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Quantitative microbial risk assessment for *Escherichia Coli* O157: H7 via drinking water in the Gaza Strip, Palestine

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Abstract

Introduction: Microbial contamination of drinking water, particularly by pathogens such as *Escherichia coli* O157: H7, is a significant public health concern worldwide, especially in regions with limited access to clean water like the Gaza Strip. However, few studies have quantified the disease burden associated with *E. coli* O157: H7 contamination in such challenging water management contexts.

Objective: This study aimed to conduct a comprehensive Quantitative Microbial Risk Assessment to estimate the annual infection risk and disease burden attributed to *E. coli* O157: H7 in Gaza's drinking water.

Methods: Applying the typical four steps of the Quantitative Microbial Risk Assessment technique—hazard identification, exposure assessment, dose-response analysis, and risk characterization—the study assessed the microbial risk associated with *E. coli* O157: H7 contamination in Gaza's drinking water supply. A total of 1317 water samples from various sources across Gaza were collected and analyzed for the presence of *E. coli* O157: H7. Using Microsoft ExcelTM and @RISKTM software, a Quantitative Microbial Risk Assessment model was constructed to quantify the risk of infection associated with *E. coli* O157: H7 contamination. Monte Carlo simulation techniques were employed to assess uncertainty surrounding input variables and generate probabilistic estimates of infection risk and disease burden.

Results: Analysis of the water samples revealed the presence of *E. coli* O157: H7 in 6.9% of samples, with mean, standard deviation, and maximum values of 1.97, 9.74, and 112 MPN/100 ml, respectively. The risk model estimated a median infection risk of $3.21 \times 10\text{-}01$ per person per year and a median disease burden of $3.21 \times 10\text{-}01$ Disability-Adjusted Life Years per person per year, significantly exceeding acceptable thresholds set by the WHO.

Conclusion: These findings emphasize the urgent need for proactive strategies to mitigate public health risks associated with waterborne pathogens in Gaza.

Keywords

Burden of disease, *E. coli* O157: H7, Gaza Strip, QMRA, waterborne diseases, water safety plan

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Introduction

The persistent issue of microbiological contamination in drinking water supply systems (DWSSs) is a global concern, especially in developing countries where access to safe drinking water remains a challenge.[1] The Gaza Strip exemplifies this crisis with significant microbial contamination of its drinking water, as evidenced by numerous studies detecting coliform bacteria in Gaza's water sources.[2,3] Despite these findings, there is a lack of comprehensive assessments concerning the associated burden of diseases resulting from contaminated drinking water.

Several factors contribute to the compromised quality and quantity of groundwater in the region. The high population density, coupled with excessive groundwater extraction and improper wastewater disposal, exacerbates the issue.[4,5] Despite efforts to address this challenge, such as the establishment of commercial small-scale brackish desalination plants, these solutions have vulnerabilities. Cross-contamination risks persist during water handling, transportation via tanker trucks, and storage, which contribute to ongoing health hazards.[6] Furthermore, outdated municipal water distribution systems and lapses in disinfection processes further jeopardize water quality.[7]

The epidemiological landscape vividly reflects the consequences of this water quality crisis, particularly in terms of diarrheal diseases, which continue to be a leading cause of child morbidity in the Gaza Strip. Notably, there has been a concerning increase in the prevalence of diarrhea cases, highlighting the urgent need for effective interventions.[8]

Recognizing the imperative for a comprehensive approach to water safety management, the World Health Organization (WHO) advocates for the implementation of Water Safety Plans (WSP) and quantitative microbial risk assessment (QMRA). These frameworks offer systematic methodologies for managing microbial risks throughout the water supply chain.[9–11]

QMRA, adapted from chemical risk assessment paradigms, encompasses hazard identification, exposure assessment, dose-response analysis, and risk characterization. This approach provides a robust tool for evaluating and mitigating health risks associated with waterborne pathogens.[12]

The use of disability-adjusted life years (DALYs) in risk assessment provides a comprehensive measure of disease burden attributable to contaminated drinking water. DALYs offer insights into the potential impact of waterborne pathogens on public health, aiding in resource allocation and intervention prioritization.[9,13]

Escherichia coli (*E. coli*) serves as a critical indicator organism for assessing drinking water quality, with certain pathogenic strains posing significant health risks. Among these, *E. coli* O157: H7, a member of the *Enterohemorrhagic E. coli* (EHEC) group, has garnered particular attention due to its association with waterborne outbreaks worldwide.[14,15] The fecal-oral transmission route underscores the importance of implementing multiple-barrier principles to safeguard drinking water from microbial contaminants.[16,17]

Infections with *E. coli* O157: H7 can lead to a spectrum of symptoms, ranging from mild diarrhea to severe, bloody diarrhea, often accompanied by abdominal cramping. Vulnerable populations, such as young children and the elderly, may experience systemic complications, including thrombotic thrombocytopenic purpura, hemolytic-uremic syndrome, and acute renal failure.[18–20]

Despite the significance of *E. coli* O157: H7 as a waterborne pathogen, limited studies have explored its quantitative microbial risk in drinking water systems globally. Moreover, specific investigations into the risk posed by this pathogen in Gaza's drinking water are notably lacking. Therefore, this study aims to fill this critical knowledge gap by employing QMRA to estimate infection risks and disease burdens associated with *E. coli* O157: H7 contamination in Gaza's drinking water. By providing decision-makers and stakeholders with actionable insights, this research endeavors to inform evidence-based interventions and optimize investment in DWSS infrastructure.

Materials and methods

Description of the study area and water supply system

Gaza Strip is the southwestern gateway of Palestine, with around 1.9 million Palestinians on some 365 km^2. Gaza ranks as the third most densely populated polity in the world. The territory borders Israel to the north and east, Egypt to the south, and the Mediterranean Sea to the West. Gaza Strip consists of five governorates namely: Northern, Gaza, Mid Zone, Khan Younis, and Rafah.[21] Gaza Strip has a unique DWSS. First, municipalities provide households and other facilities with groundwater via underground network pipes. Second, private commercial firms and Non-Governmental Organizations (NGOs) provide households and other facilities with trucked desalinated water from small-scale brackish water desalination plants. Third, households, particularly in rural areas, rely on their own private wells for drinking and domestic uses (Figure 1).

In the Gaza Strip, chlorination is the very popular method of water disinfection as insufficient amounts of chlorine are usually added to only two points of water supply system (after desalination and before pumping in the municipal network pipelines) mainly due to aesthetic issues such as odor and taste issues.[22,23]

Sampling and confirmation of E. coli *O157: H7*

In the current cross-sectional study, a total of 1317 water samples were collected from multiple points from catchment to consumer's tap within the Gaza water supply system over the four seasons in the period between March 2018 and January 2019. Sampling frequency varied based on

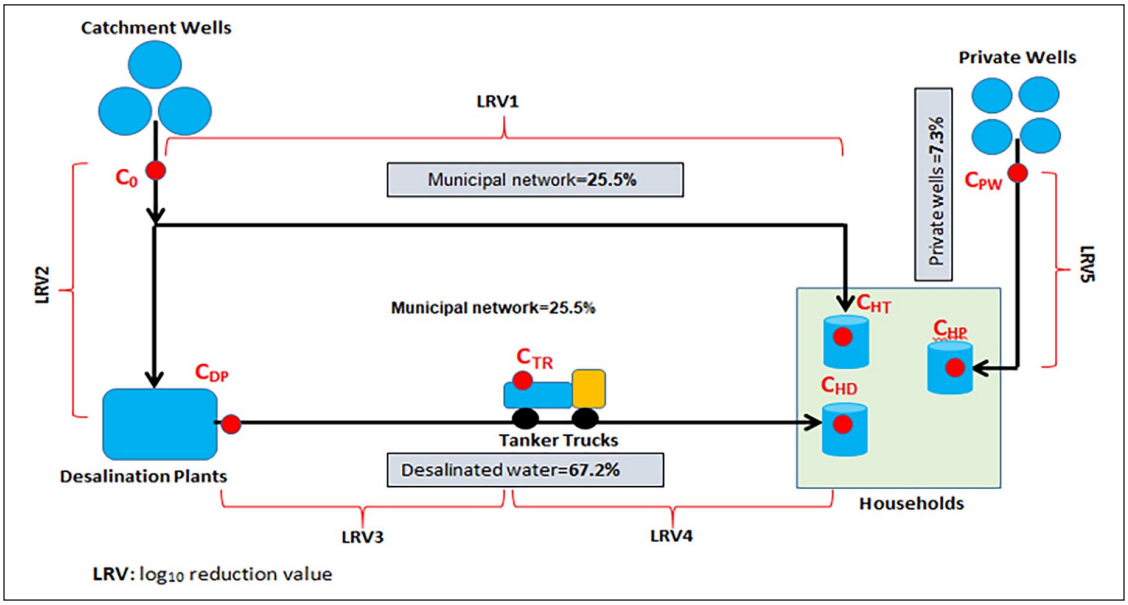

Figure 1. Schematic illustration map of a typical Gaza Strip's water supply system.

operational conditions and water quality monitoring protocols. Each sample was analyzed for *E. coli* O157:H7 concentrations using standard microbiological methods.

About 109, 109, 197, 384, 384, 67, and 67 water samples were taken from seven reference points of DWSS in the Gaza Strip, which were water wells, small-scale water desalination plants, tanker trucks, desalinated water at households, municipal water at households, private wells, private well water at households, respectively. Stratified random sampling was employed to warrant the representative distribution of the study sample into neighborhoods of the five Gaza Strip governorates in accordance with the number of households in each governorate. The standard methods for water microbiological examination were followed.[24]

Water samples were sent to a private, well-equipped, licensed laboratory for microbiological analysis in a container containing ice cubes and analyzed immediately upon arrival at the laboratory. A community-based survey was conducted among 1857 Gaza households to collect information about drinking water sources and drinking water consumption per capita per day at households.

A Quanti-Tray/2000 with 49 large wells and 48 small wells was used without additional serotyping. The "Quanti-Tray/2000" system is manufactured by IDEXX Laboratories, Inc., a leading global provider of water testing solutions. The Quanti-Tray/2000 system is a widely used method for the enumeration of microbial contaminants, including *E. coli* O157: H7, in water samples. IDEXX Laboratories, Inc. is headquartered in Westbrook, Maine, USA, and has a global presence, providing innovative solutions for water quality testing and microbiological analysis.

A snap pack of metabolized Colisure's nutrient-indicator MUG (4-Methylumbelliferyl β-D-glucopyranoside was added to 100 ml water sample and then poured into the Quanti-Tray. The Quanti-Tray thereafter was sealed using a Quanti-Tray sealer and incubated at 37°C for 24 h. To determine the number of *E. coli*, the Quanti-Tray was exposed to an ultra-violet lamp with 6-watt and 365-nanometer placed in a dark box, the red/magenta, and fluorescence wells mean the sample is positive for *E. coli*. Yello/Gold wells mean the sample is negative for *E. coli*. The most probable number (MPN) table was used to obtain the MPN of *E. coli* per 100 ml water sample.

For *E. coli* O157: H7 examination, a sample was taken from each confirmed Quanti-Tray well with positive *E. coli* individually and then struck on Petri dishes (60 × 15 mm) contains cefixime tellurite sorbitol-MacConkey (CT–SMAC) agar, thereafter incubated for 24 h at 37°C. The majority of *E. coli* isolates do ferment sorbitol and give characteristic pink colonies, therefore, they give colorless colonies on the medium. For the identification and confirmation of *E. coli* serogroup O157, an oxoid *E. coli* O157: H7 latex agglutination test kit was used. Also, the MPN table was used to estimate the *E. coli* O157: H7 densities per 100 ml water sample according to the number of positive large and small wells for *E. coli* O157: H7.[25,26]

Simulation methodology and implications of uncertainty and variability

In this study, we employed a two-dimensional simulation approach using @RISKTM software (Palisade, Ivybridge, UK) integrated with Microsoft ExcelTM to conduct a comprehensive Quantitative Microbial Risk Assessment (QMRA) for *E. coli* O157: H7 contamination in Gaza's drinking water supply. The "two-dimensional simulation

technique" involves considering uncertainty or variability across different model parameters and percentiles of the estimated infection risk distribution. This methodology allowed us to evaluate the complex interplay of multiple variables influencing microbial risk, including microbial concentrations, exposure pathways, and dose-response relationships.

Derivation of probability distributions

The probability distributions used in our simulation model were derived from a combination of empirical data collected during our sampling campaign and literature-based estimates. Specifically, we parameterized our model using measured microbial concentrations from water samples across various sources within the Gaza Strip, as well as dose-response relationships obtained from published epidemiological studies.

Addressing uncertainty and variability

Our study acknowledges and distinguishes between uncertainty (due to lack of precise knowledge about input parameters) and variability (inherent differences in microbial concentrations and exposure scenarios). The Monte Carlo simulation technique allowed us to quantify the uncertainty surrounding input variables and generate probabilistic estimates of infection risk and disease burden.

Central to our risk assessment methodology was the implementation of Monte Carlo simulation techniques.[27] Monte Carlo simulation provides a powerful framework for probabilistic modeling, generating numerous random samples from the specified probability distributions. Through the simulation of a large number of scenarios, Monte Carlo simulation allows us to quantitatively evaluate the likelihood of different outcomes and assess the associated risks with a high degree of confidence.

In further strengthening the statistical rigor of our analysis, we drew upon recent advancements in the field of microbial risk assessment. Studies such as Custodio et al.[28] 2023 have demonstrated the effectiveness of Monte Carlo simulation in evaluating microbial contamination levels in drinking water systems. By leveraging insights from these studies, we optimized our risk assessment approach, ensuring the reliability and validity of our results.

Calculation of log10 reduction values

To assess treatment effectiveness and attenuation of *E. coli* O157:H7 concentrations throughout the water distribution system, Log10 Reduction Values (LRVs) were calculated. LRVs were determined by comparing the log reduction in *E. coli* O157:H7 concentrations after treatment to the initial concentrations before treatment for each specific sampling event.

LRVs were computed using paired sample analysis, where the difference in log-transformed concentrations (post-treatment minus pre-treatment) was calculated for each sample point and sampling date. Individual LRVs were then used to construct a distribution, capturing the variability and uncertainty in treatment efficacy across different sampling events and locations.

Stochastic assessment

The stochastic nature of treatment effectiveness and microbial attenuation was characterized by analyzing the distribution of LRVs. Each measured LRV represented a data point in the distribution, allowing for statistical analysis to quantify variability and uncertainty associated with treatment processes within the water supply system.

Statistical methods, including descriptive statistics and probability distributions, were employed to assess the effectiveness of treatment interventions and the overall microbial risk reduction achieved at different stages of the water distribution network.

Gamma distributions derivation

The Gamma distributions were derived to represent the observed concentrations of *E. coli* and *E. coli* O157: H7 in the water samples, facilitating the analysis and interpretation of microbial contamination levels in the study; the following steps were followed:

1. *Data Collection and Pre-processing*:
   - Data on the concentrations of *E. coli* and *E. coli* O157: H7 in water samples were collected from the laboratory experiments.
   - These concentrations typically represent counts or levels of microbial contamination per unit volume (e.g., CFU/ml or MPN/100 ml).
2. *Fitting Gamma Distributions*:
   - The collected concentration data were fitted to Gamma distributions using statistical software.
   - The Gamma distribution is commonly used to model positive-valued continuous data, such as microbial counts, where the shape (α) and rate (β) parameters of the distribution can be estimated based on the observed data.
   - The shape parameter (α) of the Gamma distribution is related to the variance and skewness of the data, while the rate parameter (β) influences the scale and location of the distribution.
3. *Parameter Estimation*:
   - The parameters (α and β) of the Gamma distribution were estimated based on the concentration data.
   - Maximum likelihood estimation (MLE) approach was employed to estimate these parameters.
4. *Model Validation*:
   - After fitting the Gamma distribution to the concentration data, model validation techniques were employed to assess the goodness-of-fit.

Table 1. Input model parameters.

Variable	Symbol	Unit	Distributional assumption	Reference
E.coli O157:H7 concentration	C_0	MPN/100 ml	Gamma.inv (0.0634, 6.920) × Sum(C_0)	This study
	C_{DP}	MPN/100 ml	Gamma.inv (0.0323, 3.526) × Sum(C_{DP})	This study
	C_{TR}	MPN/100 ml	Gamma.inv (0.0365, 7.209) × Sum(C_{TR})	This study
	C_{HD}	MPN/100 ml	Gamma.inv (0.0212, 8.168) × Sum(C_{HD})	This study
	C_{HT}	MPN/100 ml	Gamma.inv (0.0472, 18.149) × Sum(C_{HT})	This study
	C_{PW}	MPN/100 ml	Gamma.inv (0.113, 7.574) × Sum(C_{PW})	This study
	C_{HP}	MPN/100 ml	Gamma.inv (0.181, 12.170) × Sum(C_{HP})	This study
Calculation of log reduction values (LRV)	LRV_1	Log	$-\log_{10}(C_{HT}/C_0)$	This study
	LRV_2	Log	$-\log_{10}(C_{DP}/C_0)$	This study
	LRV_3	Log	$-\log_{10}(C_{TR}/C_{DP})$	This study
	LRV_4	Log	$-\log_{10}(C_{HD}/C_{TR})$	This study
	LRV_5	Log	$-\log_{10}(C_{HP}/C_{PW})$	This study
Water intake rate (IR)	IR_{HT}	L/capita.d	Norm.inv (8.56, 1.57) × 0.24	33
	IR_{HD}	L/capita.d	Norm.inv (8.46, 1.60) × 0.24	33
	IR_{HP}	L/capita.d	Norm.inv (8.54, 1.71) × 0.24	33
Parameters for the β-Poisson model	K	—	Lognorm.inv (−8.431, 0.515)	34
Disease burden (B)	B	DALY per case	PERT (49.23, 54.7, 60.17)/1000	35
Illness: infection (I_{ill}/in_f)	I	Proportion	PERT (0.69, 0.845, 1)	36–38
Susceptible fraction of the population (S)	S	Proportion	Constant (1)	This study

Most probable number (MPN) was assumed as a surrogate for the colony-forming unit (CFU).

- This validation step ensures that the Gamma distribution adequately describes the observed data and provides reliable estimates of the underlying distribution of microbial concentrations.

5. *Interpretation and Application*:
   - The derived Gamma distributions were then used to characterize the variability and uncertainty associated with the concentrations of *E. coli* and *E. coli* O157: H7 in the water samples.
   - These distributions provide valuable insights into the statistical properties of the microbial data, enabling researchers to make informed decisions and conduct further analyses based on the fitted models.

QMRA model for E. coli *O157: H7*

In this study, we employed the standard four-step QMRA approach, encompassing hazard identification, exposure assessment, dose-response analysis, and risk characterization, to evaluate the health risks associated with *E. coli* O157: H7 contamination in Gaza's drinking water. Our methodology aligns with similar investigations conducted by researchers worldwide, including studies by Smith et al.[29] and Jones et al.,[30] who utilized the QMRA framework to assess microbial risks in various waterborne disease outbreaks. The input parameters for our model were derived from both the data collected in our study and relevant scientific literature, ensuring a comprehensive and evidence-based analysis (Table 1). This approach is consistent with methodologies employed in studies by Brown et al.[31] and García et al.,[32] underscoring the importance of incorporating both primary data and existing research findings to enhance the accuracy and reliability of QMRA models. By adopting established QMRA methodologies and parameterization techniques, our study provides valuable insights into the microbial risks associated with drinking water sources in Gaza, contributing to the broader body of literature on waterborne disease risk assessment and management.

Results

Microbial contamination analysis

Analysis of 1317 water samples from various sources across the Gaza Strip revealed the presence of *E. coli* O157: H7 in 6.9% of samples. The mean, standard deviation, and maximum values of *E. coli* O157: H7 concentrations were 1.97, 9.74, and 112 MPN/100 ml, respectively.

Hazard identification

E. coli O157: H7 was selected as the reference waterborne organism for the QMRA model due to its documented role in waterborne disease outbreaks globally. This decision was informed by extensive literature and recommendations from international health organizations such as the WHO and the Centers for Disease Control and Prevention (CDC).

Exposure assessment

Our study quantitatively determined the magnitude of *E. coli* O157: H7 exposure through drinking water consumption from various sources. Log10 reduction values (LRVs) were calculated for different points within Gaza's water supply

Table 2. Concentration of *E. coli* O157: H7 in drinking water and $\log_{10}$ reduction values.

Sample source	*E. coli* O157: H7 (MPN/100 ml)						
	Mean	SE	SD	Left	Right	Max	Min
Water wells (C_0)	4.355	3.297	17.364	1.058	7.652	112	0
Desalination plants (C_{DP})	0.541	0.574	3.023	−0.033	1.115	20.9	0
Tanker trucks (C_{TR})	0.93	0.685	4.876	0.245	1.615	39.5	0
Desalinated water at households (C_{HD})	0.598	0.412	4.107	0.186	1.01	39.2	0
Municipal water at households (C_{HT})	1.725	0.797	7.944	0.928	2.522	72.9	0
Private wells (C_{PW})	5.696	4.163	17.067	1.533	9.859	112	0
Private well water at households (C_{HP})	9.097	5.246	21.506	3.851	14.343	101.2	0
DWSS reference points	$\log_{10}$ reduction value (Log)						
	Mean	SE	SD	Left	Right	Max	Min
LRV1	2.715	0.221	11.25	2.494	2.936	82.202	−46.233
LRV2	7.09	0.29	14.817	6.8	7.38	111.907	−52.24
LRV3	−1.465*	0.348	17.75	−1.813	−1.117	92.552	−107.684
LRV4	8.5	0.473	24.137	8.027	8.973	208.069	−95.721
LRV5	−1.465*	0.088	4.513	−1.553	−1.377	22.915	−36.819

Table 3. Summary statistics for estimated infection risk across percentiles.

Statistic	Mean	SD	Min	2.50%	25%	50%	75%	97.50%	Max
HT									
Median	3.16E-01	4.55E-01	0.00E+00	0.00E+00	0.00E+00	8.17E-07	1.00E+00	1.00E+00	1.00E+00
Mean	3.11E-01	4.51E-01	0.00E+00	0.00E+00	3.11E-13	2.23E-05	8.98E-01	1.00E+00	1.00E+00
2.50%	2.15E-01	4.02E-01	0.00E+00	0.00E+00	0.00E+00	7.38E-12	2.28E-02	1.00E+00	1.00E+00
97.50%	3.85E-01	4.76E-01	0.00E+00	0.00E+00	2.31E-12	1.80E-04	1.00E+00	1.00E+00	1.00E+00
HD									
Median	3.00E-01	4.55E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	1.00E+00	1.00E+00
Mean	2.98E-01	4.53E-01	0.00E+00	0.00E+00	0.00E+00	4.05E-16	9.56E-01	1.00E+00	1.00E+00
2.50%	2.45E-01	4.26E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.29E-01	1.00E+00	1.00E+00
97.50%	3.39E-01	4.70E-01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.00E+00	1.00E+00	1.00E+00
HP									
Median	5.38E-01	4.74E-01	0.00E+00	4.70E-12	4.48E-04	8.49E-01	1.00E+00	1.00E+00	1.00E+00
Mean	5.32E-01	4.72E-01	3.44E-15	9.46E-10	2.26E-03	6.75E-01	1.00E+00	1.00E+00	1.00E+00
2.50%	3.82E-01	4.55E-01	0.00E+00	0.00E+00	4.86E-08	6.71E-03	1.00E+00	1.00E+00	1.00E+00
97.50%	6.40E-01	4.81E-01	0.00E+00	7.94E-09	1.67E-02	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Avg									
Median	3.21E-01	3.32E-01	0.00E+00	3.32E-09	7.18E-02	2.55E-01	6.72E-01	1.00E+00	1.00E+00
Mean	3.18E-01	3.31E-01	3.93E-13	5.64E-08	5.62E-02	1.92E-01	6.58E-01	9.98E-01	1.00E+00
2.50%	2.60E-01	3.12E-01	0.00E+00	1.34E-13	2.40E-03	7.30E-02	3.28E-01	9.76E-01	1.00E+00
97.50%	3.59E-01	3.44E-01	1.23E-12	4.71E-07	7.30E-02	2.56E-01	6.99E-01	1.00E+00	1.00E+00

system to assess the attenuation of *E. coli* O157: H7 concentrations (Table 2).

Dose-response assessment

The Beta-Poisson dose-response model was employed to estimate the risk of *E. coli* O157: H7 infection, incorporating two-dimensional Monte Carlo simulation techniques to account for uncertainties in model parameters (Tables 3 and 4).

Risk characterization

The study evaluated the probability of adverse health effects among Gaza's population resulting from *E. coli* O157: H7 contamination, comparing findings with U.S. EPA and WHO benchmarks for infection risk and DALYs. The boxplot represents different percentiles of the estimated infection risk distribution across different drinking water supply sources (Figure 2).

Figure 3 displays cumulative distribution plots illustrating the variability in estimated *E. coli* O157: H7 infection

Table 4. Summary statistics for estimated burden of disease across percentiles.

Statistic	Mean	SD	Min	2.50%	25%	50%	75%	97.50%	Max
HT									
Median	1.50E-02	2.16E-02	0.00E+00	0.00E+00	0.00E+00	3.84E-08	4.68E-02	4.77E-02	4.77E-02
Mean	1.48E-02	2.15E-02	0.00E+00	0.00E+00	1.51E-14	1.08E-06	4.28E-02	4.78E-02	4.78E-02
2.50%	9.86E-03	1.76E-02	0.00E+00	0.00E+00	0.00E+00	3.10E-13	8.28E-04	4.09E-02	4.09E-02
97.50%	1.93E-02	2.51E-02	0.00E+00	0.00E+00	1.14E-13	8.65E-06	5.45E-02	5.47E-02	5.47E-02
HD									
Median	1.43E-02	2.17E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	4.74E-02	4.77E-02	4.77E-02
Mean	1.42E-02	2.17E-02	0.00E+00	0.00E+00	0.00E+00	2.03E-17	4.57E-02	4.78E-02	4.78E-02
2.50%	1.09E-02	1.83E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	6.45E-03	4.09E-02	4.09E-02
97.50%	1.74E-02	2.50E-02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.47E-02	5.47E-02	5.47E-02
HP									
Median	2.54E-02	2.25E-02	0.00E+00	2.23E-13	2.05E-05	3.89E-02	4.77E-02	4.77E-02	4.77E-02
Mean	2.54E-02	2.26E-02	1.79E-16	4.56E-11	1.08E-04	3.22E-02	4.78E-02	4.78E-02	4.78E-02
2.50%	1.79E-02	1.93E-02	0.00E+00	0.00E+00	2.44E-09	3.44E-04	4.09E-02	4.09E-02	4.09E-02
97.50%	3.22E-02	2.59E-02	0.00E+00	3.64E-10	8.24E-04	5.32E-02	5.47E-02	5.47E-02	5.47E-02
Avg									
Median	1.52E-02	1.58E-02	0.00E+00	1.54E-10	3.18E-03	1.11E-02	3.20E-02	4.76E-02	4.77E-02
Mean	1.52E-02	1.58E-02	1.51E-14	2.69E-09	2.68E-03	9.18E-03	3.14E-02	4.77E-02	4.78E-02
2.50%	1.17E-02	1.34E-02	0.00E+00	6.65E-15	1.14E-04	3.16E-03	1.60E-02	4.08E-02	4.09E-02
97.50%	1.84E-02	1.82E-02	5.56E-14	2.17E-08	3.90E-03	1.38E-02	3.71E-02	5.47E-02	5.47E-02

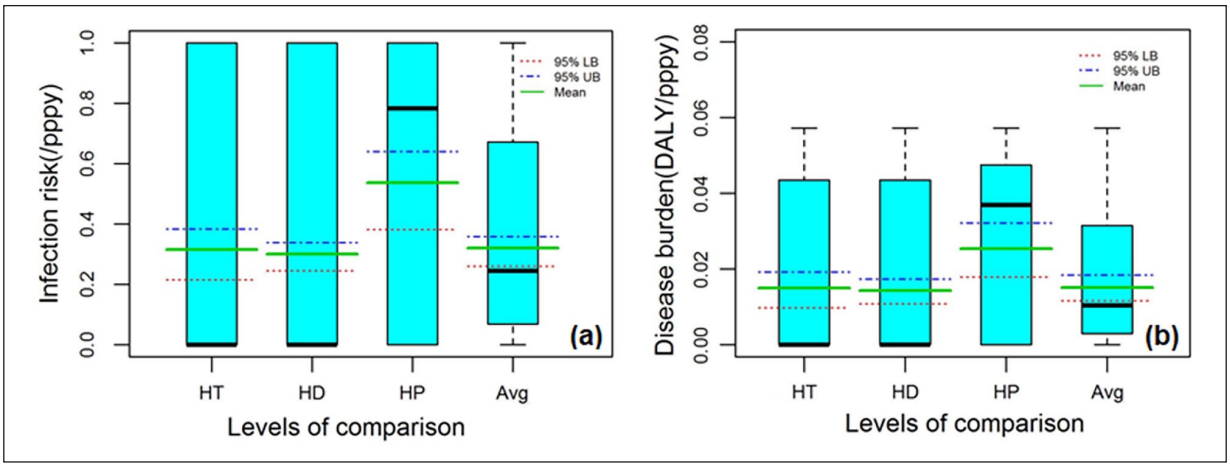

Figure 2. The box plots of estimated (a) infection risk (Inf; case pppy) and (b) burden of disease (DB; DALY pppy) for municipal network (HT), desalinated water (HD), private wells (HP) at households and drinking water supplies on average (Avg).

risk for each drinking water supply source at households in Gaza, as well as for the average of all three drinking water sources. The dark gray bands represent the 50% uncertainty range, while the light gray bands indicate the 95% uncertainty range on each quantile of variability. The *Y*-axis (proportion of population) corresponds to the *X*-axis (Yearly probability of infection), providing estimates of infection risk. For instance, for the average of all three drinking water sources at households (Av), the 20th percentile of variability for infection risk is approximately 0.03 pppy, with a credible interval between 0.00 and 0.07 pppy.

Tornado diagram (Figure 4) illustrates the sensitivity of a mathematical model's results to fluctuations in selected variables, showcasing how different sources of uncertainty in inputs impact the outputs of the system. The main factors affecting the variability of risks for the population and the estimated burden of disease include municipal water at households (HT), desalinated water at households (HD), private well water at households (HP), the average of all three drinking water sources at households (Av), and the 25% concentration of *E. coli* O157: H7 in water wells. Additionally, significant negative associations with LRV1-5 were observed.

Discussion

Our analysis of 1317 water samples from various sources across the Gaza Strip revealed a notable presence of *E. coli*

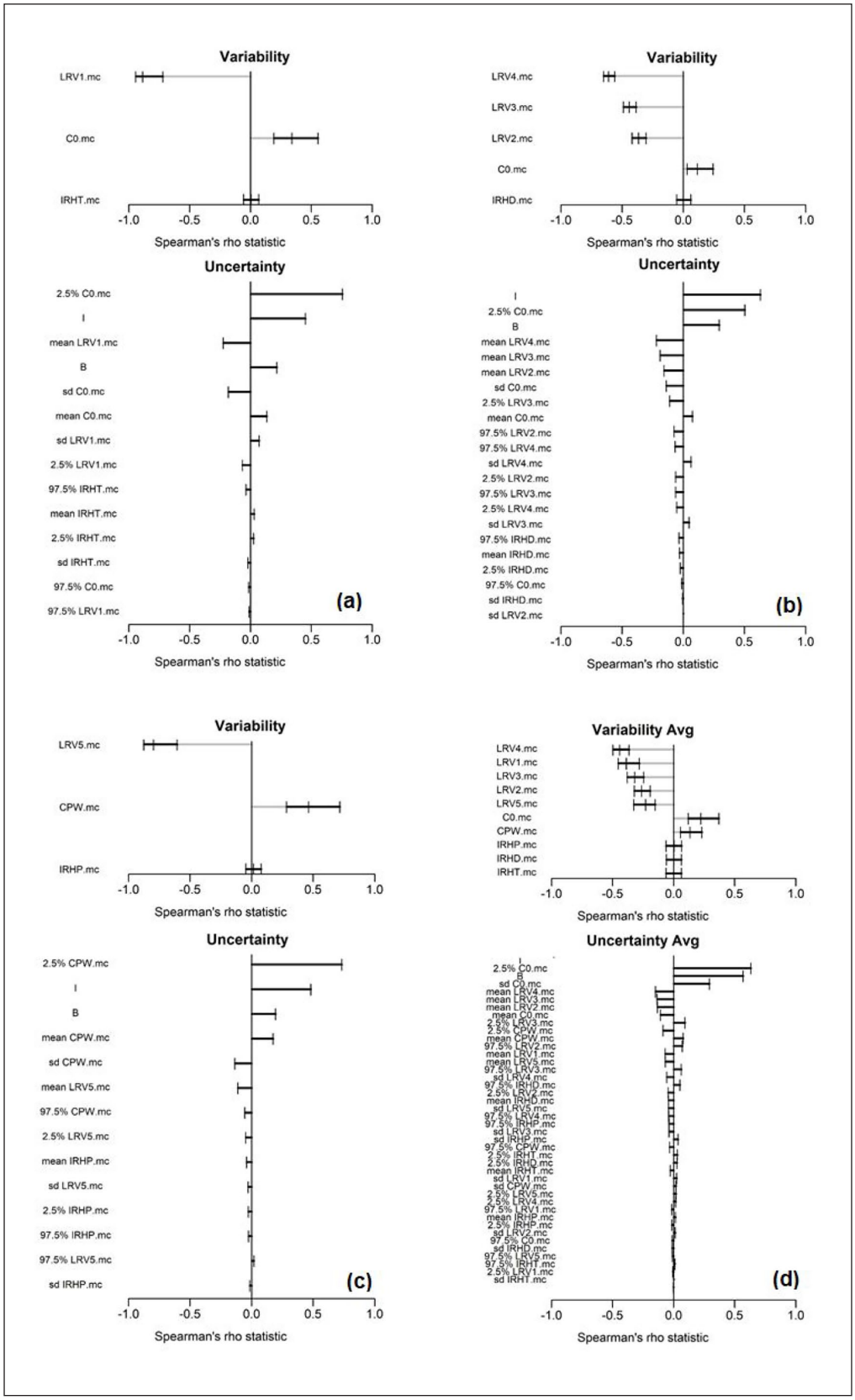

Figure 3. Tornado chart in the variability and uncertainty dimension for median estimates of the spearman's rank correlation between the input variables and burden of disease for (a) municipal network, (b) desalinated water, (c) private wells at households and (d) drinking water supplies on average.

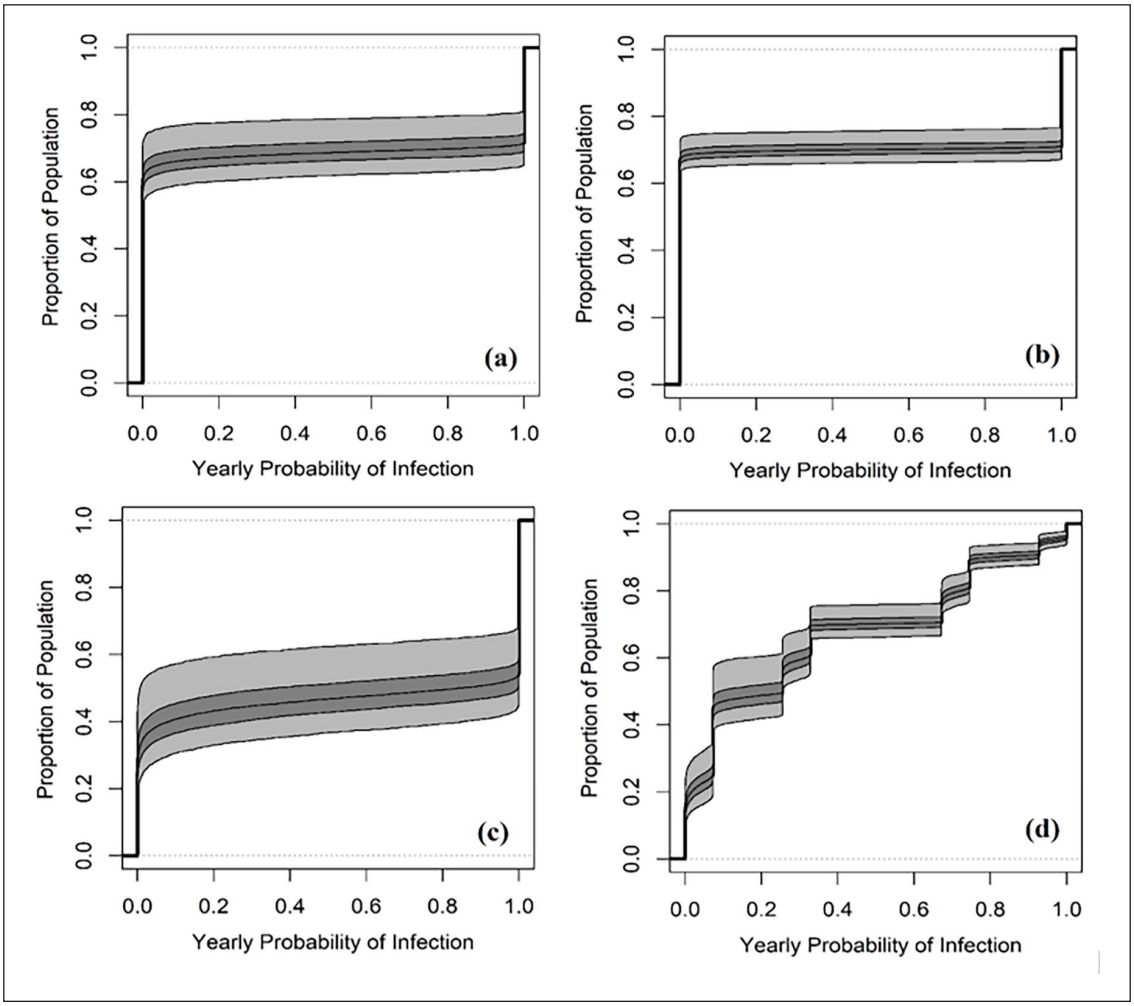

Figure 4. Variability cumulative distribution plots of infection risk for (a) HT, (b) HD, (c) HP, and (d) average.

O157: H7, with 6.9% of samples testing positive. The mean, standard deviation, and maximum concentrations of *E. coli* O157: H7 were calculated at 1.97, 9.74, and 112 MPN/100 ml, respectively, indicating variability in contamination levels within Gaza's water supply.

The selection of *E. coli* O157: H7 as the reference organism for our QMRA model was informed by its documented role in global waterborne disease outbreaks.[38–40] Recommendations from international health organizations such as the WHO and CDC underscore the importance of monitoring and controlling this pathogen in drinking water systems.[32,41] By leveraging extensive literature on *E. coli* O157: H7 epidemiology, our study contributes to understanding microbial risks and emphasizes the need for targeted interventions to improve drinking water quality.

Building upon previous research highlighting microbiological contamination in Gaza's drinking water,[42,43] our study quantitatively assessed *E. coli* O157: H7 exposure through water consumption. This approach aligns with methodologies used in similar investigations.[44,45] and included calculating LRVs to evaluate attenuation of *E. coli* O157: H7 concentrations in Gaza's water supply system.[46,47]

Employing the Beta-Poisson dose-response model integrated with Monte Carlo simulation techniques aligns with established methodologies for assessing infection risks from microbial contamination.[29,48] The comparison of risk estimates with U.S. EPA and WHO benchmarks provides valuable insights into potential health impacts.[49,50]

The cumulative distribution plots for estimated *E. coli* O157: H7 infection risks demonstrate variability across different drinking water sources. Our analysis aligns with findings from comparable studies,[29,48] highlighting the robustness and consistency of our results. The tornado diagram underscores key factors influencing population risks and disease burden estimates, supported by sensitivity analyses conducted in similar contexts.[29,30]

Despite providing critical insights, our study has limitations that warrant consideration. The cross-sectional design limits causal inference, emphasizing the need for longitudinal studies. Sampling strategies may introduce biases, and the absence of a formal power analysis affects result interpretation. Future

research should address broader microbial contaminants and validate findings in diverse settings to enhance generalizability.

Conclusion

Our study enhances understanding of *E. coli* O157: H7 contamination risks in Gaza's drinking water. By integrating quantitative assessments with real-world data and leveraging established methodologies, our findings contribute to evidence-based interventions aimed at improving water safety and safeguarding public health in similar settings globally.

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Author contributions statement

SA and MH designed the study. SN supervised the work. SA collected the data and carried out the implementation. MH performed the data analysis and carried out the simulations. AHM and SHM wrote the manuscript with input from all authors. KZ and RN contributed to the design and implementation of the research, to the analysis of the results and to the writing of the manuscript. All authors reviewed the manuscript.

Declaration of conflicting interests

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Ethics approval

The study protocol was approved by the Ethics Committee of Tehran University of Medical Sciences (Code: IR. TUMS. REC.1396.3917) and by the Helsinki Ethical Committee in the Gaza Strip (Code: PHRC/HC/288/17).

Informed consent

Not applicable.

Trial registration

Not applicable.

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References

1. WHO/UNICEF. *Drinking-water*. Geneva, Switzerland: World Health Organization, 2019.
2. Amr SSA and Yassin MM. Microbial contamination of the drinking water distribution system and its impact on human health in Khan Yunis Governorate, Gaza Strip: seven years of monitoring (2000–2006). *Public Health* 2008; 122(11): 1275–1283.
3. Yassin MM, Amr SSA and Al-Najar HM. Assessment of microbiological water quality and its relation to human health in Gaza Governorate, Gaza Strip. *Public Health* 2006; 120(12): 1177–1187.
4. Abu Mayla YS and Amr AS. Chemical and microbiological quality of drinking water in Gaza Strip, Palestine. *Sci Vision* 2010; 10: 80–88.
5. Assaf K. *Water as a human right: the understanding of water in Palestine: the understanding of water in the Arab countries of the Middle East*. Berlin, Germany: Heinrich Boll Stiftung Foundation, 2004, pp. 136–165.
6. Aish AM. Water quality evaluation of small scale desalination plants in the Gaza Strip, Palestine. *Desalin Water Treat* 2011; 29(1–3): 164–173.
7. Yassin MM, Amr SSA and Al-Najar HM. Assessment of microbiological water quality and its relation to human health in Gaza Governorate, Gaza Strip. *Public Health* 2006; 120(12): 1177–1187.
8. MOH. Epidemiological bulletin. Ministry of Health, 2013; 3(1). http://www.moh.gov.ps
9. WHO. *Guidelines for drinking-water* quality. Geneva: World Health Organization, 2004.
10. Howard G, Pedley S and Tibatemwa S. Quantitative microbial risk assessment to estimate health risks attributable to water supply: can the technique be applied in developing countries with limited data? *J Water Health* 2006; 4(1): 49–65.
11. Haas CN, Rose JB and Gerba CP. *Quantitative microbial risk assessment*. Hoboken, NJ: John Wiley & Sons, 1999.
12. WHO. *Quantitative microbial risk assessment: application for water safety management*. Geneva, Switzerland: World Health Organization, 2016.
13. Havelaar A and Melse J. *Quantifying public health risk in the WHO Guidelines for drinking-water quality: a burden of disease approach*. RIVM report: 734301022. Bilthoven: RIVM, 2003.
14. CDC. Isolation of *E. coli* O157: H7 from sporadic cases of hemorrhagic colitis—United States. *MMWR Morb Mortal Wkly Rep* 1982; 46(30): 700.
15. Pedritis H, Kidder G and Ogram A. *E. coli O157: H7, a potential healt concern*. Gainesville SL: IFAS Extension University of Florida, 2002, pp. 1461–1464.
16. Matthews L, Low J, Gally D, et al. Heterogeneous shedding of *Escherichia coli* O157 in cattle and its implications for control. *Proc Natl Acad Sci U S A* 2006; 103(3): 547–552.
17. Betancourt WQ and Rose JB. Drinking water treatment processes for removal of Cryptosporidium and Giardia. *Vet Parasitol* 2004; 126(1–2): 219–234.
18. Erickson MC, Liao JY, Payton AS, et al. Survival and internalization of *Salmonella* and *Escherichia coli* O157: H7 sprayed

onto different cabbage cultivars during cultivation in growth chambers. *J Sci Food Agri* 2019; 99(7): 3530–3537.
19. Pollari F, Christidis T, Pintar KD, et al. Evidence for the benefits of food chain interventions on *E. coli* O157: H7/NM prevalence in retail ground beef and human disease incidence: a success story. *Can J Public Health* 2017; 108(1): e71–e78.
20. Atnafie B, Paulos D, Abera M, et al. Occurrence of *Escherichia coli* O157: H7 in cattle feces and contamination of carcass and various contact surfaces in abattoir and butcher shops of Hawassa, Ethiopia. *BMC Microbiol* 2017; 17(1): 24.
21. PCBS. *Statistic brief in the international population day*. Ramallah, Palestine: Palestinian Central Bureau of Statistics, 2017, p. 2.
22. Al-Safady M and Al-Najar H. Disinfection process of water supply system in the Gaza strip between real practice and WHO limitations. *Res J Environ Sci* 2011; 5(5): 414.
23. Abuzerr S, Hadi M, Zinszer K, et al. Comprehensive risk assessment of health-related hazardous events in the drinking water supply system from source to tap in Gaza Strip, Palestine. *J Environ Public Health* 2020; 2020: 7194780.
24. Eaton AD, Clesceri LS, Franson MAH, et al. *Standard methods for the examination of water and wastewater*. Washington, DC: American Public Health Association, 2005.
25. March SB and Ratnam S. Latex agglutination test for detection of *Escherichia coli* serotype O157. *J Clin Microbiol* 1989; 27(7): 1675–1677.
26. Kinzelman J, Singh A, Ng C, et al. Use of IDEXX Colilert-18 registered and Quanti-Tray/2000 as a rapid and simple enumeration method for the implementation of recreational water monitoring and notification programs. *Lake Reserv Manag* 2005; 21(1): 73–77.
27. Cassin MH, Paoli GM and Lammerding AM. Simulation modeling for microbial risk assessment. *J Food Protect* 1998; 61(11): 1560–1566.
28. Custodio M, Peñaloza R, Ochoa S, et al. Microbial and potentially toxic elements risk assessment in high Andean river water based on Monte Carlo simulation, Peru. *Scient Rep* 2023; 13(1): 21473.
29. Smith JL, Fratamico PM and Gunther NW. Shiga toxin-producing *Escherichia coli. Adv Appl Microbiol* 2014; 86: 145–197.
30. Jones CH, Wylie V, Ford H, et al. A robust scenario analysis approach to water recycling quantitative microbial risk assessment. *J Appl Microbiol* 2023; 134(3): lxad029.
31. Brown CA, Harmon BG, Zhao T, et al. Experimental *Escherichia coli* O157: H7 carriage in calves. *Appl Environ Microbiol* 1997; 63(1): 27–32.
32. García A, Fox JG and Besser TE. Zoonotic enterohemorrhagic *Escherichia coli*: a one health perspective. *ILAR J* 2010; 51(3): 221–232.
33. Abuzerr S, Nasseri S, Yunesian M, et al. Household drinking water safety among the population of Gaza Strip, Palestine: knowledge, attitudes, practices, and satisfaction. *J Water Sanit Hygiene Develop* 2019; 9(3): 500–512.
34. Cornick NA and Helgerson A. Transmission and infectious dose of *Escherichia coli* O157: H7 in swine. *Appl Environ Microbiol* 2004; 70(9): 5331–5335.
35. Seidu R, Abubakari A, Dennis IA, et al. A probabilistic assessment of the contribution of wastewater-irrigated lettuce to *Escherichia coli* O157: H7 infection risk and disease burden in Kumasi, Ghana. *J Water Health* 2015; 13(1): 217–229.
36. Strachan NJ, Doyle MP, Kasuga F, et al. Dose response modelling of *Escherichia coli* O157 incorporating data from foodborne and environmental outbreaks. *Int J Food Microbiol* 2005; 103(1): 35–47.
37. Teunis P, Ogden I and Strachan N. Hierarchical dose response of *E. coli* O157: H7 from human outbreaks incorporating heterogeneity in exposure. *Epidemiol Infect* 2008; 136(6): 761–770.
38. Saxena T, Kaushik P and Mohan MK. Prevalence of *E. coli* O157: H7 in water sources: an overview on associated diseases, outbreaks and detection methods. *Diagn Microbiol Infect Dis* 2015; 82(3): 249–264.
39. Müller EE, Ehlers MM and Grabow WO. The occurrence of *E. coli* O157: H7 in South African water sources intended for direct and indirect human consumption. *Water Res* 2001; 35(13): 3085–3088.
40. Olsen SJ, Miller G, Breuer T, et al. A waterborne outbreak of *Escherichia coli* O157: H7 infections and hemolytic uremic syndrome: implications for rural water systems. *Emerg Infect Dis* 2002; 8(4): 370.
41. Patel J, Sharma M and Ravishakar S. Effect of curli expression and hydrophobicity of *Escherichia coli* O157: H7 on attachment to fresh produce surfaces. *J Appl Microbiol* 2011; 110(3): 737–745.
42. Sharif FA and Arafa HZ. Occurrence of *Escherichia coli* O157 in Gaza Strip: a preliminary study. *IUG J Nat Stud* 2015; 12(1): 81–90.
43. Abuzerr S, Nasseri S, Yunesian M, et al. Microbiological quality of drinking water and prevalence of waterborne diseases in the Gaza strip, Palestine: a narrative review. *J Geosci Environ Protect* 2019; 7(04): 122.
44. Ahmed W, Neller R and Katouli M. Evidence of septic system failure determined by a bacterial biochemical fingerprinting method. *J Appl Microbiol* 2005; 98(4): 910–920.
45. Mahmoud NE, Altayb HN and Gurashi RM. Detection of carbapenem-resistant genes in *Escherichia coli* isolated from drinking water in Khartoum, Sudan. *J Environ Public Health* 2020; 2020: 2571293.
46. Hassan FM and Mahmood AR. Evaluate the efficiency of drinking water treatment plants in Baghdad City–Iraq. *J Appl Environ Microbiol* 2018; 6(1): 1–9.
47. Saleh TA. Protocols for synthesis of nanomaterials, polymers, and green materials as adsorbents for water treatment technologies. *Environ Technol Innov* 2021; 24: 101821.
48. Johnson PT and Paull SH. The ecology and emergence of diseases in fresh waters. *Freshwater Biol* 2011; 56(4): 638–657.
49. EPA US. *Occurrence and exposure assessment for the final Long Term 2 Enhanced Surface Water Treatment Rule*. United States Environmental Protection Agency. 2005; EPA 815-R-06-002. Washington, DC: Office of Water.
50. WHO. *Guidelines for drinking-water quality: incorporating the first and second addenda*. Geneva: World Health Organization, 2008.
51. Abuzerr S, Hadi M, Zinszer K, et al. Quantitative microbial risk assessment to estimate annual infection risk and disease burden attributable to *Escherichia coli* O157: H7 in drinking water in the Gaza Strip: a prospective study. *Lancet* 2022; 399: S4.