 0.08 to 2.58%. It is observed that master composters were 2.18–8.48 times more exposed to microbial risk than the emptiers. This confirmed that master composters are the most exposed to microbial risk. As for the risk per operation, the most likely pathogens to cause disease were poliovirus, *V. cholerae*, *Shigella* spp., and *A. lumbricoides*. It is noteworthy that the results of the pessimistic scenario are identical to those of the realistic scenario in terms of the annual probability of illness.

Limitations

The QMRA is now recognized as an important tool for decision-makers in preventing infections and/or infectious illnesses related to water, excreta, and food. This tool has some limitations, such as not taking into account the potential immunity of a portion of the exposed population. However, it is important to note that its purpose is not to determine the quantity of infection and illness in a given area, but rather to assess the probability that infection and illness could occur in the area based primarily on available microbiological, epidemiological, and demographic data. This is precisely the perspective from

Table 6 | Probability of illness per exposure

Pathogens	Emptiers	Master composters	
	50th percentile	50th percentile	95th percentile
A. lumbricoides	1.16×10^{-2}	7.27×10^{-2}	7.97×10^{-2}
Campylobacter spp.	6.06×10^{-4}	8.1×10^{-3}	10^{-2}
C. parvum	3.64×10^{-4}	1.22×10^{-2}	1.98×10^{-2}
E. coli O157:H7	4.55×10^{-5}	1.42×10^{-3}	2.52×10^{-3}
G. intestinalis	4.32×10^{-4}	9.89×10^{-3}	1.2×10^{-2}
Poliovirus	1.77×10^{-1}	3.87×10^{-1}	3.87×10^{-1}
Salmonella spp.	8.61×10^{-4}	2.22×10^{-2}	4.17×10^{-2}
Shigella spp.	9.44×10^{-3}	7.47×10^{-2}	8.75×10^{-2}
V. cholerae	5.59×10^{-2}	2.27×10^{-1}	2.5×10^{-1}

Table 7 | Annual probability of illness

Pathogens	Emptiers 50th percentile	Master composters 50th percentile
A. lumbricoides	2.58×10^{-2}	1.34×10^{-1}
Campylobacter spp.	2.81×10^{-3}	2.11×10^{-2}
C. parvum	2.81×10^{-3}	2.11×10^{-2}
E. coli O157:H7	8.64×10^{-4}	7.33×10^{-3}
G. intestinalis	1.55×10^{-3}	1.2×10^{-2}
Poliovirus	1.77×10^{-1}	3.87×10^{-1}
Salmonella spp.	2.14×10^{-2}	1.34×10^{-1}
Shigella spp.	2.58×10^{-2}	1.34×10^{-1}
V. cholerae	8.59×10^{-2}	2.9×10^{-1}

which the QMRA was used in this study to quantitatively evaluate the potential microbial health risks associated with the use of CBTs.

Like any study of this type, this study is subject to uncertainties. Data on the concentration of pathogens in feces were not collected in Grande Plaine but mainly came from previous studies that were not carried out in Haiti. Data specific to the study area would be more relevant. Furthermore, the equation used in the QMRA framework assumes that the ingested dose is the same at each exposure and does not take into account the fact that some people who have previously been infected with certain pathogens may become immune to them (Health Canada 2019). In reality, the most vulnerable people are generally those who are immunocompromised (people with AIDS and others), seniors, pregnant women, infants, and people suffering from malnutrition (Haas *et al.* 1999; De Giudici *et al.* 2011; U.S. EPA 2012). Epidemiological and demographic data on the area (population health status, age groups, number of pregnant women, etc.) would allow for the identification of the most vulnerable groups and a more exhaustive analysis of the situation, but such data are not available in the existing literature.

MICROBIAL RISK MANAGEMENT

Microbial risk management primarily falls under the jurisdiction of political authorities, namely the Ministry of Public Health and Population (MSPP). The MSPP is responsible for developing and enforcing barrier measures in accordance with the sanitation approaches adopted in the country to protect the health of the population. Implementing adequate hygienic and sanitary measures can significantly reduce the microbial risks associated with the use of CBTs. The measures adopted must prevent any contact with feces, such as the use of PPE (gloves, boots, and protective masks) and hand washing. Another way to prevent contact with feces is to reduce the concentration of pathogens in the feces by removing the full bucket from the CBT and allowing the sludge to dry, while another bucket is put into service right next to it. The full bucket would be covered with ash and a lid to reduce the nuisance caused by odors and harmful insects.

CONCLUSION

The study results show that the risk of infection by most of the targeted pathogenic organisms is high among operators (emptiers and master composters), which is not the case for the risk of illness. The results highlight the fact that the risks of illness associated with poliovirus, *V. cholerae*, and *Ascaris* are generally the highest, while those associated with *E. coli* O157:H7 and *C. parvum* are the lowest. The annual infection risks were found to be 8,281.36–10,000 times higher than the established acceptable risk level, while the annual disease risks ranged from 8.64 to 3,870.28 times higher than the acceptable risk level, depending on the pathogen considered. However, these results do not necessarily mean that the operators in question will be infected and/or fall ill, but rather illustrate what could happen if they do not take necessary precautions during their usual operations.

The obtained results suggest that political authorities should develop guidelines in this regard to ensure a safer use of the technology. This requires training and raising awareness in the population concerned, either by public authorities or local organizations mandated by the authorities. These actions would be a suitable lever for implementing barrier measures and self-protection mechanisms for regular monitoring of feces-composting operations to ensure that established guidelines have been respected and that the compost produced is truly sanitized.

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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

Association des Originaires de Grande Plaine 2022 Personal communication.

Berendes, D., Levy, K., Knee, J., Handzel, T. & Hill, V. R. 2015 *Ascaris* and *Escherichia coli* inactivation in an ecological sanitation system in Port-au-Prince, Haiti. *PLoS ONE* **10**, e0125336. https://doi.org/10.1371/journal.pone.0125336.

Brooks, J. P., McLaughlin, M. R., Gerba, C. P. & Pepper, I. L. 2012 Land application of manure and class B biosolids: an occupational and public quantitative microbial risk assessment. *Journal of Environmental Quality* **41**, 2009–2023. https://doi.org/10.2134/jeq2011.0430.

Cloeckaert, A. & Kuchler, K. 2020 Grand challenges in infectious diseases: are we prepared for worst-case scenarios? *Frontiers in Microbiology* **11**, 1–7.

Darimani, H., Ito, R., Sou/Dakouré, M., Funamizu, N., Yacouba, H. & Maiga, A. H. 2015 Design of post-treatment unit for compost from a composting toilet with microbial risk assessment. *Journal of Residuals Science and Technology* **12**, 43–51. https://doi.org/10.12783/issn.1544-8053/12/2/2.

De Giudici, P., Guillam, M.-T. & Ségala, C. 2011 *Microbiologie et déchets: évaluation des risques sanitaires (Microbiology and Waste: Health Risks Assessment) (Rapport Final No. 09-0669/1A)*. RECORD, France.

Dickin, S., Bayoumi, M., Giné, R., Andersson, K. & Jiménez, A. 2020 Sustainable sanitation and gaps in global climate policy and financing. *npj Clean Water* **3**, 24. https://doi.org/10.1038/s41545-020-0072-8.

Esrey, S. A., Gough, J., Rapaport, D., Sawyer, R., Simpson-Hébert, M., Vargas, J. & Winblad, U. 1998 *Ecological Sanitation*, 1st edn. SIDA, Stockholm, Sweden.

Feachem, R. G., Bradley, D. J., Garelick, H. & Mara, D. D. 1983 *Sanitation and Disease: Health Aspects of Excreta and Wastewater Management*. John Wiley & Sons, New York, NY, USA.

Gerba, C. P., Pepper, I. L. & Whitehead III, L. F. 2002 A risk assessment of emerging pathogens of concern in the land application of biosolids. *Water Science and Technology* **46**, 225–230. https://doi.org/10.2166/wst.2002.0338.

Gholipour, S., Nikaeen, M., Farhadkhani, M. & Nikmanesh, B. 2020 Survey of *Listeria monocytogenes* contamination of various environmental samples and associated health risks. *Food Control* **108**, 106843. https://doi.org/10.1016/j.foodcont.2019.106843.

Google Earth. 2022 *Grande Plaine, Haiti [WWW Document]*. Available from: https://earth.google.com/web/search/Grande+Plaine,+Ha%c3%afti/@18.52149572,-74.33888873,186.44213367a,36.60278341d,35y,56.74281529h,44.96926512t,0.00000085r/data=CoABGlYSUAolMHg4ZWM2NDlkZThjNzM4MGJiOjB4MmEzN2Y2ZWI4NzRjODkyZBmOQYI9gYUyQCGxWk9jsZVSwCoVR3JhbmRlIFBsYWluZSwgSGHDr3RpGAEgASImCiQJm0nlH8yjMkAR3iJk32ejMkAZV7sh5myHUsAhdD7fJaSHUsA (accessed 10 December 2022).

Griffiths, K., Moise, K., Piarroux, M., Gaudart, J., Beaulieu, S., Bulit, G., Marseille, J.-P., Jasmin, P. M., Namphy, P. C., Henrys, J.-H., Piarroux, R. & Rebaudet, S. 2021 Delineating and analyzing locality-level determinants of Cholera, Haiti. *Emerging Infectious Diseases Journal* **27**, 12. https://doi.org/10.3201/eid2701.191787.

Guimier, L. 2011 L'épidémie de choléra en Haïti : lecture géopolitique d'un enjeu de santé publique (The cholera epidemic in Haiti: geopolitical Reading of a public health issue). *Hérodote*, 184–206. https://doi.org/10.3917/her.143.0184.

Haas, C. N., Rose, J. B. & Gerba, C. P. 1999 *Quantitative Microbial Risk Assessment*, 1st edn. John Wiley & Sons, New York, NY, USA.

Havelaar, A. H. & Swart, A. N. 2014 Impact of acquired immunity and dose-dependent probability of illness on quantitative microbial risk assessment. *Risk Analysis* **34**, 1807–1819. https://doi.org/10.1111/risa.12214.

Health Canada 2019 *Guidance on the Use of Quantitative Microbial Risk Assessment in Drinking Water*. Health Canada, Ottawa, ON, Canada.

Hovi, T., Stenvik, M., Partanen, H. & Kangas, A. 2001 Poliovirus surveillance by examining sewage specimens. quantitative recovery of virus after introduction into sewerage at remote upstream location. *Epidemiology & Infection* **127**, 101–106. https://doi.org/10.1017/S0950268801005787.

Jean, G. 2018 *Conditions pour la mise en place durable d'une filière d'assainissement par toilettes sèches à litière bio-maîtrisée dans les zones rurales des pays en développement. Application au contexte haïtien (Conditions for the Sustainable Establishment of a Sanitation System Using Dry Toilets with Bio-Controlled Litter in Rural Areas of Developing Countries. Application to the Haitian Context)*. PhD Thesis. INSA de Lyon, France.

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**, 9. https://doi.org/10.4267/dechets-sciences-techniques.3618.

Kumwenda, S., Msefula, C., Kadewa, W., Ngwira, B. & Morse, T. 2017 Estimating the health risk associated with the use of ecological sanitation toilets in Malawi. *Journal of Environmental and Public Health* **2017**, e3931802. https://doi.org/10.1155/2017/3931802.

LaGier, M. J., Joseph, L. A., Passaretti, T. V., Musser, K. A. & Cirino, N. M. 2004 A real-time multiplexed PCR assay for rapid detection and differentiation of *Campylobacter jejuni* and *Campylobacter coli*. *Molecular and Cellular Probes* **18**, 275–282. https://doi.org/10.1016/j.mcp.2004.04.002.

Lécopot. 2022 *Le Butterfly Douglas – Dry Toilet [WWW Document]*. Lécopot – Dry Toilets. Available from: https://www.lecopot.com/en/indoor-dry-toilets/76-butterfly-douglas-dry-toilet.html (accessed 6 December 2022).

Lodder, W. J., Buisman, A. M., Rutjes, S. A., Heijne, J. C., Teunis, P. F. & de Roda Husman, A. M. 2012 Feasibility of quantitative environmental surveillance in poliovirus eradication strategies. *Applied and Environmental Microbiology* **78**, 3800–3805. https://doi.org/10.1128/AEM.07972-11.

Mackinnon, E., Campos, L. C., Sawant, N., Ciric, L., Parikh, P. & Bohnert, K. 2018 Exploring exposure risk and safe management of container-based sanitation systems: a case study from Kenya. *Waterlines* **37**, 280–306. https://doi.org/10.3362/1756-3488.00016.

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

Misawa, N., Kawashima, K., Kawamoto, H. & Kondo, F. Y. 2001 Development of a combined filtration-enrichment culture followed by a one-step duplex PCR technique for the rapid detection of *Campylobacter jejuni* and *C. coli* in human faecal samples. *Journal of Medical Microbiology* **51**, 86–89. https://doi.org/10.1099/0022-1317-51-1-86.

Mokhtari, W., Nsaibia, S., Majouri, D., Ben Hassen, A., Gharbi, A. & Aouni, M. 2012 Detection and characterization of *Shigella* species isolated from food and human stool samples in Nabeul, Tunisia, by molecular methods and culture techniques. *Journal of Applied Microbiology* **113**, 209–222. https://doi.org/10.1111/j.1365-2672.2012.05324.x.

Nakagawa, N., Oe, H., Otaki, M. & Ishizaki, K. 2006 Application of microbial risk assessment on a residentially-operated bio-toilet. *Journal of Water and Health* **4**, 479–486. https://doi.org/10.2166/wh.2006.0031.

Navarro, I., Jiménez, B., Lucario, S. & Cifuentes, E. 2009 Application of *Helminth* ova infection dose curve to estimate the risks associated with biosolid application on soil. *Journal of Water and Health* **7**, 31–44. https://doi.org/10.2166/wh.2009.113.

O'Connor, N. A., Surapaneni, A., Smith, D. & Stevens, D. 2017 Occurrence and fate of *Ascaris lumbricoides* ova in biosolids in Victoria, Australia: a human health risk assessment of biosolids storage periods. *Water Science and Technology* **76**, 1332–1346. https://doi.org/10.2166/wst.2017.222.

Sadeghi, S., Nikaeen, M., Mohammadi, F., Hossein Nafez, A., Gholipour, S., Shamsizadeh, Z. & Hadi, M. 2022 Microbial characteristics of municipal solid waste compost: occupational and public health risks from surface applied compost. *Waste Management* **144**, 98–105. https://doi.org/10.1016/j.wasman.2022.03.012.

Saleem, M., Burdett, T. & Heaslip, V. 2019 Health and social impacts of open defecation on women: a systematic review. *BMC Public Health* **19**, 158. https://doi.org/10.1186/s12889-019-6423-z.

Schonning, C., Westrell, T., Stenstrom, T. A., Arnbjerg-Nielsen, K., Hasling, A. B., Hoibye, L. & Carlsen, A. 2007 Microbial risk assessment of local handling and use of human faeces. *Journal of Water and Health* **5**, 117–128. https://doi.org/10.2166/wh.2006.049.

Stahel, W. R. 2016 The circular economy. *Nature* **531**, 435–438. https://doi.org/10.1038/531435a.

Straub, T. M., Pepper, I. L. & Gerba, C. P., 1993 Hazards from pathogenic microorganisms in land-disposed sewage sludge. In: *Reviews of Environmental Contamination and Toxicology, Reviews of Environmental Contamination and Toxicology* (Ware, G. W., ed.). Springer, New York, NY, USA, pp. 55–91. https://doi.org/10.1007/978-1-4684-7065-9_3.

Teh, C. S. J., Lau, M. Y., Chong, C. W., Ngoi, S. T., Chua, K. H., Lee, W. S. & Thong, K. L. 2021 One-step differential detection of *Salmonella enterica* serovar Typhi, serovar Paratyphi A and other *Salmonella* spp. by using a quadruplex real-time PCR assay. *Journal of Microbiological Methods* **183**, 106184. https://doi.org/10.1016/j.mimet.2021.106184.

Teunis, P. F. M., Ogden, I. D. & Strachan, N. J. C. 2008 Hierarchical dose response of *E. coli* o157:H7 from human outbreaks incorporating heterogeneity in exposure. *Epidemiology & Infection* **136**, 761–770. https://doi.org/10.1017/S0950268807008771.

Ufomba, E., Ubi, A., Njoku, L. A., Oyalabu, S., Emurotu, A., Kwaskebe, J. & Uwaoma, A. N. 2021 Ethico-medical implications of open defecation in a multi-religious society: a study of three communities in Ibadan, Oyo State, Nigeria. *Sapientia Foundation Journal of Education, Sciences and Gender Studies* **3**, 213–223.

U.S. EPA. 2012 *Microbial Risk Assessment Guideline: Pathogenic Microorganisms with Focus on Food and Water. (No. EPA/100/J-12/001)*. USA.

Valdez, L. M., Dang, H., Okhuysen, P. C. & Chappell, C. L. 1997 Flow cytometric detection of *Cryptosporidium* oocysts in human stool samples. *Journal of Clinical Microbiology* **35**, 2013–2017. https://doi.org/10.1128/jcm.35.8.2013-2017.1997.

Westrell, T. 2004 *Microbial Risk Assessment and its Implications for Risk Management in Urban Water Systems*. PhD Thesis. Linköping Studies in Arts and Science, Sweden.

Westrell, T., Schönning, C., Stenström, T. A. & Ashbolt, N. J. 2004 QMRA (quantitative microbial risk assessment) and HACCP (hazard analysis and critical control points) for management of pathogens in wastewater and sewage sludge treatment and reuse. *Water Science and Technology* **50**, 23–30. https://doi.org/10.2166/wst.2004.0079.

WHO 2006 *Guidelines for the Safe use of Wastewater, Excreta and Greywater. 4: Excreta and Greywater use in Agriculture*, 4th edn. World Health Organization, Geneva, Switzerland.

WHO 2022 *Guidelines for Drinking-Water Quality: Fourth Edition Incorporating the First and Second Addenda*, 4th ed + 1st add + 2nd add. edn. World Health Organization, Geneva, Switzerland.

Yavzori, M., Cohen, D., Wasserlauf, R., Ambar, R., Rechavi, G. & Ashkenazi, S. 1994 Identification of *Shigella* species in stool specimens by DNA amplification of different loci of the Shigella virulence plasmid. *European Journal of Clinical Microbiology & Infectious Diseases* **13**, 232–237. https://doi.org/10.1007/BF01974542.

Yin Ngan, G. J., Ng, L. M., Lin, R. T. P. & Teo, J. W. P. 2010 Development of a novel multiplex PCR for the detection and differentiation of *Salmonella enterica* serovars Typhi and Paratyphi A. *Research in Microbiology* **161**, 243–248. https://doi.org/10.1016/j.resmic.2010.03.005.

Zhang, Q. 2022 Data science approaches to infectious disease surveillance. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **380**, 20210115. https://doi.org/10.1098/rsta.2021.0115.

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