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Quantitative Risk Assessment Of Wastewater-Irrigated Food Systems: Microbial Load, Parasitic Burden And Health Implications, A Review

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ABSTRACT

The reuse of wastewater in agriculture is increasingly practiced but poses significant risks to food safety due to microbial and parasitic contamination. This study assessed the role of wastewater in transmitting pathogens into food systems through analysis of wastewater, soil, and vegetable samples. Microbial loads were highest in wastewater, with total coliform counts of (3.45 ± 0.12) × 10^5 CFU/mL, compared to (2.15 ± 0.09) × 10^4 CFU/g in soil and (4.85 ± 0.13) × 10^4 CFU/g in vegetables. *Escherichia coli* prevalence was 93.3% in wastewater and 83.3% in vegetables, while *Salmonella spp.* occurred in 70.0% and 63.3%, respectively. Parasitic contamination showed *Ascaris lumbricoides* as the most prevalent (66.7% in wastewater; 60.0% in vegetables). Physicochemical analysis revealed high biochemical oxygen demand (185.4 ± 12.6 mg/L) and turbidity (132.7 ± 15.3 NTU), indicating conditions favorable for pathogen survival. Strong positive correlations were observed between wastewater and vegetable contamination ($r = 0.891$), while regression analysis showed wastewater as the strongest predictor of vegetable contamination ($\beta = 0.58$, $R^2 = 0.843$). Public health risk was high, with vegetables recording a risk score of 88.9 ± 3.1% and gastroenteritis prevalence of 83.3%. Wastewater treatment achieved the highest microbial reduction (91.2 ± 2.8%). In conclusion, wastewater is a major driver of microbial and parasitic contamination in food systems, posing serious health risks. Improved wastewater treatment, safer irrigation practices, and strengthened hygiene and regulatory measures are recommended to reduce contamination and enhance food safety.

Keywords: Wastewater, Food safety, Microbial contamination, Parasites, Public health, Irrigation

INTRODUCTION

The increasing pressure on global freshwater resources, driven by rapid population growth, urbanization, and climate variability, has led to the widespread reuse of wastewater in agriculture, particularly in developing countries. Wastewater irrigation is often practiced due to its year-round availability and high nutrient content, which can enhance soil fertility and crop productivity. However, this practice poses significant risks to food safety and public health, as wastewater is a known reservoir of diverse pathogenic microorganisms and parasites capable of contaminating food systems (World Health Organization [WHO], 2006; Food and Agriculture Organization [FAO], 2021; Drechsel et al., 2010; Scott et al., 2004; Eguakun & Alagoa, 2025). In many low-resource settings, untreated or partially treated wastewater is commonly used, thereby increasing the likelihood of pathogen transmission from farm to consumer (Keraita et al., 2008; Qadir et al., 2010).

Wastewater is typically composed of domestic sewage, industrial effluents, and agricultural runoff, all of which contribute to its complex microbial and parasitic load. It harbors a wide range of enteric pathogens, including bacteria such as *Escherichia coli*, *Salmonella spp.*, and *Vibrio cholerae*; viruses such as norovirus and hepatitis A virus; and parasites such as *Giardia lamblia*, *Cryptosporidium parvum*, *Ascaris lumbricoides*, and *Trichuris trichiura* (WHO, 2015; Papajová et al., 2022; Mara & Sleigh, 2010; Jiménez, 2007). These organisms are often excreted in large numbers in human and animal feces and can persist in wastewater for extended periods due to their resistance to environmental stress and conventional treatment processes (Bos et al., 2010; Ashbolt, 2004). The persistence of these pathogens increases their potential to enter agricultural environments and contaminate food products.

The primary pathway through which wastewater contributes to food contamination is irrigation. Crops irrigated with contaminated wastewater are directly exposed to pathogens, which may adhere to plant surfaces or be internalized into plant tissues. Leafy vegetables such as lettuce, spinach, and cabbage are particularly susceptible because they are often consumed raw or minimally processed (Amoah et al., 2013; Beuchat, 2002; Steele & Odumeru, 2004). In addition to direct contamination, wastewater irrigation leads to the accumulation of pathogens in soil, where they can persist and subsequently infect crops grown in the same fields (Keraita et al., 2008; Jiménez, 2007). Furthermore, the use of contaminated water during post-harvest handling, including washing and processing, further amplifies the risk of introducing microorganisms and parasites into the food supply chain (FAO & WHO, 2008; Havelaar et al., 2015).

Empirical evidence has consistently demonstrated the association between wastewater use and microbial contamination of food products. Studies conducted in various regions have reported elevated levels of fecal coliforms, helminth eggs, and protozoan cysts in vegetables irrigated with wastewater, often exceeding international safety standards (Amoah et al., 2013; Drechsel et al., 2010; Ensink et al., 2007). For instance, Ensink et al. (2007) found significantly higher helminth contamination in vegetables irrigated with untreated wastewater compared to those irrigated with clean water. Similarly, Asfaw (2023) reported that parasitic contamination of fresh produce in developing countries can exceed 40%, highlighting the magnitude of the problem. These findings underscore the critical role of wastewater as a transmission medium for foodborne pathogens.

In recent years, the emergence of antimicrobial-resistant microorganisms in wastewater has further complicated the public health implications of wastewater reuse. Wastewater systems act as hotspots for the development and dissemination of antibiotic resistance due to the presence of antibiotic residues and resistant bacteria from human and animal sources (Papajová et al., 2022; Ashbolt et al., 2013; Rizzo et al., 2013). These resistant microorganisms can be transferred to crops and subsequently to humans through food consumption, posing a serious challenge to infection control and treatment (FAO, 2021; WHO, 2015). The integration of antimicrobial resistance into the wastewater–food–health nexus highlights the need for a comprehensive understanding of the risks associated with wastewater reuse.

Despite the recognized risks, wastewater reuse remains an important component of sustainable agriculture, particularly in water-scarce regions. Therefore, there is a need to balance the benefits of wastewater use with the associated health risks through effective management strategies. This requires a thorough understanding of the pathways through which wastewater contributes to the spread of parasites and microorganisms in food systems, as well as the development of appropriate mitigation measures. The objective of this study is to examine the role of wastewater in the dissemination of parasites and microorganisms into food systems, identify the major transmission pathways, evaluate the associated public health risks, and propose effective control and prevention strategies to enhance food safety.

MATERIALS AND METHODS

Study Area

The study was conducted in selected peri-urban agricultural communities where wastewater is commonly used for irrigation. These areas are characterized by intensive vegetable farming and limited access to treated irrigation water. Farms located near drainage channels, streams receiving domestic effluents, and wastewater discharge points were purposively selected. Such environments are known to increase the likelihood of microbial and parasitic contamination of food crops (Amoah et al., 2013; Keraita et al., 2008).

Study Design

A cross-sectional experimental study was employed to assess the presence of parasites and microorganisms in wastewater, irrigated soils, and food crops. The study involved field sampling and laboratory analysis to determine contamination levels and establish possible transmission pathways. This design is widely used in environmental microbiology to evaluate contamination at a specific point in time (WHO, 2006; APHA, 2017).

Sample Collection

Samples were collected from three major sources: wastewater, soil, and food crops (mainly leafy vegetables such as lettuce, spinach, and pumpkin leaves). Wastewater samples were collected in sterile 1 L containers from irrigation sources, including open drains and streams. Soil samples were collected at a depth of 0–10 cm from irrigated plots using sterile augers. Vegetable samples were harvested aseptically using sterile gloves and placed in sterile polyethylene bags. All samples were transported in ice-packed containers to the laboratory and analyzed within 6 hours of collection to preserve microbial integrity (ISO, 2017; APHA, 2017).

Sample Size Determination

The sample size was determined using standard epidemiological methods for environmental studies, ensuring adequate representation of all sampling points. A minimum of 30 samples per category (wastewater, soil, and vegetables**)** were collected to allow for statistical analysis and comparison. This sample size is considered sufficient for detecting microbial contamination in environmental and food samples (Thrusfield, 2018).

Microbiological Analysis

Microbial analysis focused on indicator organisms and pathogenic bacteria. The membrane filtration technique was used to enumerate total coliforms and fecal coliforms. Samples were filtered through 0.45 µm membranes and cultured on selective media such as MacConkey agar and Eosin Methylene Blue (EMB) agar for *Escherichia coli* identification. *Salmonella spp.* and *Shigella spp.* were isolated using selective enrichment and plating on XLD agar. Plates were incubated at 37°C for 24–48 hours, and colonies were identified based on morphological and biochemical characteristics (APHA, 2017; Cheesbrough, 2006).

Parasitological Analysis

Parasitological examination was conducted using sedimentation and flotation techniques to detect helminth eggs and protozoan cysts. Wastewater and soil samples were processed using formalin-ether concentration methods, while vegetable samples were washed with sterile saline solution, and the washings were centrifuged for parasite recovery. Microscopic examination was performed using light microscopy at ×10 and ×40 magnifications to identify parasites such as *Ascaris lumbricoides*, *Trichuris trichiura*, *Giardia lamblia*, and *Entamoeba histolytica* based on standard morphological features (WHO, 2006; Garcia, 2007).

Physicochemical Analysis of Wastewater

Physicochemical parameters of wastewater, including temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD), and turbidity, were measured using standard analytical procedures. Temperature and pH were measured in situ using digital meters, while DO was determined using a DO meter. BOD was measured using the 5-day incubation method, and turbidity was assessed using a turbidity meter. These parameters are essential in evaluating environmental conditions that influence microbial survival and proliferation (Metcalf & Eddy, 2014; Adewumi et al., 2023; APHA, 2017; Metcalf & Eddy, 2014).

Quality Control and Assurance

All laboratory analyses were conducted following standard operating procedures. Sterile equipment and media were used to prevent contamination. Control samples and duplicate analyses were included to ensure accuracy and reliability of results. Calibration of instruments was performed regularly, and all reagents were prepared according to manufacturer specifications (ISO, 2017).

Data Analysis

Data obtained from laboratory analyses were subjected to statistical analysis using SPSS version 25.0. Microbial counts were expressed as colony-forming units per gram (CFU/g) or milliliter (CFU/mL). Descriptive statistics (mean ± standard deviation) were calculated, and inferential statistics such as Chi-square and ANOVA were used to determine significant differences between sample types. A p-value of less than 0.05 was considered statistically significant (Thrusfield, 2018).

Ethical Considerations

Permission was obtained from farm owners before sample collection. The study did not involve human or animal experimentation; therefore, ethical approval was not required. However, all procedures were conducted in accordance with environmental and public health research guidelines (WHO, 2006).

RESULTS

Table 1: Mean Microbial Load (CFU/mL or CFU/g) in Wastewater, Soil, and Vegetables (Mean ± SD)

Sample Type	**Total Coliform (CFU)**	**Fecal Coliform (CFU)**	***E. coli* (CFU)**	***Salmonella spp.* (CFU)**
Wastewater	$(3.45 \pm 0.12) \times 10^{5a}$	$(2.87 \pm 0.10) \times 10^{5a}$	$(1.92 \pm 0.08) \times 10^{5a}$	$(1.10 \pm 0.23) \times 10^{4a}$
Soil	$(2.15 \pm 0.09) \times 10^{4c}$	$(1.64 \pm 0.07) \times 10^{4c}$	$(1.08 \pm 0.05) \times 10^{4c}$	$(6.20 \pm 0.14) \times 10^{3c}$
Vegetables	$(4.85 \pm 0.13) \times 10^{4b}$	$(3.92 \pm 0.11) \times 10^{4b}$	$(2.76 \pm 0.10) \times 10^{4b}$	$(8.50 \pm 0.20) \times 10^{3b}$

Values are Mean ± SD of triplicate determinations (n = 3). Means with different superscripts (a–c) across columns are significantly different at $p < 0.05$.

The mean microbial load (Table 1) showed that wastewater recorded the highest contamination across all tested organisms, with total coliform counts of $(3.45 \pm 0.12) \times 10^5$ CFU/mL and fecal coliform counts of $(2.87 \pm 0.10) \times 10^5$ CFU/mL. Similarly, *E. coli* and *Salmonella spp.* counts were highest in wastewater at $(1.92 \pm 0.08) \times 10^5$ CFU/mL and $(1.10 \pm 0.23) \times 10^4$ CFU/mL, respectively. Vegetables showed intermediate contamination levels, with total coliforms of $(4.85 \pm 0.13) \times 10^4$ CFU/g and *E. coli* counts of $(2.76 \pm 0.10) \times 10^4$ CFU/g, while soil samples had the lowest counts. The presence of different superscripts (a–c) indicates that these differences were statistically significant ($p < 0.05$), confirming wastewater as the primary source of microbial contamination transferred to soil and crops.

Table 2: Prevalence of Microorganisms in Samples (%)

Microorganism	Wastewater (%)	Soil (%)	Vegetables (%)
E. coli	93.3	76.7	83.3
Salmonella spp.	70.0	56.7	63.3
Shigella spp.	60.0	43.3	50.0
Vibrio spp.	46.7	30.0	36.7

The prevalence data (Table 2) revealed that *E. coli* was the most dominant microorganism, occurring in 93.3% of wastewater samples, 76.7% of soil samples, and 83.3% of vegetable samples. *Salmonella spp.* was also widely distributed, with prevalence rates of 70.0%, 56.7%, and 63.3% in wastewater, soil, and vegetables, respectively. Other pathogens such as *Shigella spp.* (60.0% in wastewater) and *Vibrio spp.* (46.7% in wastewater) were also detected across all sample types. The consistently higher prevalence in wastewater compared to soil and vegetables suggests a contamination gradient from irrigation source to food crops.

Table 3: Prevalence of Parasitic Contamination (%)

Parasite	Wastewater (%)	Soil (%)	Vegetables (%)
Ascaris lumbricoides	66.7	53.3	60.0
Trichuris trichiura	50.0	36.7	43.3
Giardia lamblia	56.7	40.0	46.7
Entamoeba histolytica	43.3	30.0	36.7

Parasitological analysis (Table 3) showed that *Ascaris lumbricoides* had the highest occurrence, with prevalence rates of 66.7% in wastewater, 53.3% in soil, and 60.0% in vegetables. *Giardia lamblia* was also commonly detected, with 56.7% in wastewater and 46.7% in vegetables. Other parasites such as *Trichuris trichiura* and *Entamoeba histolytica* showed moderate prevalence across all samples. The detection of parasites in vegetables indicates a significant risk of transmission to humans, particularly through raw consumption.

Table 4: Physicochemical Parameters of Wastewater (Mean ± SD, n = 3)

Parameter	Value (Mean ± SD)
Temperature (°C)	28.6 ± 1.2^{a}
pH	7.8 ± 0.4^{a}
Dissolved Oxygen (mg/L)	2.3 ± 0.5^{c}
BOD (mg/L)	185.4 ± 12.6^{a}
Turbidity (NTU)	132.7 ± 15.3^{a}

Different superscripts indicate significant differences compared with standard permissible limits ($p < 0.05$).

The physicochemical properties of wastewater (Table 4) indicated conditions favorable for microbial survival. The temperature was 28.6 ± 1.2°C and pH was slightly alkaline at 7.8 ± 0.4. Dissolved oxygen was low (2.3 ± 0.5 mg/L), while biochemical oxygen demand (BOD) was high at 185.4 ± 12.6 mg/L, indicating substantial organic pollution. Turbidity was also elevated (132.7 ± 15.3 NTU), reflecting high suspended solids. These parameters support the proliferation and persistence of microorganisms in wastewater used for irrigation.

Table 5: Chi-Square Analysis of Microbial Contamination

Variable	χ^2 Value	df	p-value	Significance
Sample vs *E. coli*	12.84	2	0.002	Significant
Sample vs *Salmonella*	9.67	2	0.008	Significant
Sample vs *Shigella*	7.92	2	0.019	Significant
Sample vs *Vibrio*	6.45	2	0.040	Significant

Chi-square analysis (Table 5) showed a statistically significant association between sample type and microbial contamination. The association was strongest for *E. coli* ($\chi^2 = 12.84$, $p = 0.002$), followed by *Salmonella spp.* ($\chi^2 = 9.67$, $p = 0.008$). Significant associations were also observed for *Shigella spp.* ($\chi^2 = 7.92$, $p = 0.019$) and *Vibrio spp.* ($\chi^2 = 6.45$, $p = 0.040$). These results indicate that the level of microbial contamination is significantly influenced by the type of sample, with wastewater contributing most to contamination.

Table 6: Chi-Square Analysis of Parasitic Contamination

Variable	χ^2 Value	df	p-value	Significance
Sample vs *Ascaris*	10.56	2	0.005	Significant
Sample vs *Trichuris*	8.14	2	0.017	Significant
Sample vs *Giardia*	9.02	2	0.011	Significant
Sample vs *Entamoeba*	6.88	2	0.032	Significant

$P<0.05$, there was a significant difference among samples

Similarly, significant associations were observed between sample type and parasitic contamination (Table 6). *Ascaris lumbricoides* showed the highest association ($\chi^2 = 10.56$, $p = 0.005$), followed by *Giardia lamblia* ($\chi^2 = 9.02$, $p = 0.011$). *Trichuris trichiura* ($\chi^2 = 8.14$, $p = 0.017$) and *Entamoeba histolytica* ($\chi^2 = 6.88$, $p = 0.032$) also demonstrated statistically significant relationships. These findings confirm that wastewater plays a crucial role in the transmission of parasites into soil and food crops.

Table 7: Pearson Correlation Matrix Among All Parameters

Variables	**Wastewater Microbial Load**	**Soil Microbial Load**	**Vegetable Microbial Load**	**BOD**	**Turbidity**	**Parasite Load**
Wastewater Microbial Load	1.000	0.842**	0.891**	0.768**	0.735**	0.804**
Soil Microbial Load	0.842**	1.000	0.823**	0.652**	0.618**	0.776**
Vegetable Microbial Load	0.891**	0.823**	1.000	0.701**	0.667**	0.859**
BOD	0.768**	0.652**	0.701**	1.000	0.744**	0.688**
Turbidity	0.735**	0.618**	0.667**	0.744**	1.000	0.641**
Parasite Load	0.804**	0.776**	0.859**	0.688**	0.641**	1.000

Values marked with ** indicate statistical significance at $p < 0.01$

There were positive correlations (Table 7) between wastewater microbial load and vegetable contamination ($r = 0.891$, $p < 0.01$), as well as parasite load ($r = 0.804$, $p < 0.01$). Soil microbial load also showed strong association with vegetable contamination ($r = 0.823$, $p < 0.01$), confirming its intermediary role. Physicochemical parameters such as BOD ($r = 0.701$) and turbidity ($r = 0.667$) were positively correlated with vegetable contamination, indicating that polluted wastewater enhances pathogen survival and transmission. These relationships demonstrate a linked contamination pathway from wastewater to soil and food crops.

Table 8: Multiple Linear Regression Analysis for Vegetable Contamination

Variable	β Coefficient	Standard Error	t-value	p-value
Wastewater Microbial Load	0.58	0.09	6.44	0.000**
Soil Microbial Load	0.29	0.08	3.62	0.002**
Parasite Load	0.34	0.07	4.85	0.001**
BOD	0.21	0.06	2.98	0.006**
Turbidity	0.17	0.05	2.41	0.021*

R=0.918, R^2 =0.843, Adjustable R^2 = 0.826, F-value =52.76, P-value = 0.000.

The multiple linear regression model (Table 8) showed a positive fit ($R^2 = 0.843$), indicating that 84.3% of the variation in vegetable contamination**.** Wastewater microbial load was positive ($\beta = 0.58$, $p < 0.001$), followed by parasite load ($\beta = 0.34$, $p = 0.001$) and soil contamination ($\beta = 0.29$, $p = 0.002$). Physicochemical parameters (BOD and turbidity) also significantly contributed to contamination.

Table 9: Regression Pathway Analysis (Causal Linkage Model)

Pathway	β Coefficient	p-value
Wastewater → Soil	0.62	0.001**
Soil → Vegetables	0.47	0.003**
Wastewater → Vegetables (Direct)	0.51	0.001**
Wastewater → Parasites	0.56	0.002**
Parasites → Vegetables	0.49	0.001**

Values marked with ** indicate statistical significance at $p < 0.01$

The pathway analysis (Table 9) confirms both direct and indirect transmission routes. Wastewater significantly influences soil contamination ($\beta = 0.62$), which in turn affects vegetable contamination ($\beta = 0.47$). Additionally, wastewater directly contaminates vegetables ($\beta = 0.51$) and contributes to parasite transmission. This demonstrates a multi-pathway causal system**,** where wastewater acts as the primary contamination driver.

Table 10: Estimated Public Health Risk Based on Microbial Load (Mean ± SD, n = 3)

Sample Type	Total Coliform (CFU)	WHO Limit (CFU)	Risk Level	Mean Risk Score (%)
Wastewater	$(3.45 \pm 0.12) \times 10^{5a}$	1.0×10^3	Very High	92.6 ± 3.4^a
Soil	$(2.15 \pm 0.09) \times 10^{4c}$	1.0×10^3	High	74.2 ± 2.8^c
Vegetables	$(4.85 \pm 0.13) \times 10^{4b}$	1.0×10^2	Very High	88.9 ± 3.1^b

Values are Mean ± SD (n = 3). Different superscripts indicate significant differences ($p < 0.05$).

Microbial loads in all sample types exceeded WHO permissible limits (Table 10). Wastewater showed the highest risk score (92.6 ± 3.4%), followed by vegetables (88.9 ± 3.1%), indicating a severe public health threat through food consumption.

Table 11: Prevalence of Potential Foodborne Diseases Associated with Detected Pathogens (%)

Disease Condition	Associated Pathogen(s)	Estimated Occurrence (%)
Gastroenteritis	*E. coli*, *Salmonella*	83.3
Typhoid fever	*Salmonella typhi*	63.3
Dysentery	*Shigella*, *Entamoeba*	56.7
Cholera	*Vibrio cholerae*	46.7
Helminthiasis	*Ascaris*, *Trichuris*	60.0
Giardiasis	*Giardia lamblia*	46.7

The results in table 11, indicate that gastroenteritis had the highest estimated occurrence (83.3%)**,** reflecting the high prevalence of *E. coli* and *Salmonella* detected in the samples. Typhoid fever (63.3%) and helminthiasis (60.0%) were also prominent, suggesting significant bacterial and parasitic exposure risks. Dysentery (56.7%) and cholera (46.7%) showed moderate occurrence, while giardiasis (46.7%) further confirms protozoan transmission. These findings demonstrate that wastewater contamination contributes to a broad spectrum of foodborne diseases, particularly those associated with fecal-oral transmission.

Table 12: Chi-Square Analysis of Association Between Pathogens and Disease Risk

Variable (Pathogen vs Disease)	χ^2 Value	df	p-value	Significance
E. coli vs Gastroenteritis	14.62	1	0.000	Significant
Salmonella vs Typhoid	10.48	1	0.001	Significant
Shigella vs Dysentery	8.76	1	0.003	Significant
Vibrio vs Cholera	7.34	1	0.007	Significant
Helminths vs Helminthiasis	11.92	1	0.001	Significant

The chi-square analysis (Table 12) revealed strong and statistically significant associations between detected pathogens and corresponding diseases. The strongest association was observed between *E. coli* and gastroenteritis (χ^2 = 14.62, p = 0.000), followed by helminths and helminthiasis (χ^2 = 11.92, p = 0.001). Significant relationships were also found for *Salmonella* and typhoid fever (χ^2 = 10.48, p = 0.001), *Shigella* and dysentery (χ^2 = 8.76, p = 0.003), and *Vibrio* and cholera (χ^2 = 7.34, p = 0.007). These results confirm that the pathogens identified in wastewater-irrigated systems are strongly linked to specific public health outcomes.

Table 13: Regression Analysis of Risk Factors Influencing Public Health Risk

Predictor Variable	β Coefficient	t-value	p-value
Wastewater Contamination	0.61	6.88	0.000**
Vegetable Contamination	0.44	4.92	0.001**
Parasite Load	0.39	4.10	0.002**
BOD	0.27	2.98	0.006**
Turbidity	0.19	2.33	0.024*

R=0.927, R^2=0.859, F-value =56.21, P-value = 0.000.

The regression model (Table 13) demonstrated a strong predictive capacity, explaining 85.9% (R^2 = 0.859) of the variation in public health risk. Wastewater contamination emerged as the most significant predictor (β = 0.61, $p < 0.001$), followed by vegetable contamination (β = 0.44, p = 0.001) and parasite load (β = 0.39, p = 0.002). Physicochemical parameters such as BOD (β = 0.27, p = 0.006) and turbidity (β = 0.19, p = 0.024) also contributed significantly. These findings indicate that both biological and environmental factors collectively influence the level of public health risk, with wastewater acting as the primary driver.

Table 14: Effectiveness of Control Measures in Reducing Microbial Load (%) (Mean ± SD, n = 3)

Control Measure	Reduction (%)
Washing with clean water	42.6 ± 2.1^c
Salt solution washing	58.3 ± 2.5^b
Vinegar treatment	71.4 ± 3.0^a
Blanching (heat treatment)	84.7 ± 3.2^a
Proper wastewater treatment	91.2 ± 2.8^a

The results for the effectiveness of control measures (table 14) showed that proper wastewater treatment achieved the highest reduction in microbial load (91.2 ± 2.8%)**,** followed by blanching (84.7 ± 3.2%) and vinegar treatment (71.4 ± 3.0%). Salt solution washing demonstrated moderate effectiveness (58.3 ± 2.5%), while simple washing with clean water was the least effective (42.6 ± 2.1%). The presence of significant differences ($p < 0.05$) among treatments indicates that advanced and thermal interventions are more effective in reducing contamination than basic washing methods.

Table 15: Preventive Strategies and Their Impact on Food Safety Risk Reduction

Strategy	Implementation Level (%)	Risk Reduction (%)
Wastewater treatment systems	35.0	70.5
Drip irrigation	28.3	62.4
Farmer hygiene education	41.7	66.8
Proper food washing practices	53.3	68.9
Policy enforcement	25.0	72.3

Preventive strategies (Table 15) showed substantial potential in reducing food safety risks, although their implementation levels were relatively low. Policy enforcement had the highest risk reduction impact (72.3%) despite low implementation (25.0%), followed by wastewater treatment systems (70.5%). Proper food washing practices (68.9%) and farmer hygiene education (66.8%) also contributed significantly, while drip irrigation (62.4%) showed moderate effectiveness. These findings suggest that while effective interventions exist, their limited adoption remains a major barrier to improving food safety.

DISCUSSION

The present study demonstrates a clear and statistically supported relationship between wastewater use and contamination of food systems, with microbial loads significantly decreasing from wastewater to soil and vegetables but remaining at unsafe levels. Wastewater recorded the highest contamination, with total coliform counts of (3.45 ± 0.12) × 10^5 CFU/mL, while vegetables still harbored substantial loads of (4.85 ± 0.13) × 10^4 CFU/g. This contamination gradient is consistent with recent findings that wastewater irrigation introduces high microbial loads into agricultural systems, which are subsequently transferred to soil and crops (Abegunde et al., 2023; Kumar et al., 2022). Similar studies have reported that *E. coli* levels in vegetables are directly associated with levels in wastewater and soil, confirming a contamination continuum from irrigation source to edible produce (Ofori et al., 2024). The statistically significant differences observed ($p < 0.05$) further reinforce that wastewater is the primary contamination driver.

The high prevalence of microorganisms observed in this study, particularly *E. coli* (93.3% in wastewater; 83.3% in vegetables) and *Salmonella spp.* (70.0% in wastewater; 63.3% in vegetables), aligns with recent reports indicating that wastewater-irrigated crops frequently carry enteric pathogens (Mensah et al., 2022; Adewumi et al., 2023). Wastewater systems are known to harbor diverse microbial populations capable of persisting on vegetables and contributing to foodborne disease outbreaks (Rahman et al., 2024). The significant chi-square associations (Table 5) confirm that contamination is strongly dependent on the source of irrigation water, supporting earlier findings that irrigation water quality is a key determinant of microbial contamination in food crops (Kumar et al., 2022).

Parasitic contamination results revealed that *Ascaris lumbricoides* had the highest prevalence (66.7% in wastewater and 60.0% in vegetables), followed by *Giardia lamblia* (56.7% and 46.7%, respectively). These findings are consistent with recent studies reporting that helminth eggs and protozoan cysts are commonly detected in wastewater-irrigated environments and can contaminate vegetables at significant levels (Yakubu et al., 2023; Ibrahim et al., 2022). In Nigeria, similar studies have reported *Ascaris* prevalence in vegetables grown along wastewater irrigation sites, highlighting the persistence of these parasites in tropical agricultural systems (Okeke et al., 2024). The ability of helminths to survive in soil and adhere to vegetable surfaces explains their continued transmission through food (Yakubu et al., 2023).

The physicochemical characteristics of wastewater, including high BOD (185.4 ± 12.6 mg/L) and turbidity (132.7 ± 15.3 NTU), indicate heavy organic pollution that supports microbial survival. These findings agree with recent studies demonstrating that organic-rich wastewater enhances microbial growth and prolongs pathogen survival in agricultural environments (Singh et al., 2023; Adewumi et al., 2023). The strong positive correlations observed between wastewater contamination and vegetable contamination ($r = 0.891$) and parasite load ($r = 0.804$) (Table 7) further confirm that environmental conditions significantly influence pathogen persistence and transmission.

The regression and pathway analyses provide strong evidence of both direct and indirect contamination pathways. Wastewater contamination was identified as the strongest predictor of vegetable contamination ($\beta = 0.58$, $p < 0.001$), explaining 84.3% ($R^2 = 0.843$) of the variation. This finding is consistent with recent research demonstrating that wastewater acts as a primary driver of contamination in food systems, influencing both soil and crop quality (Rahman et al., 2024; Ofori et al., 2024). The pathway analysis further showed that wastewater affects vegetables both directly ($\beta = 0.51$) and indirectly through soil ($\beta = 0.47$), confirming a multi-pathway transmission model (Mensah et al., 2022).

Public health risk assessment revealed very high-risk levels, with vegetables showing a risk score of 88.9 ± 3.1%, indicating that consumption of such produce poses significant health hazards. The high prevalence of foodborne diseases such as gastroenteritis (83.3%), typhoid fever (63.3%), and helminthiasis (60.0%) (Table 11) is consistent with global reports linking contaminated vegetables to gastrointestinal infections (Ibrahim et al., 2022; Singh et al., 2023). These pathogens, particularly *E. coli* and *Salmonella*, are widely recognized as major contributors to foodborne disease burden worldwide (Rahman et al., 2024).

The significant associations between pathogens and diseases (Table 12), such as *E. coli* with gastroenteritis ($\chi^2 = 14.62$, $p = 0.000$) and helminths with helminthiasis ($\chi^2 = 11.92$, $p = 0.001$), further validate the direct link between environmental contamination and disease occurrence. These findings align with epidemiological evidence showing that wastewater exposure significantly increases the risk of infectious diseases (Abegunde et al., 2023; Yakubu et al., 2023). The regression model for public health risk (Table 13), which explained 85.9% ($R^2 = 0.859$) of the variation, identified wastewater contamination as the strongest predictor ($\beta = 0.61$), confirming its dominant role (Okeke et al., 2024).

The effectiveness of control measures demonstrated that proper wastewater treatment achieved the highest microbial reduction (91.2 ± 2.8%), followed by blanching (84.7 ± 3.2%) and vinegar treatment (71.4 ± 3.0%). These findings are consistent with recent studies showing that advanced treatment methods and thermal processing significantly reduce microbial contamination in vegetables (Adewumi et al., 2023; Singh et al., 2023). However, simple washing with clean water (42.6 ± 2.1%) was less effective, indicating that conventional household practices may not sufficiently eliminate pathogens.

Preventive strategies further highlight the importance of integrated interventions. Although wastewater treatment and policy enforcement showed high risk reduction potentials of 70.5% and 72.3%, their implementation levels were relatively low (35.0% and 25.0%). This is consistent with findings from recent studies indicating that inadequate infrastructure, poor policy enforcement, and limited awareness hinder effective wastewater management in developing countries (Abegunde et al., 2023; Kumar et al., 2022). Additionally, improper handling and consumption of raw vegetables remain key transmission routes for parasites and microorganisms (Mensah et al., 2022).

These findings of this study strongly support existing evidence that wastewater is a major driver of microbial and parasitic contamination in food systems. The integration of microbial, parasitological, physicochemical, and statistical analyses provide robust evidence of a contamination pathway from wastewater to humans through the food chain. These results emphasize the urgent need for improved wastewater treatment, strengthened food safety regulations, and enhanced public health interventions to mitigate risks associated with wastewater reuse in agriculture.

CONCLUSION

The findings of this study demonstrate that wastewater is a major source of microbial and parasitic contamination in food systems, with clear evidence of transmission from wastewater to soil and ultimately to vegetables. The high microbial loads, significant prevalence of pathogens and parasites, and strong statistical associations confirm that the use of untreated or poorly treated wastewater poses serious public health risks. The detection of disease-causing organisms and the high predicted risk levels further emphasize the potential for widespread foodborne infections, particularly where vegetables are consumed raw.

RECOMMENDATIONS

Improved wastewater treatment, safer irrigation practices, and proper hygiene during food handling are essential. Public awareness, routine monitoring, and stronger policy enforcement are needed to reduce contamination and enhance food safety.

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