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Estimating the Risk of Acute Gastrointestinal Disease Attributed to *E. coli* O157:H7 in Irrigation Water and Agricultural Soil: A Quantitative Microbial Risk Assessment

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Abstract: Introduction: The occurrence of *E. coli* O157:H7 in the agricultural environment poses a serious threat to public health. The primary aim was to estimate the probability of illness caused by *E. coli* O157:H7 in irrigation water and agricultural soil niches. Methods: The Quantitative Microbial Risk Assessment was used and the risks were characterized using the Monte Carlo simulation with 10,000 iterations. Results: The mean levels of *E. coli* O157:H7 in the irrigation water and agricultural soil samples was 1.328×10^3 CFU/100 mL (Range: 0.00 to 13.000×10^3 CFU/100 mL) and 2.482×10^3 CFU/g (Range: 0.167×10^3 to 16.333×10^3 CFU/g), respectively. The risk of infection in humans exposed to this water and soil was 100%. In addition, a high risk of acute diarrheal disease was estimated at 25.0×10^{-2} for humans exposed to contaminated water and/or soil. Summary: These results exceeded the WHO diarrheal disease risk standard of 1.0×10^{-3}. These findings demonstrated a high probability of acute gastrointestinal disease among humans exposed to *E. coli* O157:H7 in irrigation water and agricultural soil samples collected from the study sites representing a huge public health threat.

Keywords: diarrhoea; modelling; agroecosystem; microbial hazard; public health

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1. Introduction

The agricultural environment plays a huge role in the transmission of infectious disease pathogens [1]. At the pre-harvest level of agricultural production, the irrigation water, agricultural soil, biological amendments and animal intrusion serves as the main sources of fresh produce contamination, introducing pathogens into the food system [2]. Water used for irrigation are majorly sourced from groundwater, surface water, stored rainwater and human wastewater [3]. These water bodies are easily contaminated by human pathogens from various sources including surface runoffs [4]. In addition, the agricultural soil is a famous environmental niche for numerous foodborne pathogens which are usually introduced via contaminated irrigation water, surface runoffs and soil amendments [5]. For instance, *E. coli* O157:H7 was observed in slaughtered animals' fecal samples including camels, goats, and cattle in Al Ain, United Arab Emirates (UAE) which may be used for soil amendment [6].

Several foodborne pathogens capable of causing severe gastrointestinal disease including *Salmonella* spp., *Klebsiella* spp., *Enterobacter* spp., *E. coli* O157:H7 and *Listeria monocytogenes* have been recovered from irrigation water and agricultural soil samples [7–9]. These pathogens have the potential to internalize leafy vegetables [10]. *E. coli* O157:H7 is of great concern because it is easily transferred to the food web from the farm and can cause severe disease under low ingestion dose. *E. coli* O157:H7 is ubiquitous in nature and is ecologically adaptable within the agro-ecosystem and the food processing environments [11]. *E. coli* O157:H7 can persist in water and soil for up to 60 to 120 days under acidic and dry conditions [12]. Once ingested, *E. coli* O157:H7 produces shigatoxins which causes syndromes such as dysentery, hemolytic anaemia, hemorrhagic colitis, haemolytic uremic syndrome (HUS), reduced platelet count and thrombic thrombocytopenic purpura (TTP) whose sequelae may include renal disorder and death [13]. Interestingly, some students from the New York University Abu Dhabi (NYUAD) recently developed a portable and affordable device called E.coLAMP that can detect *E. coli* O157:H7 in just 20 min [14].

While the presence of *E. coli* O157:H7 in irrigation water and agricultural soil poses a huge threat to human health, there is a need to quantitatively predict the risks attributed to this pathogen using a risk-based assessment technique. This approach systematically pools information about the presence and nature of a given microbial hazard within a particular system, including its fate, transmission routes, routes of human exposure and the health effects associated with the exposure [15]. A quantitative microbial risk assessment (QMRA) was, therefore, carried out to estimate the risk of acute gastrointestinal disease attributed to *E. coli* O157:H7 in irrigation water and agricultural soil samples collected from Amathole and Chris Hani District Municipalities, Eastern Cape Province, South Africa. To the best of our knowledge, this is the first QMRA study on *E. coli* O157:H7 in irrigation water and agricultural soil to be carried out in the Province. Food samples were not considered as they are beyond the scope of this study.

2. Materials and Methods

2.1. Study Setting

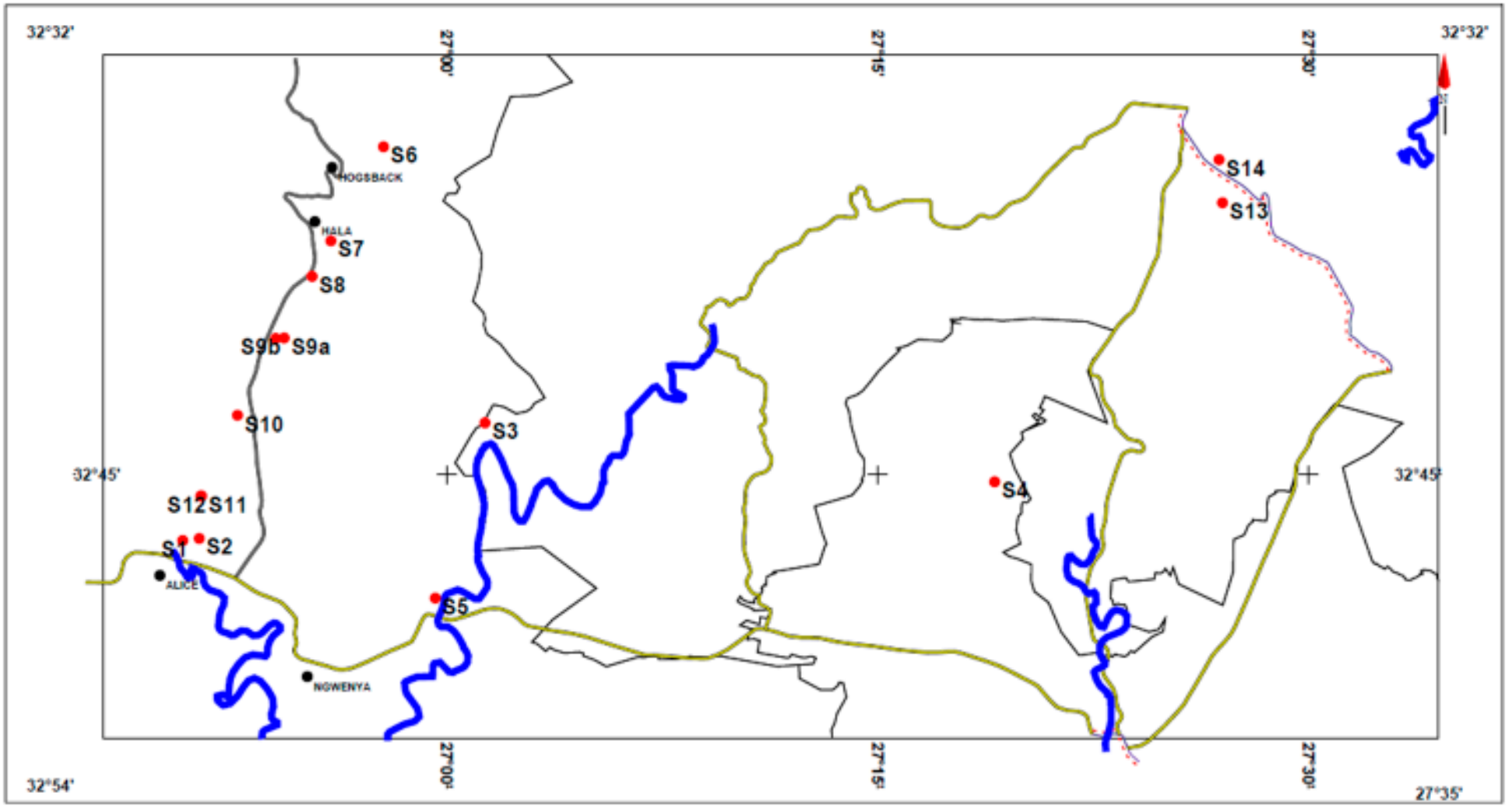
We carried out this study in Amathole (Figure 1A) and Chris Hani (Figure 1B) District Municipalities (DMs) in the Eastern Cape Province of South Africa. Located in the South-Eastern part of the country, the province is considered the second largest province and one of the most impoverished. Agriculture and agro-processing are among the major industries in the province. In 2016, Amathole DM was made up of 862,000 people which is about 12.3% of the Eastern Cape population and 1.55% of the South Africa population [16]. In 2017, Chris Hani District Municipality was made up of 849,000 people which is about 12.0% of the Eastern Cape population and 1.5% of South Africa population [17].

2.2. Microbiological Analysis

This section may be divided by subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

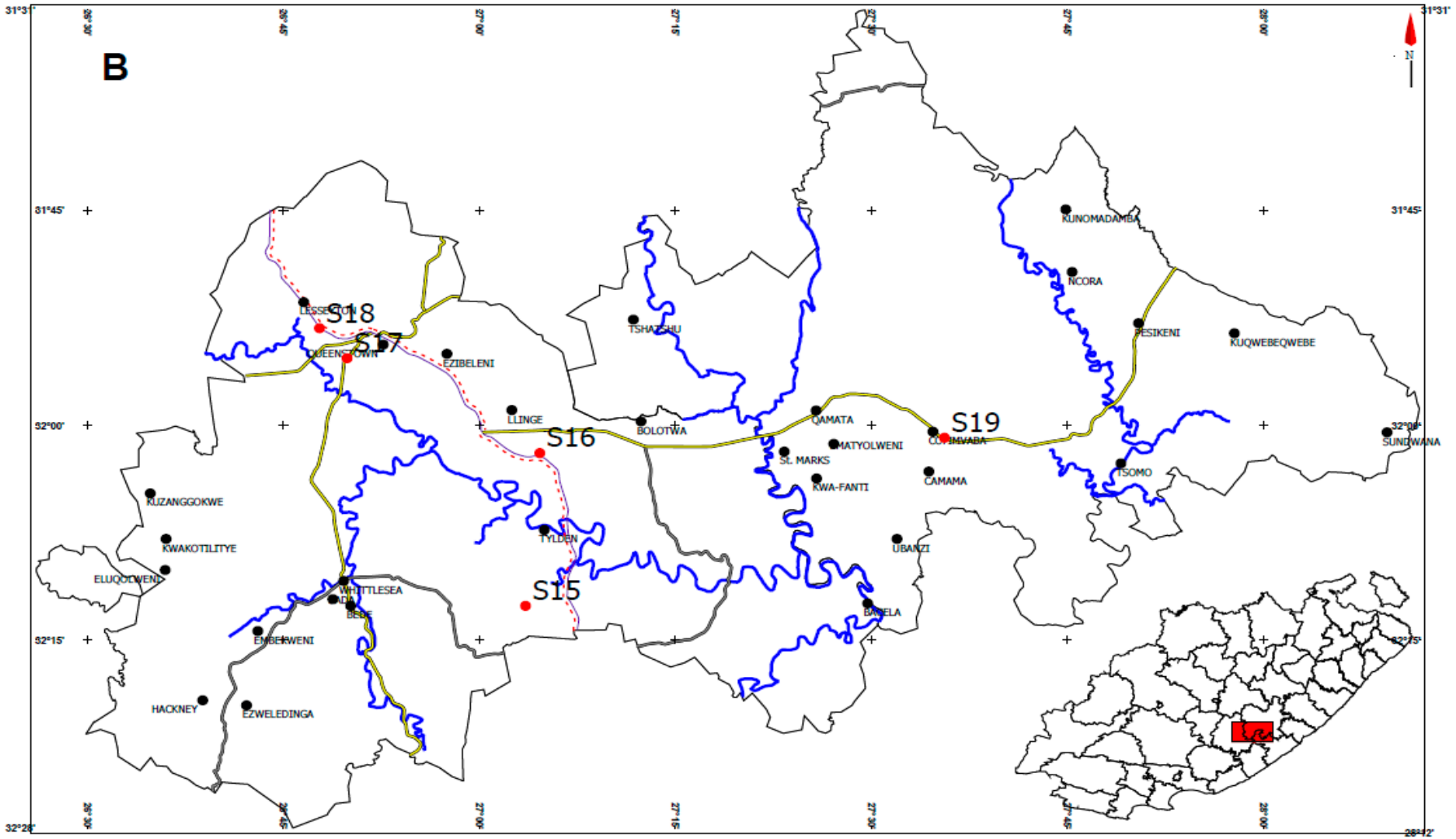
Sterile sample bottles and sterile plastic bags were used to collect the irrigation water samples (n = 19, approximately 1 litre each) and agricultural soil samples (n = 13, approximately 30 g each), respectively. All the samples were properly labelled, kept on ice and shipped to the laboratory within 4 h for further processing.

Irrigation water samples were subjected to serial dilution (10^{-1}, 10^{-2} and 10^{-3}) and then membrane filtration (100 mL) for the enumeration of *E. coli* O157:H7 [7]. Agricultural soil samples were subjected to serial dilution (10^{-1}, 10^{-2} and 10^{-3}) and then spread plate culture method (100 µL) for the enumeration of *E. coli* O157:H7 [7]. All the culture was carried out in triplicates using Sorbitol-MacConkey agar (SMA) (Merck, Johannesburg, South Africa) supplemented with cefixime (50 µg/L) and tellurite (25 mg/L). *E. coli* O157:H7 concentrations were presented in CFU/100 mL of irrigation water samples and CFU/g of agricultural soil samples.



(**A**)

Figure 1. *Cont.*



(**B**)

Figure 1. (**A**) Study sites in Amathole District Municipality, Eastern Cape Province, South Africa; (**B**) Study sites in Chris Hani District Municipality, Eastern Cape Province, South Africa.

Molecular confirmation of the isolates was carried out by targeting the *rfbE*$_{O157}$ (encodes the *E. coli* O157 serotype) and *fliC*$_{H7}$ (encodes the *E. coli* flagellum H7 serotype) genes in a polymerase chain reaction (PCR) as described by Wang and colleagues [18]. The PCR products (5.0 µL aliquot each) were electrophoresed in 2% (*w*/*v*) agarose gel (Merck, Johannesburg, South Africa) as described by Wang and colleagues [18] and photographed using the ultraviolet transilluminator. A 100-bp DNA ladder (Inqaba Biotec, Pretoria, South Africa) was included in each reaction to serve as a DNA size marker. The primer sequences used in the PCR and the expected amplicon sizes are shown in Table 1. The PCR cycling conditions were: 5 min, 94 °C; 33 cycles [45 s, 94 °C; 30 s, 56 °C; 1 min, 72 °C]; 5 min, 72 °C.

Shiga toxins 1 and 2 encoded by the *stx1* and *stx2* genes were screened in the confirmed *E. coli* O157:H7 isolates using PCR as described by Paton and colleagues [19]. These toxins play a role in the development of HUS and happens to be the hallmark of virulence in *E. coli* O157:H7 [20]. The specific primers used in the screening of the Shiga toxins is shown in Table 1 while the cycling conditions include: 94 °C 3 min, 35 cycles [93 °C 60 s, 55 °C 60 s, 72 °C 60 s] 72 °C 7 min. "*E. coli* O157:H7 ATCC 35150" was used as a control strain.

Table 1. Primer sequence and expected amplicon sequence sizes used in the detection of *E. coli* O157:H7 and the screening of shiga toxins.

Primer	Primer Sequence (5′-3′)	Target Genes	Amplicon Size (bp)	Reference
FliCH7	F: TACCATCGCAAAAGCAACTCC R: GTCGGCAACGTTAGTGATACC	*fliC*$_{H7}$	247	[18]
RfbE	F: CTACAGGTGAAGGTGGAATGG R: ATTCCTCTCTTTCCTCTGCGG	*rfbE*$_{O157}$	327	[21]
Stx1	F: ATAAATCGCCATTCGTTGACTAC R: AGAACGCCCACTGAGATCATC	*stx1*	180	[19]
Stx2	F: GGCACTGTCTGAAACTGCTCC R: TCGCCAGTTATCTGACATTCTG	*stx2*	255	[19]

2.3. Quantitative Microbial Risk Modelling

Quantitative microbial risk assessment modelling was carried out as described by Codex Alimentarius Commission [22] to determine the probability of illness caused by *E. coli* O157:H7 in irrigation water and agricultural soil. This was organized into a four-step science-based approach including hazard identification, hazard characterization, exposure assessment and risk characterization.

2.3.1. Hazard Identification

E. coli O157:H7 is an important foodborne pathogen. The identification of this pathogen, and its virulence potentials was carried out in the laboratory as described above. Its frequency distribution was analyzed to predict the health risks associated with contaminated irrigation water and agricultural soil.

2.3.2. Hazard Characterization

The adverse health effects associated with the occurrence of *E. coli* O157:H7 in irrigation water and agricultural soil was carried out using the hazard characterization. This analysis assumed that a single cell of *E. coli* O157:H7 will cause an infection and defines the relationship between the doses of *E. coli* O157:H7 and the corresponding negative health effects on the exposed population [23]. The ingestion dose of *E. coli* O157:H7 was therefore calculated using the following equation [24];

$$D = (I_v \times M_c) \quad (1)$$

where D denotes the ingestion dose of *E. coli* O157:H7, I_v denotes the ingested volume of irrigation water and agricultural soil and M_c denotes the mean concentration of *E. coli* O157:H7.

A "Beta-Poisson model" [25] was used to estimate the risk allied to *E. coli* O157:H7 as shown in the following equation;

$$P_{inf} = 1 - (1 + D/\beta)^{-\alpha} \quad (2)$$

where P_{inf} denotes the probability of infection that will occur in an individual exposed to a particular dose (D) of *E. coli* O157:H7, D denotes the ingestion dose of *E. coli* O157:H7, α and β denote the shape parameters and in this case, α is 0.0571 and β is 2.2183 [24].

2.3.3. Exposure Assessment

This assessment was carried out to: (a) assess the pathways by which *E. coli* O157:H7 can be moved from irrigation water and agricultural soil to the point of contact with human beings and (b) evaluate the amount of exposure that exists between humans and *E. coli* O157:H7. The exposure parameter (E) was evaluated by considering factors such as the concentration of pathogen in the environmental matrix, ingested volumes of the matrix, viability of the pathogen, and recovery efficacy of the methods in the following equation [26]:

$$E = CR^{-1} \cdot IM \quad (3)$$

where E denotes Exposure., C denotes the mean concentration of *E. coli* O157:H7 per 100 mL of irrigation water samples or per gram of soil samples., R denotes the recovery efficacy of the isolation method., I denote the fraction of detected *E. coli* O157:H7 capable of causing severe infection- that is, the isolates that produce the shiga toxins., and M denotes the amount of irrigation water and soil ingested per day. Parameters inputted for exposure assessment are shown in Table 2.

Table 2. Exposure assessment parameters in children and adult population.

Irrigation Water			Agricultural Soil		
Parameter	**Data**	**Source**	**Parameter**	**Data**	**Source**
Concentration (C) of *E. coli* O157:H7 (CFU/100mL)	Min: 0.000 Mean: 1.328×10^3 Max: 13.000×10^3	This study	Concentration (C) of *E. coli* O157:H7 (CFU/g)	Min: 0.167×10^3 Mean: 2.482×10^3 Max: 16.333×10^3	This study
Recovery efficiency (R) (%)	83	This study	Recovery efficiency (R) (%)	71	This study
Proportion (I) of *E. coli* O157:H7 capable of causing severe infection (that is STEC O157:H7) (%)	50	This study	Proportion (I) of *E. coli* O157:H7 capable of causing severe infection (that is STEC O157:H7) (%)	14	This study
Amount (M) of water ingested by adults during farming (mL/day)	10	[27]	Amount (M) of soil and dust ingested by adults (mg/day)	50	[28]
Amount (M) of water ingested by children during farming	Not given		Amount (M) of soil and dust ingested by children (mg/day)	100	[28]

Min: Minimum, Max: Maximum.

Recovery efficacy (R) was considered to prevent the over/underestimation of the pathogen concentration as well as the exposure using the following equation [26]:

$$R = (Po - P/Po) \times 100 \quad (4)$$

where "Po" denotes the presumptive number of *E. coli* O157:H7 isolates in irrigation water and agricultural soil samples and "P" denotes the confirmed isolates following cultural and molecular methods.

2.3.4. Risk Characterization

This was carried out to predict the incidence of health issues related to *E. coli* O157:H7 based on hazard identification, hazard characterization and exposure assessment. In this study, data from the dose-response and exposure assessment were integrated into a yearly probability of infection ($P_{inf/y}$) equation [24] as shown below.

$$P_{inf/y} = 1 - (1 - P_{inf})^{E} \quad (5)$$

where $P_{inf/y}$ denotes the yearly probability of infection, P_{inf} denotes the probability of infection due to a single exposure to an ingested dose (D) of *E. coli* O157:H7 and E denote the exposure.

To predict the annual risk of acute gastrointestinal disease, the following risk of illness equation was used [24];

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

where P_{ill} denotes the annual risk of diarrheal disease, $P_{inf/y}$ denotes the annual probability of infection and $P_{ill/inf}$ denotes the illness constant with respect to the etiologic agents. $P_{ill/inf}$ for *E. coli* is 0.25 [29].

A Monte Carlo simulation with 10,000 iterations was used to evaluate the risk associated with the exposure to *E. coli* O157:H7. The modelling was performed using R software version 3.0.3 (Development Core Team from Vienna, Austria) with the application of the R package (fitdistrplus) to fit the distribution of pathogen concentrations.

3. Results

3.1. The Concentration and Identification of E. coli O157:H7 in the Samples

In this study, the concentration of *E. coli* O157:H7 in irrigation water samples ranged from 0.000 in S12 and S17 to 13.000 × 10^3 CFU/100 mL in S18 with a mean level of 1.328 × 10^3 CFU/100 mL as shown in Figure 2. In addition, the concentration of *E. coli* O157:H7 in agricultural soil samples ranged from 0.167 × 10^3 in S12 to 16.333 × 10^3 CFU/g in S9 with a mean level of 2.482 × 10^3 CFU/g as shown in Figure 2.

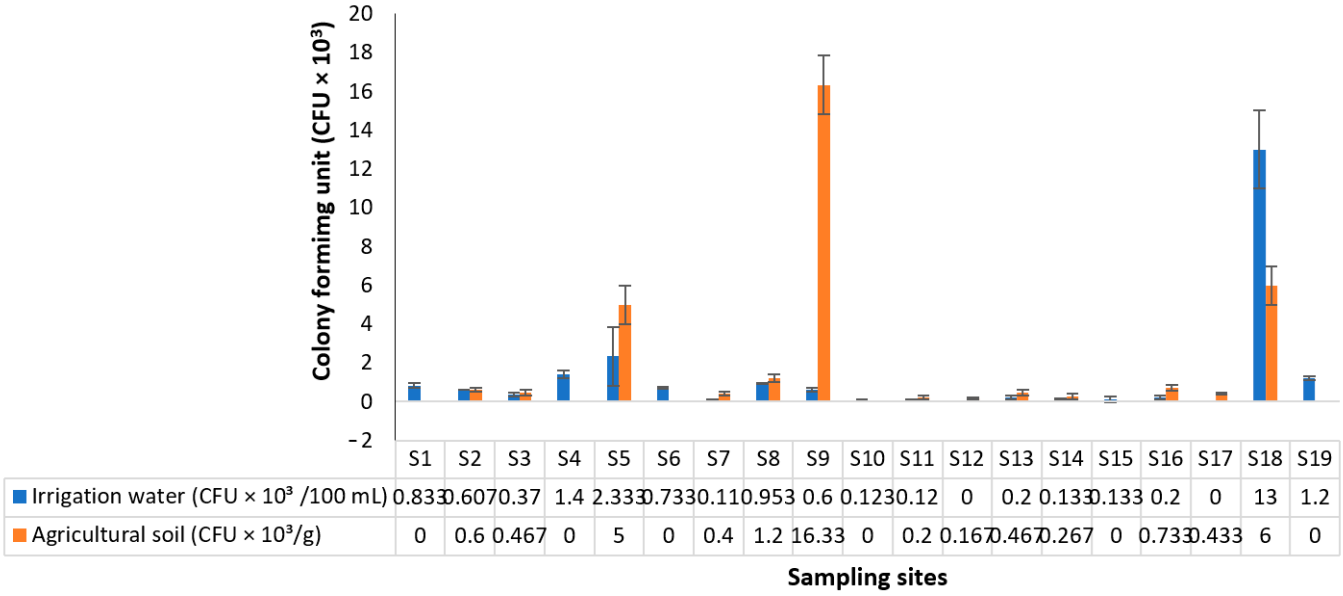


Figure 2. The Concentration of *E. coli* O157:H7 in irrigation water and agricultural soil samples. Soil samples were not collected from S1, S4, S6, S10, S15 and S19 due to our inaccessibility to the farms.

The occurrence of the confirmed *E. coli* O157:H7 and its shigatoxigenic variants in the samples are shown in Figure 3. Out of 202 presumptive isolates recovered from the irrigation water and soil samples, 46 (23%) were confirmed following the molecular

techniques. Here, 18 (39%) of these were confirmed in the irrigation water samples while 28 (61%) were confirmed in the soil samples.

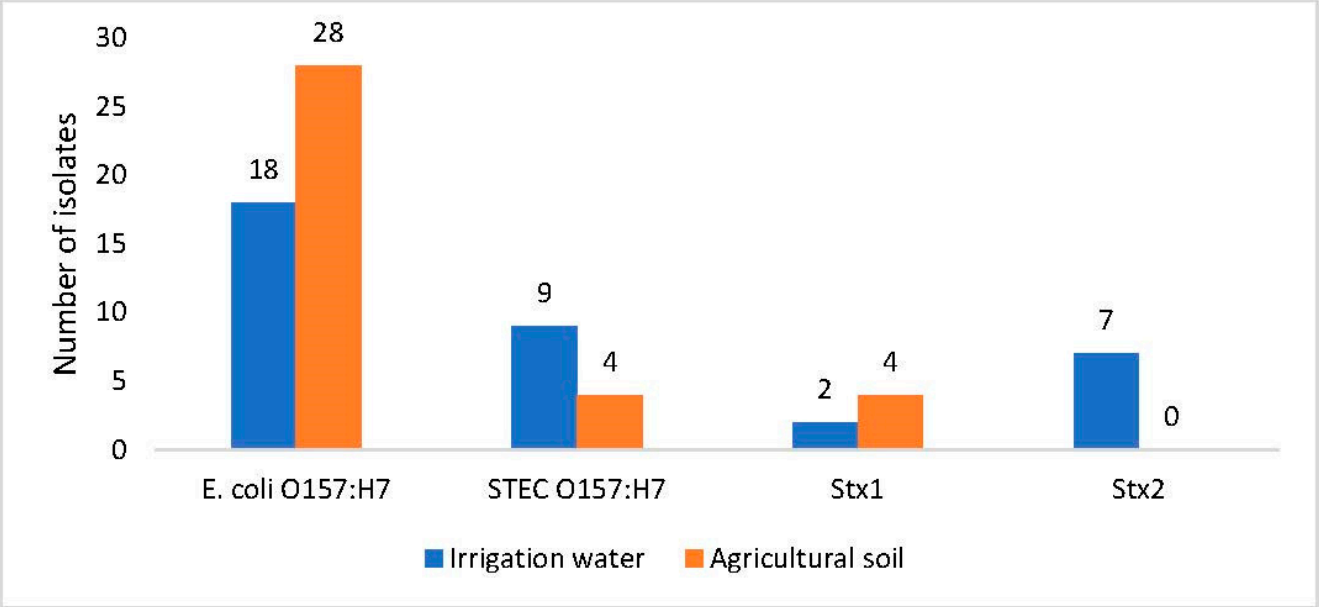


Figure 3. The number of confirmed *E. coli* O157:H7, its shiga toxigenic strains and *stx* genes in irrigation water and agricultural soil samples.

Of the confirmed *E. coli* O157:H7, 13 (28%) are shiga toxin *E. coli* O157:H7 (STEC O157:H7). Nine (50%) of which were detected in irrigation water samples and 4 (14%) were detected in the soil samples. Of the STEC O157:H7 isolated from the irrigation water samples, 2 (22%) harbored the *stx1* gene while 7 (78%) harbored the *stx2* gene. All the STEC O157:H7 isolated from the soil samples harbored the *stx1* gene as shown in Figure 3.

3.2. Dose Modelling and Hazard Characterization

The results of dose modelling and hazard characterization of *E. coli* O157:H7 in irrigation water and agricultural soil in the study sites are presented in Table 3. In adults, a 3.30×10^{-1} probability of infection due to 13.28×10^{3} ingestion dose of *E. coli* O157:H7 in irrigation water was recorded. At maximum ingestion dose of 130.00×10^{3}, a 4.70×10^{-1} probability of infection was recorded. A 0.00 probability of infection was recorded at minimum ingestion dose of 0.00. The probability of infection in children was not recorded because the parameter for the ingested volume of irrigation water by children was not available. Conversely, a 4.30×10^{-1} probability of infection due to 124.10×10^{3} ingestion dose of *E. coli* O157:H7 in agricultural soil was recorded for adults. At minimum ingestion dose of 8.33×10^{3}, the probability of infection was 3.80×10^{-1} while at maximum ingestion dose of 816.67×10^{3}, the probability of infection was 5.20×10^{-1}. In children, a 4.50×10^{-1} probability of infection at 248.21×10^{3} ingestion dose of *E. coli* O157:H7 in agricultural soil was recorded. At minimum ingestion dose of 16.67×10^{3}, a 4.00×10^{-1} probability of infection was recorded while at maximum ingestion dose of 1633.33×10^{3}, a 5.40×10^{-1} probability of infection was recorded.

3.3. Exposure Assessment

The scope of human exposure to *E. coli* O157:H7 in irrigation water and agricultural soil is shown in Figure 4. Based on the parameters inputted for exposure assessment, the estimated adult exposure to *E. coli* O157:H7 in irrigation water was found to be 8.000×10^{3} ranging from 0.000 to 78.313×10^{3} as shown in Table 4. The exposure parameter for children exposed to *E. coli* O157:H7 in irrigation water was not determined. In addition, the estimated exposure for adults exposed to *E. coli* O157:H7 in agricultural soil was found to be

24.470 × 10^3 ranging from 1.647 × 10^3 to 161.030 × 10^3. In children, the exposure to *E. coli* O157:H7 in agricultural soil was 48.941 ×10^3 ranging from 3.293 × 10^3 to 322.059 × 10^3 as shown in Table 4.

Table 3. The daily probability of infection based on hazard characterization in irrigation water and agricultural soil samples.

Parameter	Irrigation Water			Agricultural Soil		
	Min	**Mean**	**Max**	**Min**	**Mean**	**Max**
Ingestion dose (D) in adults	0.00	13.28 × 10^3	130.00 × 10^3	8.33 × 10^3	124.10 × 10^3	816.67 × 10^3
Ingestion dose (D) in children	-	-	-	16.67 × 10^3	248.21 × 10^3	1633.33 × 10^3
Probability of infection (P_{inf}) in adults (daily risk)	0.00	3.30 × 10^{-1}	4.70 × 10^{-1}	3.80 × 10^{-1}	4.30 × 10^{-1}	5.20 × 10^{-1}
Probability of infection (P_{inf}) in children (daily risk)	-	-	-	4.00 × 10^{-1}	4.50 × 10^{-1}	5.40 × 10^{-1}

Min: Minimum, Max: Maximum.

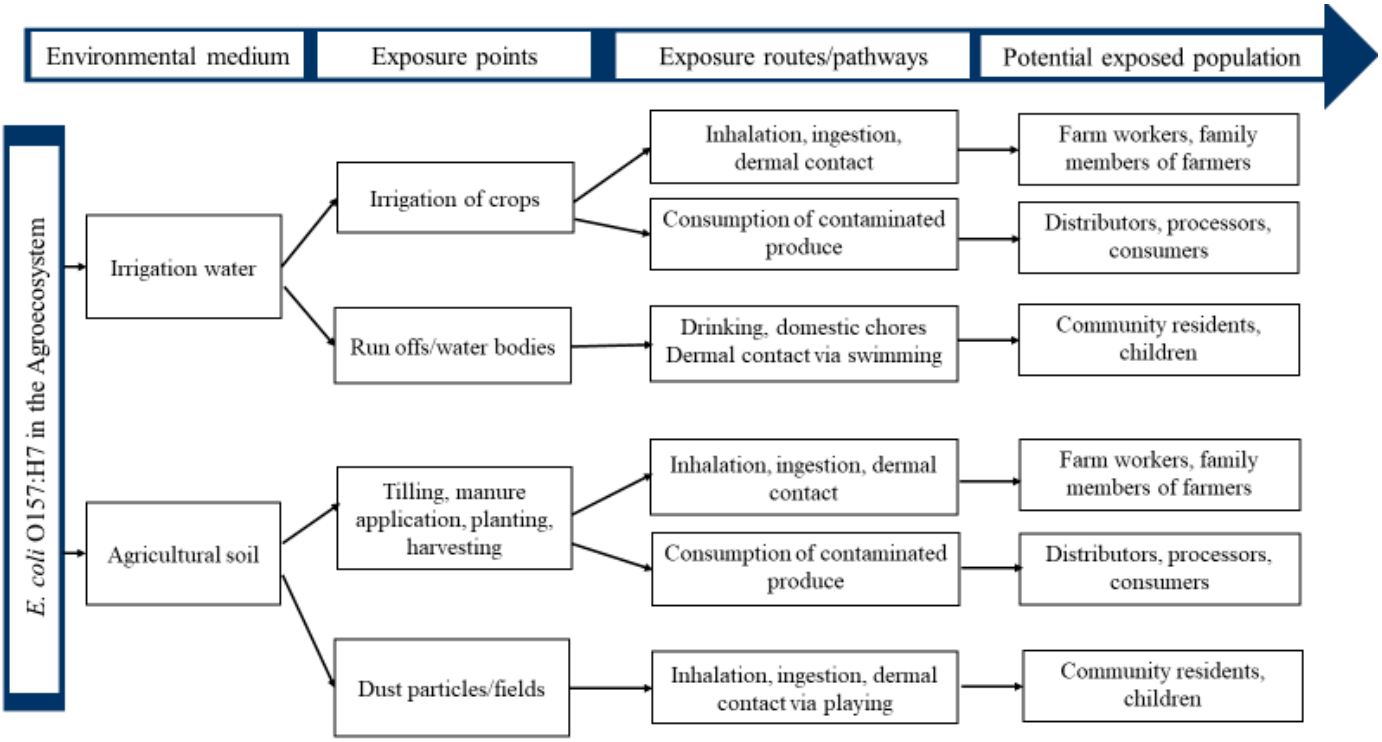


Figure 4. Possible ways humans can be exposed to *E. coli* O157:H7 in irrigation water and agricultural soil.

Table 4. The evaluated exposures in children and adults.

Parameter	Irrigation Water	Agricultural Soil
Exposure (E) in adults	Min: 0.000 Mean: 8.000 × 10^3 Max: 78.313 × 10^3	Min: 1.647 ×10^3 Mean: 24.470 × 10^3 Max: 161.030 × 10^3
Exposure (E) in children	Not determined	Min: 3.293 × 10^3 Mean: 48.941 × 10^3 Max: 322.059 × 10^3

Min: Minimum, Max: Maximum.

3.4. Risk Characterization

The annuitized risk of infection and risk of acute gastrointestinal disease in exposed adults and children to *E. coli* O157:H7 in irrigation water and agricultural soil are presented in Table 5. The mean and maximum annual risk of infection in adults exposed to contaminated irrigation water was 1.0, with a 0.0 minimum risk of infection. The annual risk of infection among children exposed to contaminated irrigation water was not determined. Interestingly, the mean, minimum and maximum annual risk of infection in both adults and children exposed to contaminated agricultural soil was 1.0.

Table 5. The annual health risk due to ingestion of *E. coli* O157:H7 in irrigation water and agricultural soil.

Parameter	Irrigation Water			Agricultural Soil		
	Min	**Mean**	**Max**	**Min**	**Mean**	**Max**
Annual risk ($P_{inf/y}$) in adults	0.0	1.0	1.0	1.0	1.0	1.0
Annual risk ($P_{inf/y}$) in children	-	-	-	1.0	1.0	1.0
Annual risk of diarrheal disease (P_{ill}) in adults	0.0	25.0×10^{-2}	25.0×10^{-2}	25.0×10^{-2}	25.0×10^{-2}	25.0×10^{-2}
Annual risk of diarrheal disease (P_{ill}) in children	-	-	-	25.0×10^{-2}	25.0×10^{-2}	25.0×10^{-2}

Min: Minimum, Max: Maximum.

The annuitized risk of diarrheal disease in adults exposed to *E. coli* O157:H7 in irrigation water was 25.0×10^{-2} with a range of 0.0 to 25.0×10^{-2}. The annual risk of diarrheal disease in children exposed to *E. coli* O157:H7 in irrigation water was not evaluated. However, the mean, minimum and maximum annual risk of diarrheal disease in both adults and children exposed to *E. coli* O157:H7 in agricultural soil was 25.0×10^{-2}.

4. Discussion

In this study, the probability of infection and risk of acute gastrointestinal disease attributed to *E. coli* O157:H7 in irrigation water and agricultural soil samples collected from Amathole and Chris Hani District Municipalities were estimated using the science-based stochastic QMRA approach. For over 35 years, the QMRA has been employed to proffer recommendations for improving the general wellbeing of the population with respect to food, water, environment, remediation and so on [30]. Through the combination of exposure assessments and microbial analysis, the QMRA can complement epidemiological studies in assessing public health risks especially in developing countries [31].

E. coli O157:H7 represents one of the significant foodborne pathogens due to its high virulence potentials and ability to cause severe diseases in humans. The perseverance of this pathogen within the agricultural niche is detrimental to food safety and the general wellbeing of the population. In this study, a relatively high abundance of *E. coli* O157:H7 was recorded in the irrigation water and agricultural soil samples, exacerbating the risk of infection among the exposed population. The mean concentration of *E. coli* O157:H7 in irrigation water samples exceeded the South African Department of Water Affairs (DWAF) standard for faecal coliforms in domestic water (0.0 CFU/100 mL) [32] as well as the World Health Organization (WHO) standard for coliforms in wastewater used for agriculture and aquaculture ($\leq$100 CFU/100 mL) [33], thus making it a chief exposure medium for *E. coli* O157:H7. There are no established guidelines for the tolerable concentration of *E. coli* O157:H7 in agricultural soil. However, the soil naturally harbours diverse pathogenic bacteria and it's open to several points and non-point sources of contamination, also making it a chief exposure medium for *E. coli* O157:H7.

The occurrence of confirmed *E. coli* O157:H7 and its shigatoxigenic strains in agricultural niches such as irrigation water an agricultural soil indicates a threat to food safety and the general wellbeing of the potential exposed population. At a prevalence rate of

23%, the occurrence of *E. coli* O157:H7 in the irrigation water and agricultural soil in the present study is relatively high, exceeding that recorded in diverse farm environments including beef, dairy, poultry and swine environments [34]. This is catastrophic as 28% of the confirmed isolates are shigatoxigenic with great potential of causing severe forms of gastrointestinal disease.

The common routes by which susceptible population including adults and children can be exposed to *E. coli* O157:H7 in irrigation water and agricultural soil were presented in the present study (Figure 4). It was indicated that the consumption of fresh produce contaminated by irrigation water and soil is an important exposure pathway for *E. coli* O157:H7, potentially putting the lives of consumers, distributors and processors in peril. This is consistent with the findings of Park et al., 2012 who indicated that irrigation water is a significant contamination route of fresh produce during primary agricultural production [35]. The unintentional inhalation, dermal contact and ingestion of irrigation water and soil particles containing *E. coli* O157:H7 could potentially endanger the lives of farmers, co-workers and family members carrying out agricultural activities on the farms. Children and community residents playing in the soil, swimming and fetching water from irrigation water sources for domestic reasons could potentially become exposed to *E. coli* O157:H7 via ingestion, inhalation and dermal contact, thus increasing their risks of infection.

Generally, the risk of infection resulting from the exposure to pathogenic microbes is contingent upon certain factors such as the virulence and infectivity of the pathogen, the exposure routes which is usually influenced by the behaviour of the environmental matrix, and the ingestion dose of the pathogen [36]. According to the WHO, the annual tolerable reference level of human health risk attributed to drinking water is 1×10^{-4} [37] and that attributed to excreta and greywater used for agricultural activities is 1×10^{-6} DALY [38]. These standards were used as benchmarks to critique the health risks generated in the present study.

In this study, the daily risk (probability) of infection among adults exposed to *E. coli* O157:H7 in irrigation water was 3.3×10^{-1} and 4.7×10^{-1} at maximum, assuming they intentionally or unintentionally ingest 10 mL of contaminated irrigation water per day. At the same ingestion volume, the minimum probability of infection was 0. This is because the minimum concentration of *E. coli* O157:H7 in the water samples was 0 CFU/100 mL. This indicates that the absence of pathogens in irrigation water results in zero health risks among the population utilizing the irrigation water sources for agricultural and domestic activities. Unfortunately, the mean and maximum annuitized risk of infection among adults exposed to *E. coli* O157:H7 in irrigation water was 1, exceeding the permissible WHO benchmark. This also surpassed the findings of Kouame et al. who documented an annual risk of 20.0×10^{-2} attributed to *E. coli* O157:H7 in water used for the irrigation of vegetables [24]. Interestingly, our findings corroborate a previous study that documented a high infection risk that ranged from 90.07% to 99.9% attributed to *E. coli* O157:H7 in reclaimed wastewater and lagoon [31]. This confirms that the quality of water used for irrigation purposes in the study sites are poor, thus endangering the lives of the possible exposed population.

There is a scarcity of studies that estimate the health risks attributed to *E. coli* O157:H7 in agricultural soil. In this study, the mean (4.3×10^{-1}), minimum (3.8×10^{-1}) and maximum (5.2×10^{-1}) daily risk of infection among adults exposed to *E. coli* O157:H7 in agricultural soil are relatively high, assuming they intentionally or accidentally ingest 50 mg of contaminated soil particles per day. A much higher mean (4.5×10^{-1}), minimum (4.0×10^{-1}) and maximum (5.4×10^{-1}) daily risk of infection was recorded for children based on the assumption that they intentionally or accidentally ingest 100 mg of contaminated soil particles per day. This consequently led to a 100% annual risk of infection among adults and children exposed to *E. coli* O157:H7 in agricultural soil, exceeding the WHO tolerable limits. This corroborates a similar finding whereby the mean annual infection risk attributed to Cryptosporidium oocyst in the soil was 85% for adults and 100% for children as well as the mean annual infection risk attributed to Giardia cyst in the soil was 100%

for both adults and children [26]. However, a lower annual risk of 54.7% was recorded for *E. coli* in a contaminated soil from open space and a playground for children [36].

The sequence of events that occur between *E. coli* O157:H7 infection and the establishment of a disease is poorly understood. However, it has been shown that the ingestion of an inoculum size as low as 100 organisms is capable of causing an illness [39]. A portion of that inoculum must be able to survive the acidic nature of the stomach and then inhabit the intestine [40]. In this study, a very high probability of acute intestinal disease (diarrhoea) attributed to *E. coli* O157:H7 in irrigation water and agricultural soil in both adults and children was reported (estimated at 25.0×10^{-2} per person per year). This exceeded the maximum allowable diarrheal disease risk of 1.0×10^{-3} per person per year stipulated by the WHO [38,41]. Our results also exceeded the findings of Kouamé et al. who reported a 4.6×10^{-2} probability of diarrheal disease attributed to *E. coli* O157:H7 in wastewater used for farming activities [24]. This indicates that a high probability of diarrheal disease could occur in adults and children exposed to the irrigation water and agricultural soil within the study sites of the present study. This is catastrophic and can lead to a disease outbreak if nothing is urgently carried out.

5. Study Limitations

While this study detailed the probability of infection and the probability of illness attributed to *E. coli* O157:H7 in irrigation water and agricultural soil, it is worthy to note that the assessment assumed that all the exposed individuals will have the same chance of becoming infected. In reality, this might not always be the case as certain factors such as the immune status, ingestion dose, age, gender and presence of co-morbidities in the exposed population might influence the outcome of the exposure to *E. coli* O157:H7 in irrigation water and agricultural soil [37].

6. Conclusions

This study demonstrated a high concentration of *E. coli* O157:H7 in the irrigation water and agricultural soil samples collected from the study sites. Consequently, a high probability of infection and risk of acute gastrointestinal disease among the exposed population living around the study sites was recorded, thus posing serious health risks to the general public. This suggests the need to urgently develop evidence-based interventions to manage and minimize the health risks attributed to *E. coli* O157:H7 in the agricultural milieu. We recommend that QMRA of other preharvest contamination routes such as harvesting tools, organic manure and feral faecal materials be carried out to have a complete profile of the health risks emanating from the preharvest agricultural production for more balanced interventions.

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