Water Science & Technology

IWA PUBLISHING

 Water Science & Technology Vol 89 No 11, 3122 doi: 10.2166/wst.2024.164

Quantitative microbial risk assessment (QMRA) of the work of manual pit emptiers, commonly known as *bayakous*

Davidson Jean-Baptiste [a,b,*] and Frédéric Monette [a]

[a] École de technologie supérieure, Montréal, QC, Canada
[b] Faculté des Sciences, Université d'État d'Haïti, Port-au-Prince, Haïti
*Corresponding author. E-mail: davidson.jean-baptiste.1@ens.etsmtl.ca

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

ABSTRACT

In Haiti, manual pit emptiers, known as *bayakous*, face significant health risks. They work by descending naked into latrine pits, exposing themselves to pathogens and contributing to environmental contamination. This study employs the quantitative microbial risk assessment (QMRA) method to evaluate the microbial risks associated with this practice, considering nine prevalent pathogens in Haiti. Three ingestion scenarios were developed: hand-to-mouth contact, ingestion while immersed in excreta, and a combination of both. A sensitivity analysis assessed the impact of input data on study outcomes. The results indicate a high probability of infection and illness during pit emptying operations annually for all scenarios and pathogens. Recommendations include adopting personal protective equipment (PPE) and using a manual Gulper waste pump to eliminate the need to descend directly into the pits, thereby reducing the risk of injury from sharp objects. The study proposes the establishment of intermediate disposal points approximately 5 km from collection sites to deter illegal dumping. National regulations and professionalization of the *bayakou* profession are suggested, along with awareness campaigns to promote PPE and Gulper pump usage. Addressing these issues is crucial for safeguarding the health of *bayakou* and public health in Haiti.

Key words: bayakou, feces, health, illness, infection, QMRA

HIGHLIGHTS

- This study is the first scientific QMRA study on manual pit emptiers in Haiti.
- It considers nine pathogens and three ingestion scenarios, two of which have not been considered in previous studies.
- The results indicate that the emptiers are at higher risk of infection and illness.
- It recommends the use of PPE to mitigate health risks and the use of a Gulper pump to eliminate the need to descend directly into pit latrines.

INTRODUCTION

Feces contain pathogens capable of causing diseases in humans (Feachem *et al.* 1983; Odey *et al.* 2017; Jean-Baptiste *et al.* 2023). These pathogens typically include helminths, protozoa, bacteria, and viruses. According to Gabert *et al.* (2018), approximately 1.2 million deaths per year worldwide are attributed to diseases transmitted via the fecal-oral route. Pathogens present in feces frequently contaminate individuals through accidental ingestion, skin contact, or inhalation. Once introduced into the body, these pathogens multiply, leading to infection and potential illness. In the absence of an effective immune response, an infection can become fatal without proper medical intervention. Common symptoms of these diseases include fever, abdominal pain, headache, acute diarrhea, and vomiting (Odey *et al.* 2017).

Apart from the health problems feces cause, most individuals feel an aversion to feces because of the unpleasant odor and distance themselves as quickly as possible once their physiological needs are satisfied. However, in low-income countries like Haiti, a particular category of professionals known as *bayakous* regularly comes into direct contact with feces as part of their daily work.

Bayakous are manual pit emptiers who often work informally and are exclusively male (Neiburg & Nicaise 2010). They provide sanitation services at a lower cost than mechanical emptying companies (World Bank *et al.* 2019). Typically, they work after 10 p.m., completely naked (Neiburg & Nicaise 2010; Mazars & Earwaker 2013; Katz 2014; Smith 2014; Hersher 2017a, 2017b; Lozano-Gracia & Lozano 2017; World Bank *et al.* 2019).

Bayakous usually operate in groups of three individuals: the *boss* descends into the latrine pit; the *middleman* seeks contracts, negotiates with clients, and organizes payment; and the *majo* stays outside the pit to receive buckets filled with feces and illuminate the pit with a lantern (Neiburg & Nicaise 2010; Smith 2014; World Bank *et al.* 2019). The roles can be interchangeable (Neiburg & Nicaise 2010). Only one of them enters the pit, usually the boss (often while drunk), and this person may be nearly immersed in feces up to their neck (Smith 2014). *Bayakous*' equipment typically consists of a wheelbarrow, two barrels, and a few buckets, some of which is often rented from an external company (Neiburg & Nicaise 2010). Before entering the pit, they pour a usually soapy cleaning liquid in to reduce odors and soften the feces (Katz 2014; Smith 2014; Lozano-Gracia & Lozano 2017).

These sanitation workers are exposed to considerable personal and public health risks. The pits they empty often contain sharp or pointed objects such as razors, syringes, and pieces of glass, which pose a risk of injury, especially considering that the *bayakous* are often underequipped, not wearing personal protective equipment (PPE), and working naked (Katz 2014; Smith 2014; Hersher 2017a, 2017b; Lozano-Gracia & Lozano 2017; World Bank *et al.* 2019). Additionally, *bayakous* frequently discharge the collected fecal sludge into the environment on abandoned land, in rivers, or in ravines (Mazars & Earwaker 2013; Katz 2014; Smith 2014; Lozano-Gracia & Lozano 2017; World Bank 2018). *Bayakous* tend to have a short lifespan, as they are exposed to a range of diseases such as cholera, parasitic worms, malaria, fever, and skin conditions (Smith 2014).

Despite the risks they face, both for their own health and public health, *bayakous* seem to play an essential role in the Haitian health and socio-economic context. According to the World Bank *et al.* (2019), *bayakous* provide most sanitation services in Haiti, as the country has only five mechanical emptying companies, and these are mainly concentrated in the metropolitan area of Port-au-Prince. Moreover, these mechanical emptying companies sometimes subcontract *bayakous*, especially when they need to empty latrines for which their equipment is inadequate (Neiburg & Nicaise 2010). *Bayakous* carry out their activities every day, or almost every day, as highlighted by Neiburg & Nicaise (2010) and Smith (2014). The *bayakou* network is organized into bases, with five identified in the metropolitan area of Port-au-Prince: Cité Soleil, Marché Salomon, Fortouron, Ravine Pintade, and Fort Dimanche (Neiburg & Nicaise 2010).

No scientific study using the Quantitative Microbial Risk Assessment (QMRA) method to analyze the work of *bayakous* in Haiti has been identified in the scientific literature. The studies available in the literature are primarily descriptive and qualitative, conducted by researchers in human and social sciences, as well as by journalists (Neiburg & Nicaise 2010; Mazars & Earwaker 2013; SOIL Haiti 2013; Katz 2014; Smith 2014; Hersher 2017a, 2017b; Lozano-Gracia & Lozano 2017).

Internationally, scientific works on health risks associated with manual pit emptiers are scarce. The studies conducted by Chumo *et al.* (2021) in Kenya and by Tsai *et al.* (2022) in Zambia are primarily descriptive and/or qualitative, bearing a resemblance to those carried out in Haiti, while the work conducted by Sklar *et al.* (2021) in Rwanda and by Bischel *et al.* (2019) in South Africa utilized a QMRA methodology. However, the work of Bischel *et al.* (2019) did not examine pit emptying; rather, it focused on container-based sanitation (CBS) systems. The study by Sklar *et al.* (2021) exclusively looked at the scenario where pit emptiers accidentally ingested fecal matter through hand-to-mouth contact without considering the possibility of ingestion while immersed in latrine pits. In contrast, our study took into account the hand-to-mouth contact with feces scenario studied by Sklar *et al.* (2021), while also including a scenario of direct fecal ingestion and a combined scenario. Furthermore, unlike Sklar *et al.* (2021), who limited their study to four pathogens, our study considered nine prevalent pathogens in Haiti.

Faced with the microbiological risks inherent in the *bayakous*' work and the insufficient, if not absent, local scientific data on the microbial health risks related to *bayakous*' work in Haiti, a specific QMRA tailored to their reality was necessary. The central objective of this study was to address this information and the data gap in the scientific literature. The study is organized into six key steps, in accordance with QMRA methodology: (i) problem formulation, (ii) hazard identification, (iii) exposure assessment, (iv) dose-response assessment, (v) risk characterization, and (vi) risk management. Thus, the present study aligns with an approach aimed at contributing to the understanding and reduction of microbial risks associated with the work of *bayakous* in Haiti.

METHODOLOGY

Hazard identification

As mentioned above, *bayakous* are regularly exposed to fecal-origin pathogens during their professional activities. In the context of this study, nine fecal-origin pathogens were selected: *Ascaris lumbricoides*, *Campylobacter* spp., *Cryptosporidium* *parvum*, *Escherichia coli* O157:H7, *Giardia intestinalis*, poliovirus, *Salmonella* spp., *Shigella* spp., and *Vibrio cholerae*. The diseases associated with these pathogens have been extensively documented in the literature (Feachem *et al.* 1983; Mara 2004; Odey *et al.* 2017). The selection of these pathogens was motivated by several criteria aligned with those of USEPA (2012) and Jean-Baptiste *et al.* (2023): prevalence in Haiti, pathogenicity, infectivity, persistence in the environment after excretion, and the availability of a dose-response model in the literature.

Exposure assessment

Concentration of target pathogens in feces

The data regarding the concentration of the nine targeted pathogens in feces were extracted from the scientific literature and are summarized in Table 1.

Scenarios of ingestion and measurement of the ingestion dose

Exposure pathways generally fall into three categories: accidental fecal ingestion, skin contact, and inhalation. However, due to the lack of documented dose-response models for the latter two pathways in the scientific literature, only ingestion was considered in this study.

Considering that *bayakous* typically descend completely naked into pits and are often immersed up to their necks in excreta (Smith 2014; Lozano-Gracia & Lozano 2017), the following three ingestion scenarios have been defined:

- Scenario 1: *Bayakous* become contaminated through hand-to-mouth contact, ingesting a quantity of pathogens designated as D_{pathogen}. Equation (1) was used to determine D_{pathogen}.
- Scenario 2: *Bayakous* ingest 21 mL (or 21 g) of fecal sludge per emptying operation when immersed in excreta. This corresponds to the average volume of water inadvertently ingested in 1 h by an adult bathing in a pool, according to USEPA (2011a, 2011b).
- Scenario 3: *Bayakous* ingest the D_{pathogen} dose mentioned in Scenario 1 through hand-to-mouth contact, followed by the 21 g of fecal sludge mentioned in Scenario 2 when immersed in fecal sludge.

Formula (1), derived from Nicas & Best (2008), Beamer *et al.* (2015), and Sklar *et al.* (2021), was used to calculate the pathogen dose D_{pathogen} mentioned in Scenarios 1 and 3:

$$D_{\text{pathogen}} = \sum_{n=1}^{n=K} (C_{\text{hand}} \times A_{\text{hand}} \times H_{\text{mouth}} \times TE \times v) \quad (1)$$

$$C_{\text{hand}} = C_{\text{pathogen/feces}} \times C_{\text{palm}} \quad (2)$$

Table 1 | Concentration of target pathogens in feces (adapted from Jean-Baptiste *et al.* (2023))

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

where C_{hand} represents the concentration of viable pathogens on the hand, expressed in pathogens/cm^2. The surface area of the hand involved in touch, A_{hand}, is set at 1,070 cm^2 for an adult over 21 years old, following USEPA (2011a, 2011b). H_{mouth} represents the hand-to-mouth contact frequency, fixed at 0.133 min^{-1} according to Nicas & Best (2008). *TE* (Transfer Efficiency) denotes the pathogen transfer rate from the hand to the mouth, established at 33% according to Sklar *et al.* (2021). The variable v symbolizes the viability of detected pathogens, assuming that all detected pathogens are viable, $v = 100\%$. $C_{pathogen/feces}$, with various values available in Table 1, represents the concentration of pathogens in feces. In the context of this study, C_{palm} is set at 47 mg/cm^2, based on USEPA (2011a, 2011b) which indicate that approximately 47 mg/cm^2 of sludge adhere to the hands of a child playing in the mud.

Dose-response assessment

The dose-response model establishes the relationship between the ingested pathogen dose and the probability of infection and/or illness. Two types of dose-response models are generally considered: the β-Poisson model and the exponential model. The β-Poisson model, defined by Equation (3), is primarily applied in the case of bacteria and helminths, while the exponential model, represented by Equation (4), appears to be better suited to viruses and protozoa (Tanner *et al.* 2008; De Giudici *et al.* 2013). Information regarding the applicable dose-response models for the studied pathogens is summarized in Table 2:

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

$$P_{inf} = 1 - e^{-rD} \quad (4)$$

where P_{inf} represents the probability of host infection after the ingestion of a particular pathogen; α, β, and r are constants representing the pathogen's survival capacity in the host's body; D is the ingested dose (measured in CFU for bacteria, number of eggs for *A. lumbricoides*, number of oocysts or cysts for *C. parvum* and *G. intestinalis*, respectively, and $TCID_{50}$ for the poliovirus). The parameters α, β, and r vary depending on the pathogen considered. The specific values chosen for each of these pathogens are listed in Table 2.

Risk characterization

Determining the probability of infection and illness

Equations (3) and (4) were used to calculate the probability of infection per emptying operation (P_{inf}) according to the β-Poisson and exponential models, respectively. Additionally, Equation (5) was applied to determine the probability of infection per

Table 2 | Dose-response model applied to target pathogens (adapted from Jean-Baptiste *et al.* (2023))

Pathogens	Model	Parameters	References
A. lumbricoides	β-Poisson	$\alpha = 0.104$ $\beta = 1.1$	Navarro *et al.* (2009) and O'Connor *et al.* (2017)
Campylobacter spp.	β-Poisson	$\alpha = 0.145$ $\beta = 7.59$	Haas *et al.* (1999) and Health Canada (2019)
C. parvum	Exponential	$r = 0.0042$	Haas *et al.* (1999) and USEPA (2012)
E. coli O157:H7	β-Poisson	$\alpha = 0.248$ $\beta = 48.8$	Teunis *et al.* (2008) and USEPA (2012)
G. intestinalis	Exponential	$r = 0.0199$	USEPA (2012) and Health Canada (2019)
Poliovirus	Exponential	$r = 0.0091$	Haas *et al.* (1999) and USEPA (2012)
Salmonella spp.	β-Poisson	$\alpha = 0.3126$ $\beta = 2884$	Haas *et al.* (1999) and USEPA (2012)
Shigella spp.	β-Poisson	$\alpha = 0.21$ $\beta = 42.86$	Haas *et al.* (1999) and USEPA (2012)
V. cholerae	β-Poisson	$\alpha = 0.25$ $\beta = 16.2$	Haas *et al.* (1999) and USEPA (2012)

year ($P_{inf/year}$):

$$P_{inf/year} = 1 - (1 - P_{inf})^n \quad (5)$$

where $n = 274$, representing the average daily emptyings (365 times/year) and emptyings every 2 days (182.5 times/year), considering daily or near-daily activity according to Neiburg & Nicaise (2010) and Smith (2014).

Equation (6) was used to calculate the probability of illness per emptying (P_{ill}), while Equation (7), proposed by Havelaar & Swart (2014), determined the probability of illness per infection ($P_{ill/inf}$) for each of the considered pathogens:

$$P_{ill} = P_{inf} \times P_{ill/inf} \quad (6)$$

$$P_{ill/inf} = 1 - (1 + \eta D)^{-\rho} \quad (7)$$

where η and ρ represent the parameters of a Gamma distribution associated with the duration of the infection as described by Havelaar & Swart (2014). The suggested values for η and ρ were 5.15×10^{-4} and 0.167, respectively (Havelaar & Swart 2014).

Equation (8) was employed to determine the probability of illness per year ($P_{ill/year}$):

$$P_{ill/year} = 1 - (1 - P_{ill})^n \quad (8)$$

Sensitivity analysis of the results

A sensitivity analysis was conducted to assess the potential impact of variations in key data on the study's findings. Specifically, the following two variables were examined.

Mass of fecal sludge adhered to the *bayakous*' hands (Scenario 1)

The mass of fecal sludge adhered to the *bayakous*' hands during emptying operations was adjusted by $\pm 25\%$, resulting in 47.0 ± 11.8 mg/cm^2. Calculations were performed using these new values to determine if this variable had a significant influence on the results.

Mass of fecal sludge ingested by the *bayakous* (Scenario 2)

Similarly, the mass of fecal sludge ingested by the *bayakous* when immersed in the excreta was adjusted by $\pm 25\%$, i.e., 21.0 ± 5.25 g. The impact of this variation on the final results was evaluated.

The results obtained using the derived values were compared to verify the sensitivity of the study to these two key variables. This in-depth analysis provides a better understanding of the robustness of the study's conclusions to potential fluctuations in the input data.

Risk classification

Table 3, taken from Jean-Baptiste *et al.* (2023), was utilized to categorize the risks of infection and illness. The acceptable risk threshold (0.01%) corresponds to 10^{-4} per person per year, in accordance with Regli *et al.* (2018).

Table 3 | Proposed classification of microbial risks based on the probability of infection or illness (adapted from Westrell *et al.* (2004) and Jean-Baptiste *et al.* (2023))

Risk level	Percentage
Acceptable	$\leq$0.01
Minor	0.02 to <1.0
Moderate	1.0 to <5.0
Major	5.0 to 25
Highly elevated	> 25

RESULTS

Probability of infection

Table 4 presents the probability of infection per emptying operation. These results revealed that the probability of infection per operation is highly elevated for all the considered pathogens in all scenarios. The risks associated with *C. parvum*, *G. intestinalis*, and poliovirus reached 100%, making them the highest among the examined pathogens.

An analysis of the data from Table 4 shows that the results were substantially similar regardless of the scenario considered, with a slight increase from Scenario 1 to Scenario 3. In the case of Scenario 2, the probability of infection per emptying operation was 1.00–1.51 times higher than for Scenario 1, depending on the pathogen considered. Similarly, for Scenario 3, this probability was 1.00–1.01 times higher than for Scenario 2. These results demonstrated that the study was minimally influenced by the scenarios considered, especially concerning the probability of infection per emptying operation. As for the probability of infection per year, it reached 100% for all pathogens in all scenarios considered. This value was thus 10,000 times higher than the acceptable risk threshold established by Regli *et al.* (2018).

Probability of illness

Equations (6) and (7) mentioned in the methodology were used to calculate the probability of illness per operation for each pathogen considered, based on the data on probability of infection per operation presented in Table 4. Table 5 presents the probability of illness per emptying operation. The data revealed that the risks of illness were considered major and/or highly elevated, except for Scenario 1, where the risk related to *E. coli* O157:H7 was classified as moderate. Examination of the three scenarios showed that the lowest risks were associated with *E. coli* O157:H7, *G. intestinalis*, and *Campylobacter* spp. The highest risks were observed with poliovirus, *Shigella* spp., *V. cholerae*, and *A. lumbricoides*.

Table 4 | Probability of infection per emptying operation

Pathogens	Scenario 1	Scenario 2	Scenario 3
A. lumbricoides	64.3%	71.7%	72.0%
Campylobacter spp.	56.1%	68.3%	68.8%
C. parvum	100%	100%	100%
E. coli O157:H7	49.7%	70.8%	71.5%
G. intestinalis	100%	100%	100%
Poliovirus	100%	100%	100%
Salmonella spp.	49.1%	73.9%	74.7%
Shigella spp.	73.1%	83.2%	83.6%
V. cholerae	78.1%	87.5%	87.8%

Table 5 | Probability of illness per emptying operation

Pathogens	Scenario 1	Scenario 2	Scenario 3
A. lumbricoides	22.1%	39.0%	39.7%
Campylobacter spp.	6.69%	23.1%	23.9%
C. parvum	11.9%	33.8%	34.8%
E. coli O157:H7	2.58%	15.9%	16.8%
G. intestinalis	5.00%	22.0%	23.0%
Poliovirus	56.7%	70.2%	70.7%
Salmonella spp.	16.9%	40.2%	41.2%
Shigella spp.	25.1%	45.2%	46.0%
V. cholerae	17.6%	39.2%	40.2%

As previously observed in the probability of infection per emptying operation, an increase in the probability of illness per emptying operation from Scenario 1 to Scenario 3 was noted, while the results of Scenarios 2 and 3 were similar. The results of Scenario 2 were 1.24–6.15 times higher than the results of Scenario 1, depending on the pathogen considered. Similarly, the results of Scenario 3 were 1.02–1.06 times higher than for Scenario 2, depending on the pathogen considered. Just like the probability of infection per year, the probability of illness per year reached 100% for all pathogens and in all scenarios considered. These results indicate that the annual risk of illness is high among *bayakous*. These results are consistent with the studies by Smith (2014) and Chumo *et al.* (2021), which highlight that manual pit emptiers are often affected by infectious diseases such as cholera, diarrhea, skin conditions, headaches, vomiting, and tend to have a reduced lifespan.

DISCUSSION

The results of the study highlight particularly concerning microbial health risks for the *bayakous*. First, the probability of infection per emptying operation is alarming, reaching even 100% for certain pathogens, regardless of the scenario considered. This underscores the particularly high exposure of *bayakous* to infectious risks in their daily work, despite slight variations in the conditions studied.

Furthermore, the analysis reveals significant risks of illness, with most of the studied pathogens presenting risks classified as 'major' or 'highly elevated'. Particularly dangerous pathogens, such as poliovirus, *Shigella* spp., *V. cholerae*, and *A. lumbricoides*, are identified as being of particular concern, highlighting the potentially severe health consequences for the *bayakous*. The risk of illness per operation (Table 5) is logically lower than the risk of infection per operation (Table 4), as infection does not necessarily lead to illness, depending on the host's immune system robustness, or if they have already been exposed to the considered pathogens (Haas *et al.* 1999; Health Canada 2019).

A particularly alarming finding is that the probability of infection and illness per year reaches 100% for all pathogens and scenarios, significantly exceeding the acceptable risk threshold. These findings demonstrate that the working conditions of the *bayakous* expose them to considerable health risks, requiring urgent measures to protect these manual pit emptiers and significantly reduce these risks.

Overall, these results align with those of other available microbial risk assessment studies in the literature, which conclude that the microbial risk associated with manual emptying is high (Stenström *et al.* 2011; Fuhrimann *et al.* 2016; Gautam *et al.* 2021; Sklar *et al.* 2021). However, the level of risk presented in this study is higher than those mentioned in other QMRA studies (Fuhrimann *et al.* 2016; Sklar *et al.* 2021). This disparity could be explained by differences in the practice of manual pit emptying in Haiti, where manual pit emptiers generally work naked, unlike in other studies where this practice has not been identified.

These results do not imply that all *bayakous* will be systematically infected or fall ill, but rather highlight the microbial health risks to which they are exposed. The most immunologically vulnerable individuals may contract the illness, while others may not be affected. According to Haas *et al.* (1999), demographic subcategories generally vulnerable to pathogens include, among others, children (<5 years), the elderly (>65 years), pregnant women, diabetics, alcoholics, the immunocompromised (including AIDS patients and others), and those suffering from malnutrition. Conversely, those who have already been exposed to certain pathogens may have developed immunity, as mentioned earlier. However, the fact that manual pit emptiers often work under the influence of alcohol to better cope with their difficult working conditions (Smith 2014; Chumo *et al.* 2021) places them in the category of people who are more immunologically sensitive, potentially making them more vulnerable to pathogens.

Sensitivity analysis and study limitations

As mentioned in the methodology, a sensitivity analysis was conducted to determine whether a slight variation in the input data for Scenarios 1 and 2 would have a significant impact on the study's results presented in Tables 4 and 5. The data generated during the sensitivity analysis (Tables 6 and 7) indicate that the variations made did not have significant effects on the results of the study. The risk of infection and/or illness remained major, even highly elevated, with the exception of *E. coli* and *G. intestinalis*, for which the disease risk was classified as moderate when 35.2 mg/cm^2 was applied to Scenario 1. The probabilities of infection and illness per year remained constant, i.e., equal to 100%. This sensitivity analysis strengthens the reliability of the data presented in Tables 4 and 5.

The conducted study has certain inherent limitations. Particularly, data on the concentration of pathogens in feces were not directly derived from Haiti but rather from scientific literature. To achieve more representative results, field studies in

Table 6 | Sensitivity analysis on the probability of infection per emptying operation

	Scenario 1			Scenario 2		
	Mass of fecal sludge adhered to hands (mg/cm^2)			Mass of ingested fecal sludge (g)		
Pathogens	35.2 (−25%)	47.0 (Reference value)	58.8 (+25%)	15.8 (−25%)	21.0 (Reference value)	26.3 (+25%)
A. lumbricoides	63.2%	64.3%	65.1%	70.9%	71.7%	72.4%
Campylobacter spp.	54.2%	56.1%	57.5%	67.0%	68.3%	69.3%
C. parvum	100%	100%	100%	100%	100%	100%
E. coli O157:H7	46.2%	49.7%	52.3%	68.7%	70.8%	72.4%
G. intestinalis	100%	100%	100%	100%	100%	100%
Poliovirus	100%	100%	100%	100%	100%	100%
Salmonella spp.	45.0%	49.1%	52.2%	71.5%	73.9%	75.7%
Shigella spp.	71.4%	73.1%	74.3%	82.2%	83.2%	84.0%
V. cholerae	76.4%	78.1%	79.3%	86.6%	87.5%	88.2%

Table 7 | Sensitivity analysis on the probability of illness per emptying operation

	Scenario 1			Scenario 2		
	Mass of fecal sludge adhered to hands (mg/cm^2)			Mass of ingested fecal sludge (g)		
Pathogens	35.2 (−25%)	47.0 (Reference value)	58.8 (+25%)	15.8 (−25%)	21.0 (Reference value)	26.3 (+25%)
A. lumbricoides	19.8%	22.1%	23.8%	36.9%	39.0%	40.5%
Campylobacter spp.	5.32%	6.69%	7.91%	20.7%	23.1%	25.0%
C. parvum	9.79%	11.9%	13.8%	30.9%	33.8%	36.0%
E. coli O157:H7	1.90%	2.58%	3.26%	13.4%	15.9%	17.9%
G. intestinalis	3.92%	5.00%	6.02%	19.1%	22.0%	24.3%
Poliovirus	54.5%	56.7%	58.2%	68.7%	70.2%	71.3%
Salmonella spp.	14.1%	16.9.0%	19.1%	37.3%	40.2%	42.4%
Shigella spp.	22.4%	25.1%	27.2%	42.8%	45.2%	47.0%
V. cholerae	15.0%	17.6%	19.6%	36.5%	39.2%	41.3%

collaboration with the *bayakous* would be necessary to conduct microbiological tests and precisely determine the concentration of pathogens on their hands. Additionally, integrating epidemiological data specific to morbidity among *bayakous* in Haiti could have confirmed or refuted the observed trends, but such data were not available. In summary, a more in-depth and contextual approach, including data from field studies and Haiti-specific epidemiological data, would enhance the validity and relevance of the obtained results.

MICROBIAL RISK MANAGEMENT

The analysis of the data in Tables 4 and 5, as well as the sensitivity analyses (Tables 6 and 7), shows that the activity of the *bayakous* undeniably represents a microbial health risk. Indeed, the results indicate that the annual risk of infection and illness far exceeds the acceptable risk threshold recommended by Regli *et al.* (2018). However, the socio-economic and health reality in Haiti means that their work remains essential. Haiti's mechanical emptying companies are concentrated in the metropolitan area of Port-au-Prince, which means that *bayakous* are often the only emptying service providers in certain areas, especially in areas that are inaccessible to emptying trucks. To minimize the microbial risks associated with manual emptying in Haiti, sanitation management must be reconsidered. A paradigm shift in sanitation governance is an essential step in implementing more effective and safer approaches, thereby reducing the hazards arising when these sanitation workers come into direct contact with potentially contaminated fecal sludge.

Government authorities, especially the national agency responsible for this sector, should establish intermediate unloading points located within 5 km of collection sites – a distance recommended by Monvois *et al.* (2010) – to prevent *bayakous* from dumping collected sludge into the environment. The fecal sludge could be then transported to better-equipped sites. These types of facilities should be implemented in all 10 geographical departments and even in all 42 districts of the country. Additionally, government authorities must intensify efforts to regulate and professionalize the *bayakous*' profession, extending these initiatives nationwide.

A solution like the manual Gulper pump, recommended by Oxfam (2007), could be implemented so that *bayakous* would not need to descend into the pits during the emptying process. This pump, which can be manufactured from locally available materials, was detailed by Oxfam (2007), Strande *et al.* (2014), Tilley *et al.* (2016), and Gabert *et al.* (2018). *Bayakous* could use the pump to avoid coming into direct contact with sharp or pointed objects in the pits that can cause injuries. At the same time, *bayakous* should use PPE, including boots, pants, gloves, and face masks, during their interventions. Awareness campaigns are necessary to promote use of the Gulper pump and PPE to improve the working conditions of *bayakous* and reduce the microbial risks associated with their work.

CONCLUSION

The objective of this study was to quantitatively assess the microbial risks associated with the work of manual pit emptiers in Haiti, commonly known as *bayakous*, and to propose appropriate solutions. The results indicate that *bayakous* are exposed to major or highly elevated risks in all scenarios examined, exceeding the acceptable risk threshold by 514–10,000 times. In light of these results, the national authority responsible for this sector in Haiti must increase efforts to regulate and professionalize the *bayakou* profession, extending these initiatives nationwide. This would help control the number of *bayakous* operating in the country, provide adequate training, and prevent health issues related to their work. To better support these sanitation workers, the study suggests the use of PPE, the adoption of the Gulper pump during emptying operations, and the implementation of awareness campaigns to promote the acceptability of these measures.

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

Beamer, P. I., Plotkin, K. R., Gerba, C. P., Sifuentes, L. Y., Koenig, D. W. & Reynolds, K. A. 2015 Modeling of human viruses on hands and risk of infection in an office workplace using micro-activity data. *Journal of Occupational and Environmental Hygiene* **12**, 266–275. https://doi.org/10.1080/15459624.2014.974808.

Bischel, H. N., Caduff, L., Schindelholz, S., Kohn, T. & Julian, T. R. 2019 Health risks for sanitation service workers along a container-based urine collection system and resource recovery value chain. *Environmental Science & Technology* **53**, 7055–7067. https://doi.org/10.1021/acs.est.9b01092.

Chumo, I., Simiyu, S., Gitau, H., Kisiangani, I., Muindi, C. K. K. & Mberu, B. 2021 Manual pit emptiers and their health: Profiles, determinants and interventions. *International Journal of Medical and Health Sciences* **15**, 207–213.

De Giudici, P., Guillam, M.-T. & Ségala, C. 2013 Évaluation des risques sanitaires microbiologiques: Actualisation des connaissances (Microbiological health risk assessment: Updating of knowledge). *Environnement, Risques & Santé* **12**, 409–421. https://doi.org/10.1684/ers.2013.0648.

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

Fuhrimann, S., Winkler, M. S., Stalder, M., Niwagaba, C. B., Babu, M., Kabatereine, N. B., Halage, A. A., Utzinger, J., Cissé, G. & Nauta, M. 2016 Disease burden due to gastrointestinal pathogens in a wastewater system in Kampala, Uganda. *Microbial Risk Analysis* **4**, 16–28. https://doi.org/10.1016/j.mran.2016.11.003.

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

Gautam, M., Wankhade, K., Sarangan, G. & Sudhakar, S. 2021 Framework for addressing occupational safety of de-sludging operators: A study in two Indian cities. *Journal of Environmental Management* **289**, 112243. https://doi.org/10.1016/j.jenvman.2021.112243.

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

Hersher, R. 2017a *Haiti's 'Bayakou': Hauling Away Human Excrement by Hand*. NPR, Port-au-Prince, Haiti.

Hersher, R. 2017b *You Probably Don't Want To Know About Haiti's Sewage Problems [WWW Document]*. NPR. Available from: https://www.npr.org/sections/goatsandsoda/2017/07/29/537945957/you-probably-dont-want-to-know-about-haitis-sewage-problems (accessed 30 August 2023).

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-Baptiste, D., De Giudici, P. & Monette, F. 2023 Quantitative microbial risk assessment associated with the use of container-based toilets in Haiti. *Water Science & Technology* **88**, 1332–1343. https://doi.org/10.2166/wst.2023.274.

Katz, J. M. 2014 Haiti's shadow sanitation system. *The New Yorker*.

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.

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.

Lozano-Gracia, N. & Lozano, M. G. 2017 *Haitian Cities: Actions for Today with an Eye on Tomorrow*. World Bank Group, Washington, DC, USA.

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

Mazars, D. & Earwaker, P. 2013 *Improving Desludging in Haiti by Building the Capacity of Local Bayakou (Informal Manual Desludgers)*. In: 36th WEDC International Conference, Nakuru, Kenya. Loughborough University, Loughborough, UK.

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.

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

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.

Neiburg, F. & Nicaise, N. 2010 *Garbage, Stigmatization, Commerce, Politics*. Viva Rio, Port-au-Prince, Haïti.

Nicas, M. & Best, D. 2008 A study quantifying the hand-to-face contact rate and its potential application to predicting respiratory tract infection. *Journal of Occupational and Environmental Hygiene* **5**, 347–352. https://doi.org/10.1080/15459620802003896.

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.

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.

Oxfam 2007 *Manual Disludging Hand Pump*. Oxfam, Oxford, UK.

Regli, S., Rose, J. B., Haas, C. N. & Gerba, C. P. 2018 Modeling the risk from giardia and viruses in drinking water. *Journal AWWA* **110**, 68–72. https://doi.org/10.1002/awwa.1082.

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.

Sklar, R., Zhou, Z., Ndayisaba, W., Muspratt, A., Fuhrmeister, E. R., Nelson, K. & Katharine Hammond, S. 2021 Risk of adenovirus and Cryptosporidium ingestion to sanitation workers in a municipal scale non-sewered sanitation process: A case study from Kigali, Rwanda. *Journal of Water, Sanitation and Hygiene for Development* **11**, 570–578. https://doi.org/10.2166/washdev.2021.241.

Smith, S. M. 2014 *Subterranean Secrets: Defecation, the Bayakou, and Social Inequality in Haiti*. Bachelor's Thesis, Reed College, USA.

SOIL Haiti 2013 *Supporting Haiti's 'Underground' Sanitation Workers*. SOIL Haiti. Available from: http://www.oursoil.org/supporting-haitis-underground-sanitation-workers/ (accessed 30 August 2023).

Stenström, T. A., Seidu, R., Ekane, N. & Zurbrügg, C. 2011 *Microbial Exposure and Health Assessments in Sanitation Technologies and Systems*. Stockholm Environment Institute, Stockholm.

Strande, L., Ronteltap, M. & Brdjanovic, D. 2014 *Faecal Sludge Management: Systems Approach for Implementation and Operation*, 1st edn. IWA Publishing, London, UK.

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, pp. 55–91. https://doi.org/10.1007/978-1-4684-7065-9_3.

Tanner, B. D., Brooks, J. P., Gerba, C. P., Haas, C. N., Josephson, K. L. & Pepper, I. L. 2008 Estimated occupational risk from bioaerosols generated during land application of class B biosolids. *Journal of Environmental Quality* **37**, 2311–2321. https://doi.org/10.2134/jeq2007.0193.

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.

Tilley, E., Ulrich, L., Lüthi, C., Reymond, P., Zurbrügg, C. & ingénierie-conseil, S. I. A. 2016 *Compendium of Sanitation Systems and Technologies*, 2nd edn. Eawag, Dubendorf, Suisse.

Tsai, J., Wilson, N. & de los Reyes, F. L. 2022 Using illustrated system analysis for qualitative risk assessment of emptying of pit latrines. *Frontiers in Environmental Science* **10**, 1–12. https://doi.org/10.3389/fenvs.2022.1033877.

USEPA 2011a *Highlights of the Exposure Factors Handbook (Final Report) (Final Report No. EPA/600/R-10/030)*. National Center for Environmental Assessment, Washington, DC.

USEPA 2011b *Exposure Factors Handbook (Final Report) (Reports & Assessments No. EPA/600/R-09/052F)*. National Center for Environmental Assessment, Washington, DC.

USEPA 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.

World Bank 2018 *Looking Beyond Government-led Delivery of Water Supply and Sanitation Services: The Market Choices and Practices of Haiti's Most Vulnerable People*. World Bank, Washington, DC, USA.

World Bank, WHO, ILO & Water AID 2019 *Health, Safety and Dignity of Sanitation Workers: An Initial Assessment (No. SKU W19056)*. World Bank, Washington, DC, USA.

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 and 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.

First received 19 March 2024; accepted in revised form 9 May 2024. Available online 22 May 2024