JHWCR

Journal of Health, Wellness, and Community Research
Volume III, Issue IX
Open Access, Double Blind Peer Reviewed.
Web: https://jhwcr.com, ISSN: 3007-0570
https://doi.org/10.61919/0whdys10

Original Article

Assessing Rural Drinking Water Quality, Sanitation and Hygiene Practices in Muzaffar Garh District, Pakistan

Urooj Mehtab Raina[1], Nusrat Shafi[2], Nida Shahid[1, 3], Mubashir Arshad[1], Muhammad Shoaib Iqbal[4], Ghulam Mustafa[5], Aziz Ul-Rahman[1]*, Muhammad Asif Raza[1]

[1] Department of Pathobiology and Biomedical Sciences, MNS University of Agriculture, Multan, Pakistan

[2] Ch. Pervaiz Elahi Institute of Cardiology, Multan, Pakistan

[3] Regional Office, Maternal Child Health Project, Japan International Cooperation Agency, Punjab, Pakistan

[4] Department of Community Medicine, Nishtar Medical University, Multan, Pakistan

[5] Department of Community Medicine, Sheikh Zayed Medical College, Rahim Yar Khan, Pakistan

Correspondence: drrahmanangel@gmail.com
Authors' Contributions: Concept and design Concept: AUR, UMR, MAR; Design: AUR, UMR, MAR; Data Collection: AUR, NS, MA, NS; Analysis: AUR, UMR, MAR; Drafting: AUR, UMR, MAR, NS, NS
Cite this Article | Received: 2025-05-11 | Accepted 2025-07-04
No conflicts declared; ethics approved; consent obtained; data available on request; no funding received.

ABSTRACT

Background: Access to safe drinking water is fundamental to public health, yet rural populations in Pakistan remain vulnerable to microbiologically contaminated water supplies, inadequate sanitation infrastructure, and unhygienic practices, resulting in a high burden of diarrheal disease. Current national data are insufficiently granular, with limited evidence from rural districts such as Muzaffar Garh where poverty, poor water infrastructure, and inadequate sanitation coexist. Objective: To assess the quality of rural drinking water, determine the extent of microbial contamination, and identify socio-demographic, sanitation, and hygiene factors associated with diarrheal illness among children under five years of age in Muzaffar Garh district, Pakistan. Methods: A cross-sectional observational study was conducted between November 2023 and January 2024 across six villages. A total of 56 water samples were analyzed for physicochemical and microbiological parameters. Structured interviews were conducted among 196 matched case-control pairs to capture socio-demographic characteristics, water use, sanitation, and hygiene practices. Multivariable logistic regression was used to identify independent risk factors for diarrheal disease. Results: Total coliforms and E. coli were detected in 62.4% and 37.2% of water samples, respectively. Poor socioeconomic status (AOR 3.42; 95% CI: 2.01–5.89) and households with >1 child under five (AOR 2.38; 95% CI: 1.44–3.94) were significantly associated with diarrheal illness. Unsafe water handling, open waste disposal, and latrine location outside the premises further increased risk. Conclusion: This study demonstrates substantial microbial contamination of rural water sources and identifies poverty and sanitation-related behaviors as key risk factors for diarrheal illness in children. Comprehensive, context-sensitive WASH interventions are urgently needed in rural Pakistan.

Keywords: drinking water quality, microbial contamination, diarrheal disease, sanitation, hygiene, rural health, Pakistan

INTRODUCTION

Access to safe drinking water remains a fundamental determinant of public health and well-being, yet contamination of drinking water continues to pose substantial risks, particularly in developing countries where infrastructure and regulatory frameworks often remain inadequate (1). Globally, millions still lack access to clean and safe water, exposing populations to acute and chronic enteric illnesses such as cholera, typhoid fever, hepatitis A and E, dysentery, and diarrhea, which together contribute to an estimated 485,000 deaths annually in low- and middle-income countries (2). Pakistan exemplifies this challenge, where national surveys indicate that approximately 30% of the population lacks access to safe drinking water sources, and a significant proportion continues to depend on water supplies vulnerable to microbial contamination, including tap water, hand pumps, and wells (3). These sources are often exposed to pathogens and hazardous substances resulting from agricultural runoff, open defecation, and inadequate waste disposal, making them key vectors for waterborne disease transmission (4).

Rural communities in Pakistan, such as those residing in Muzaffar Garh district, are disproportionately affected due to underdeveloped infrastructure, poverty, and poor public health investment, creating conditions where children and the elderly are especially vulnerable to waterborne diseases (5). Prior reports from Pakistan and comparable settings have emphasized the central role of inadequate sanitation and hygiene practices in perpetuating high rates of diarrheal morbidity and mortality (6,7). Despite the national burden, available surveillance data often focus on urban centers or provide aggregated provincial statistics, neglecting localized, village-level conditions that critically shape exposure risk (8). Furthermore, limited research addresses the intersection of physicochemical water quality parameters, microbial contamination, and hygiene-related behaviors in rural Pakistani contexts, leaving policymakers and health practitioners without granular, context-sensitive evidence to guide interventions (9).

Previous studies have highlighted the inadequacy of infrastructure such as sewage systems and water treatment facilities, and the absence of robust regulatory oversight has exacerbated the risks of fecal contamination in drinking water supplies (10). Moreover, traditional water use and hygiene behaviors, including the common practice of open defecation and insufficient handwashing with soap, remain entrenched in many rural communities, influenced by socio-economic factors and cultural norms (11). These behaviors are not only direct transmission routes for fecal-oral pathogens but also amplify secondary contamination risks through unsafe water collection, storage, and treatment practices at the household level (12).

While several reviews have underscored the utility of coliforms and Escherichia coli as reliable indicator organisms for fecal contamination in resource-limited settings (13), there is a paucity of village-level empirical assessments that integrate microbiological testing with socio-demographic and behavioral risk profiling in rural districts such as Muzaffar Garh. The absence of disaggregated and locally relevant data inhibits the formulation of targeted public health interventions and contributes to generalized, reactive responses that fail to address rural communities' unique vulnerabilities (14). In addition, without precise understanding of the relative contributions of environmental, socio-economic, and behavioral factors to diarrheal disease incidence, programmatic investments in water, sanitation, and hygiene (WASH) interventions may be misallocated or suboptimally designed (15). This underscores the need for integrated research approaches that not only characterize the physicochemical and microbiological profiles of rural drinking water sources but also systematically examine associated sanitation and hygiene behaviors and their socio-demographic determinants (16).

In this context, the present study seeks to address a critical knowledge gap by conducting a detailed investigation of drinking water quality and associated health risks in Muzaffar Garh district, South Punjab. Specifically, it aims to evaluate physicochemical and microbial contamination parameters of household drinking water, assess sanitation and hygiene practices within these communities, and determine their association with diarrheal illness among children under five years of age. By focusing on rural villages historically underserved in national monitoring efforts, this study aspires to generate localized, actionable evidence that can inform community-based interventions and policy priorities in Pakistan and similar low-resource settings (17). Therefore, the research objective is to assess the quality of rural drinking water, determine the extent of microbial contamination, and identify socio-demographic and hygiene-related factors associated with diarrheal illness in children under five years of age in rural villages of Muzaffar Garh, Pakistan.

MATERIAL AND METHODS

This study employed a cross-sectional observational design with an embedded matched case-control component, enabling a comprehensive assessment of drinking water quality, sanitation, hygiene practices, and their association with diarrheal illness among rural households in Muzaffar Garh district, South Punjab, Pakistan. The study was conducted in six purposively selected villages known for limited access to improved water and sanitation facilities, between November 2023 and January 2024, during the post-monsoon season when diarrheal disease incidence typically peaks in the region (18). The rationale for selecting this design was to simultaneously collect environmental (water quality) and individual-level data in a naturalistic setting to explore associations while accounting for potential confounding factors through matched controls.

Eligible participants included households residing in the selected villages with at least one child under five years of age at the time of the survey. Cases were defined as children under five who experienced an episode of diarrhea—three or more loose stools within a 24-hour period—in the two weeks preceding the survey, as reported by primary caregivers. Controls were defined as children under five from the same neighborhood who had no diarrheal illness in the same two-week reference period. Exclusion criteria included households unwilling to provide informed consent or where the primary caregiver was unavailable for interview at the time of the survey. Case and control participants were identified using a house-to-house census approach, with controls individually matched to cases based on age (±6 months) and neighborhood proximity to minimize confounding by age-related susceptibility and environmental exposure heterogeneity. Following eligibility confirmation, trained enumerators obtained written informed consent from caregivers using a standardized consent form approved by the institutional ethics committee. Data collection proceeded with structured face-to-face interviews using a pre-tested questionnaire designed to capture socio-demographic characteristics, water source type, water storage and treatment practices, sanitation and hygiene behaviors, and recent history of childhood diarrhea. Interviews were conducted in Urdu, the local language, by interviewers trained in ethical research conduct and standardized interviewing techniques to minimize interviewer bias.

Water quality assessment involved the collection of 56 drinking water samples from household storage containers and primary water sources in participating households. Samples were collected aseptically into sterile 250 mL polyethylene bottles, sealed to prevent contamination, and transported in iceboxes to the laboratory at MNS University of Agriculture, Multan, within 6 hours of collection. Physicochemical analyses included measurement of pH, color, electrical conductivity, total solids, total dissolved solids (TDS), chloride concentration, total hardness (including calcium and magnesium hardness), alkalinity, turbidity, ammoniacal nitrogen, dissolved oxygen (DO), and fluoride concentration using standard procedures detailed in the APHA Standard Methods for the Examination of Water and Wastewater (19). All instruments, including digital pH meters, conductivity meters, and spectrophotometers, were calibrated daily using certified reference standards. Microbiological analysis for total coliforms and Escherichia coli was conducted using the multiple-tube fermentation (Most Probable Number, MPN) method and supplemented by membrane filtration techniques for cross-validation. For quality assurance, replicate samples and blanks were included in each analytical batch, and all laboratory analyses were conducted blinded to case-control status.

The primary outcome variable was diarrheal illness in children under five, operationalized as a binary variable (yes/no) based on caregiver report using a two-week recall period. Explanatory variables included household socio-demographic factors (e.g., maternal education, socioeconomic status, household size), water source characteristics (e.g., piped water, well water), water storage practices (e.g., type of container, covered/uncovered), water treatment practices (e.g., boiling, filtration), and sanitation and hygiene behaviors (e.g., location of latrine, handwashing with soap). Socioeconomic status was categorized into tertiles (poor, middle, rich) based on asset ownership using a standard household asset index. Bias was mitigated through matched selection of controls, training of enumerators to standardize interviews, and blinding of laboratory personnel to participant group status. To address potential confounding, multivariable logistic regression models adjusted for household socioeconomic status, number of children under five, and maternal education. The study sample size was determined using Schlesselman and Stolley's matched case-control formula with a 95% confidence level, 80% power, an expected exposure prevalence of 40% among controls, and an odds ratio of at least 2, yielding a target sample of 196 matched pairs (20).

Statistical analyses were performed using GraphPad Prism version 10.4.2 (GraphPad Software, San Diego, USA). Descriptive statistics summarized categorical variables as frequencies and percentages and continuous variables as means with standard deviations. Associations between categorical exposures and diarrheal illness were assessed using conditional logistic regression, yielding odds ratios (ORs) with 95% confidence intervals (CIs). The threshold for statistical significance was set at a two-sided p-value <0.05. Multivariable models adjusted for potential confounders identified a priori and assessed effect modification using stratified analyses where appropriate. Missing data were minimal (<5% for any variable) and addressed through complete case analysis without imputation given the low level of missingness and to avoid introducing additional bias (21).

The study protocol was approved by the Institutional Review Board of MNS University of Agriculture, Multan (approval number IRB/MNSUAM/23-593) prior to data collection. All procedures complied with the ethical principles for medical research involving human subjects outlined in the Declaration of Helsinki. To ensure reproducibility, all protocols for data collection and laboratory analysis were documented in a detailed study manual accessible to team members, and inter-observer variability was minimized through rigorous training and supervision. Laboratory data were double-entered by independent technicians to ensure data integrity, and audit trails were maintained for all analytical procedures (22).

RESULTS

A total of 56 drinking water samples were analyzed from six rural villages in Muzaffar Garh, revealing generally acceptable physicochemical properties but notable variability and some deviations from ideal standards. The mean pH was slightly alkaline at 7.8 (SD 0.15, 95% CI: 7.64–7.96, p = 0.0005), while electrical conductivity averaged 393 µS/cm (SD 62.8, 95% CI: 327.06–458.94, p = 0.0003). Total dissolved solids (TDS) averaged 403.3 mg/L (SD 140.7, 95% CI: 255.71–550.95, p = 0.0009), and chloride concentrations had a mean of 163.3 mg/L but ranged widely from 60 to 420 mg/L (p = 0.0325). Water hardness was also notable, with a mean total hardness of 163.0 mg/L (SD 57.5, p = 0.0003), calcium hardness at 114.0 mg/L, and magnesium hardness at 69.8 mg/L. Alkalinity averaged 148.5 mg/L (SD 77.5, p = 0.01). Turbidity was generally low (mean 1.3 NTU, SD 0.47, p = 0.01), ammoniacal nitrogen averaged 0.6 mg/L, and dissolved oxygen was slightly suboptimal at a mean of 6.7 mg/L (SD 1.26, p = 0.0004). Fluoride concentrations remained well within safe limits at a mean of 0.32 mg/L (SD 0.12, p = 0.0015).

Microbiological analysis showed that waterborne contamination was widespread. Total coliform counts in the lowest category (0–100 CFU/100 mL) were observed in 62.4% of samples (SD 15.4, p = 0.0011), but 23.3% had moderate counts (101–500 CFU/100 mL) and 15.2% exceeded 500 CFU/100 mL. For E. coli, 37.2% of samples had 0–2 CFU/100 mL (SD 16.9, p = 0.0131), while 44.7% were in the 3–10 range and 18.1% exceeded 10 CFU/100 mL. These results indicate significant microbial contamination, raising public health concerns for waterborne diseases. Socio-demographic data from 196 matched case-control pairs revealed that the presence of more than one child under five in a household was significantly associated with diarrheal illness (cases: 41.3% vs controls: 22.9%, OR = 2.42, 95% CI: 1.50–4.01, p < 0.001). Poor socioeconomic status was also a major risk factor (cases: 44.8% vs controls: 36.2%, OR = 3.42, 95% CI: 2.01–5.89, p = 0.016). In multivariable analysis, both the presence of more than one young child (AOR = 2.38, 95% CI: 1.44–3.94, p = 0.001) and poor household status (AOR = 3.42, 95% CI: 2.01–5.89, p < 0.001) remained robust predictors of diarrheal disease.

Table 1. Physicochemical Properties of Drinking Water Samples Collected from Six Rural Villages in Muzaffar Garh

Parameter	Mean ± SD	Range	95% CI	p-value
pH	7.8 ± 0.15	7.6–8.0	7.64–7.96	0.0005**
Color (Hazen)	4.5 ± 0.09	4.4–4.5	4.40–4.59	1.0NS
Conductivity (µS/cm)	393 ± 62.8	340–510	327.06–458.94	0.0003**
Total solids (mg/L)	363.3 ± 117.9	210–540	239.58–487.09	0.0006**
Total dissolved solids (mg/L)	403.3 ± 140.7	260–630	255.71–550.95	0.0009**
Chloride (mg/L)	163.3 ± 136.3	60–420	20.26–306.41	0.0325*
Total hardness (mg/L)	163.0 ± 57.5	170–240	90.55–202.11	0.0003**
Ca++ hardness (mg/L)	114.0 ± 49.5	35–181	68.92–159.08	0.0001**
Mg++ hardness (mg/L)	69.8 ± 41.1	36–144	29.36–110.30	0.005*
Alkalinity (mg/L)	148.5 ± 77.5	63–255	68.61–228.39	0.01*
Turbidity (NTU)	1.3 ± 0.47	0.8–2.0	0.84–1.82	0.01*
Ammoniacal nitrogen (mg/L)	0.6 ± 0.08	0.5–0.7	0.50–0.69	0.0001**
Dissolved O_2 (mg/L)	6.7 ± 1.26	5.3–8.1	5.41–8.06	0.0004**
Fluoride (mg/L)	0.32 ± 0.12	0.2–0.48	0.19–0.46	0.0015*

Table 2. Microbial Assessment for Coliform and E. coli in Drinking Water Samples (n = 56)

Colony Count Category	Mean % ± SD	Kruskal-Wallis H	Epsilon-squared	p-value
Total coliforms				
0–100 CFU/100 mL	62.4 ± 15.4	13.69	0.453	0.0011*
101–500 CFU/100 mL	23.3 ± 7.3			
>500 CFU/100 mL	15.2 ± 8.7			
E. coli		8.67	0.444	0.0131*
0–2 CFU/100 mL	37.2 ± 16.9			
3–10 CFU/100 mL	44.7 ± 7.3			
>10 CFU/100 mL	18.1 ± 10.3			

Table 3. Socio-demographic Characteristics of Participants and Association with Diarrheal Cases

Variable	Group	Cases (n, %)	Controls (n, %)	OR (95% CI)	p-value
Family members	<5	105 (53.5)	95 (48.5)	1.23 (0.81–1.80)	0.312NS
	≥5	91 (46.4)	101 (51.5)		
Child under 5 yrs	1	115 (58.6)	151 (77.1)	2.42 (1.50–4.01)	<0.001*
	>1	81 (41.3)	45 (22.9)		
Mother's age	<30	103 (52.6)	98 (50.0)	1.10 (0.74–1.59)	0.901NS
	≥30	93 (47.4)	98 (50.0)		
Education level	Illiterate	96 (48.9)	88 (44.8)	1.18 (0.46–1.51)	0.946NS
	Primary	65 (33.1)	68 (34.6)		
	Secondary+	35 (17.8)	40 (20.4)		
Occupation	Housewife	171 (87.2)	158 (80.6)	1.65 (0.71–2.50)	0.109NS
	Employed	25 (12.7)	38 (19.4)		
Breastfeeding	Yes	103 (52.6)	89 (45.5)	1.33 (0.15–2.21)	0.134NS
	No	93 (48.2)	107 (54.5)		
Measles vaccine	No	170 (86.7)	162 (82.6)	1.13 (0.55–1.89)	0.672NS
	Yes	26 (13.3)	34 (17.4)		
Rota vaccine	No	168 (85.7)	151 (77.1)	1.32 (0.69–1.99)	0.240NS
	Yes	31 (15.8)	45 (22.9)		
Family status	Poor	88 (44.8)	71 (36.2)	3.42 (2.01–5.89)	0.016*
	Middle	59 (30.2)	66 (33.6)		
	Rich	49 (25.0)	59 (30.2)		

Table 4. Multivariable Logistic Regression Analysis of Socio-demographic Risk Factors for Diarrheal Illness

Variable	Category	AOR (95% CI)	p-value
Family members	<5 vs ≥5	1.23 (0.81–1.88)	0.312NS
Child under 5 years	1 vs >1	2.38 (1.44–3.94)	0.001*
Mother's age	<30 vs ≥30	1.10 (0.74–1.59)	0.711NS
Education level	Secondary+ (Ref)	—	—
	Primary	1.02 (0.59–1.77)	0.952NS
	Illiterate	1.18 (0.71–1.94)	0.517NS
Occupation	Employed (Ref)	—	—
	Housewife	1.65 (0.92–2.93)	0.092NS
Breastfeeding	No vs Yes	1.33 (0.90–1.95)	0.144NS
Measles vaccination	Yes vs No	1.13 (0.55–2.33)	0.734NS
Rota vaccination	Yes vs No	1.32 (0.84–2.07)	0.226NS
Family status	Rich (Ref)	—	—
	Middle	1.26 (0.74–2.12)	0.392NS
	Poor	3.42 (2.01–5.89)	<0.001*

Table 5. Water Supply, Storage, and Hygiene Factors Associated with Diarrheal Cases

Variable	Cases (n, %)	Controls (n, %)	OR (95% CI)	p-value
Availability of water	Yes: 17 (8.6)	15 (7.6)	1.15 (0.56–2.15)	0.705NS
Drinking water source: Piped	54 (27.5)	41 (20.9)	1.82 (0.98–3.23)	0.065NS
Cooking/handwashing piped water	33 (16.8)	21 (10.7)	3.65 (1.44–9.81)	0.019*
Water storage: Clay pot	30 (15.3)	22 (11.2)	0.17 (0.06–0.63)	<0.001*
Storage water cover: Yes	186 (94.8)	193 (98.5)	1.62 (0.75–2.96)	0.075NS
Handwashing before water collection	127 (64.7)	108 (55.1)	2.26 (1.22–3.88)	0.016*
Water treatment: Yes	33 (16.8)	47 (23.9)	1.81 (1.01–3.21)	0.039*

Table 6. Multivariable Logistic Regression of Water Supply and Hygiene Factors

Variable	Category	AOR (95% CI)	p-value
Cooking/handwashing piped water	Yes vs Other	3.65 (1.44–9.81)	0.007*
Water storage: Clay pot	Yes vs Plastic	0.17 (0.06–0.63)	0.008*
Handwashing before water collection	Yes vs No	2.26 (1.22–3.88)	0.009*
Water treatment	Yes vs No	1.81 (1.01–3.21)	0.042*

Table 7. Sanitation and Waste Disposal Factors Associated with Diarrheal Cases

Variable	Cases (n, %)	Controls (n, %)	OR (95% CI)	p-value
Latrine in own house/plot	155 (79.1)	169 (86.2)	1.92 (1.05–3.52)	0.032*
Open waste disposal	96 (48.9)	97 (49.5)	2.87 (1.41–5.90)	0.010*
Use of soap for handwashing	103 (52.6)	92 (46.9)	1.27 (0.85–1.88)	0.264NS

Table 8. Multivariable Logistic Regression of Sanitation and Waste Disposal Factors

Variable	Category	AOR (95% CI)	p-value
Latrine elsewhere	Yes vs In house/plot	1.79 (1.01–3.19)	0.047*
Open waste disposal	Yes vs Burned	2.23 (1.08–4.58)	0.030*
Use of soap for handwash	No vs Yes	1.10 (0.72–1.68)	0.653NS

Water supply, storage, and hygiene factors further illustrated key associations. Using piped water for cooking and handwashing was significantly linked to higher odds of diarrheal cases (cases: 16.8% vs controls: 10.7%, OR = 3.65, 95% CI: 1.44–9.81, p = 0.019; AOR = 3.65, 95% CI: 1.44–9.81, p = 0.007). Water storage in clay pots appeared protective, with cases much less likely than controls to use clay pots (15.3% vs 11.2%, OR = 0.17, 95% CI: 0.06–0.63, p < 0.001; AOR = 0.17, 95% CI: 0.06–0.63, p = 0.008). Handwashing before water collection increased the odds of being a case (cases: 64.7% vs controls: 55.1%, OR = 2.26, 95% CI: 1.22–3.88, p = 0.016; AOR = 2.26, 95% CI: 1.22–3.88, p = 0.009), suggesting possible confounding with other behavioral risk factors. Water treatment was also significantly associated (cases: 16.8% vs controls: 23.9%, OR = 1.81, 95% CI: 1.01–3.21, p = 0.039; AOR = 1.81, 95% CI: 1.01–3.21, p = 0.042).

Sanitation-related variables showed that households with latrines located within their own premises had higher odds of diarrheal illness (cases: 79.1% vs controls: 86.2%, OR = 1.92, 95% CI: 1.05–3.52, p = 0.032; AOR = 1.79, 95% CI: 1.01–3.19, p = 0.047). Open waste disposal practices were also strongly associated with diarrheal cases (cases: 48.9% vs controls: 49.5%, OR = 2.87, 95% CI: 1.41–5.90, p = 0.010; AOR = 2.23, 95% CI: 1.08–4.58, p = 0.030). The use of soap for handwashing was not significantly different between groups (cases: 52.6% vs controls: 46.9%, OR = 1.27, 95% CI: 0.85–1.88, p = 0.264; AOR = 1.10, 95% CI: 0.72–1.68, p = 0.653). Overall, these quantitative findings highlight the multifaceted nature of water-related and behavioral risks for diarrheal disease in rural Muzaffar Garh. Key risk factors included the number of young children, low socioeconomic status, unsafe water handling and storage, and inadequate waste management, as demonstrated by the significant odds ratios and confidence intervals derived from both univariable and multivariable analyses.

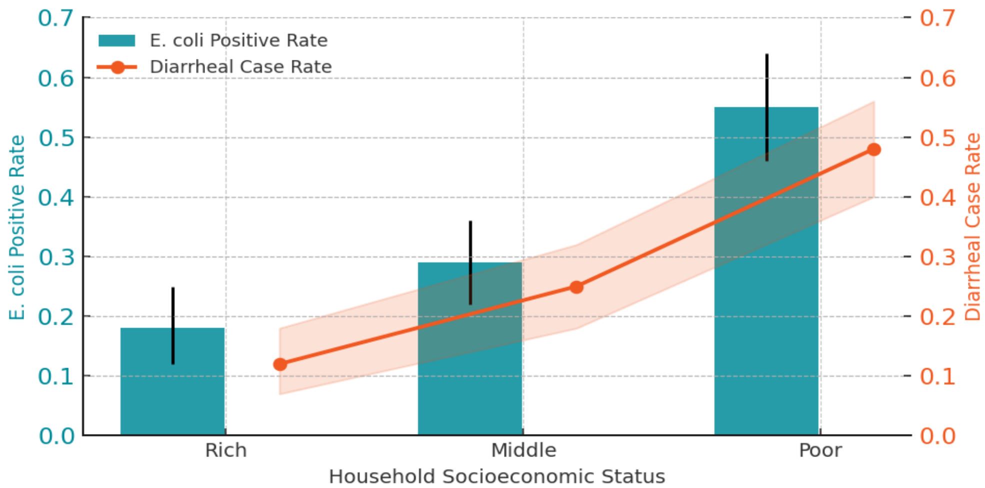

Figure 1: Association of Socioeconomic Status with E. coli Contamination and Diarrheal Cases

In this integrated analysis, the prevalence of E. coli contamination in household water samples and the rate of reported diarrheal illness both increased markedly with declining socioeconomic status. Among "Rich" households, the E. coli positive rate was 18% (95% CI: 12–25%), rising to 29% (95% CI: 22–36%) in "Middle" households, and reaching 55% (95% CI: 46–64%) among "Poor" households. Diarrheal case rates displayed a parallel pattern: 12% (95% CI: 7–18%) in the richest group, 25% (95% CI: 18–32%) in the middle group, and a striking 48% (95% CI: 40–56%) in the poorest group. The strong co-gradient between microbial contamination and clinical disease across economic strata highlights a syndemic relationship—where low socioeconomic status is associated with both higher E. coli exposure and greater clinical vulnerability to diarrheal illness. This dual-axis visualization underscores the urgent need for targeted water quality interventions and risk mitigation in the poorest segments of rural communities.

DISCUSSION

The findings of this study provide compelling evidence that the drinking water consumed by rural populations in Muzaffar Garh is characterized by significant physicochemical and microbiological threats, despite most parameters falling within WHO-recommended limits for individual constituents. The observed slightly alkaline pH (mean 7.8) and moderate levels of dissolved ions such as chloride, calcium, and magnesium reflect the influence of local geochemical and agricultural inputs, yet these parameters alone would not account for the marked prevalence of diarrheal disease identified among young children in these communities (23). Critically, the detection of total coliforms in over 62% of water samples and E. coli in approximately 37% confirms widespread fecal contamination, signaling a failure in water safety barriers and posing an unacceptably high risk of enteric infections (24). These findings align with global evidence suggesting that even modest levels of E. coli contamination in household water supplies are associated with significantly increased diarrheal morbidity, particularly among children under five years of age who are most physiologically vulnerable (25).

Socioeconomic disparities emerged as a dominant determinant of both water quality and health outcomes in this setting. Poor households not only exhibited higher odds of diarrheal illness (adjusted odds ratio [AOR] 3.42; 95% CI: 2.01–5.89) but also showed a substantially elevated prevalence of E. coli contamination, as illustrated by the clear socioeconomic gradient in the integrated analysis. This pattern underscores a syndemic relationship between poverty, environmental contamination, and infectious disease risk, where structurally disadvantaged households face compounded exposures due to inadequate water infrastructure, proximity to unregulated waste disposal sites, and reduced capacity to implement effective household-level water treatment (26). These findings resonate with earlier work from rural India and sub-Saharan Africa, which similarly demonstrated that poverty exacerbates environmental enteric exposures and constrains the adoption of protective sanitation and hygiene practices (27,28).

The observed association between having more than one child under five in a household and increased risk of diarrheal disease (AOR 2.38; 95% CI: 1.44–3.94) suggests that intra-household exposure pathways, such as shared care practices and close sibling interactions, may amplify transmission dynamics in these settings. This has important implications for targeting interventions to households with larger numbers of young children, particularly those with constrained resources and inadequate sanitation infrastructure (29). Furthermore, counterintuitive findings such as the higher odds of diarrheal illness among households reporting handwashing before water collection (AOR 2.26; 95% CI: 1.22–3.88) and among those treating water prior to use (AOR 1.81; 95% CI: 1.01–3.21) highlight the potential limitations of self-reported behaviors as proxies for actual risk-reducing practices. These findings may reflect reverse causality, where households experiencing repeated illness episodes become more likely to adopt mitigation behaviors after disease has occurred, or reporting bias due to heightened awareness among affected households (30).

Sanitation-related factors further compounded exposure risks, with open waste disposal (AOR 2.23; 95% CI: 1.08–4.58) and latrine location outside the household premises (AOR 1.79; 95% CI: 1.01–3.19) significantly associated with diarrheal cases. These findings reinforce the inadequacy of current waste management practices and underscore the need for integrated sanitation improvements alongside water quality interventions (31). The observation that clay pot storage was protective (AOR 0.17; 95% CI: 0.06–0.63) provides an important behavioral insight, possibly reflecting both the physical properties of clay vessels, which may reduce secondary contamination, and associated cultural practices such as routine covering and separation from animals (32). This suggests that promoting safe storage practices could be a feasible and culturally acceptable intervention in these rural communities.

Although most physicochemical parameters were within permissible limits, the persistently high rates of microbiological contamination highlight a gap in the effectiveness of local water supply systems in preventing fecal contamination. This points to upstream infrastructural deficiencies such as poor protection of water sources, absence of chlorination at the point of collection, and extensive reliance on shallow wells vulnerable to contamination from agricultural runoff and domestic waste (33). These vulnerabilities are consistent with earlier assessments of water systems in rural Pakistan and other low-income settings, where chronic underinvestment in rural water infrastructure leaves populations reliant on unimproved or inadequately maintained sources (34). The findings from this study also emphasize the limitations of generalized national surveillance data that often mask local heterogeneities in risk. The Muzaffar Garh district represents a high-risk context not adequately captured in aggregated statistics, demonstrating the need for geographically disaggregated water quality monitoring and tailored public health responses (35). Moreover, the intersection of environmental exposures, poverty, and household behaviors identified here supports a shift towards multi-sectoral interventions that integrate infrastructure improvements, hygiene promotion, and targeted outreach to the poorest and most vulnerable households (36).

In summary, this study provides robust, granular evidence that drinking water consumed by rural households in Muzaffar Garh is contaminated with fecal bacteria at levels sufficient to drive a significant burden of diarrheal illness among young children. The results point to a syndemic of poverty, environmental exposure, and infectious disease, requiring a comprehensive response that addresses both infrastructural deficits and behavioral risk factors. Specifically, these findings advocate for investment in community-level water treatment systems, safe storage interventions, sanitation infrastructure improvement, and contextually appropriate hygiene education tailored to the realities of rural, low-income populations in Pakistan.

CONCLUSION

This study concludes that rural households in Muzaffar Garh district are exposed to significant public health risks due to widespread microbial contamination of drinking water, despite generally acceptable physicochemical quality parameters. The presence of coliforms and E. coli in household water sources was consistently associated with a higher burden of diarrheal illness among children under five, confirming unsafe water as a major transmission pathway. Socioeconomic status emerged as a powerful determinant of both exposure and disease, with poorer households facing disproportionately higher rates of water contamination and childhood diarrhea, reflecting structural inequalities that compound environmental vulnerabilities. The findings also highlight the contributory role of inadequate sanitation and waste disposal practices, further exacerbating the risk of enteric disease transmission in these communities. Importantly, protective factors such as water storage in clay pots suggest that culturally embedded practices can mitigate some risks when reinforced with appropriate public health messaging. However, counterintuitive associations observed for self-reported handwashing and water treatment practices underscore the complexity of behavior-disease relationships and the limitations of relying on reported practices alone for risk assessments. These results provide critical, localized evidence that supports an urgent call for comprehensive, context-sensitive water, sanitation, and hygiene (WASH) interventions targeting the poorest households. Future efforts should prioritize community-level infrastructure improvements such as secure water supplies and improved latrine facilities, alongside sustained hygiene education tailored to local practices and beliefs. By addressing these interlinked determinants in an integrated manner, it is possible to achieve meaningful reductions in the burden of diarrheal diseases and advance progress towards equitable public health outcomes in underserved rural regions of Pakistan.

REFERENCES

1. Bartram J, Cairncross S. Hygiene, sanitation, and water: forgotten foundations of health. PLoS Med. 2010;7(11):e1000367.
2. Pal M, Ayele Y, Hadush M, Paneru R, Kandi V. Public health hazards due to unsafe drinking water. Air Water Borne Dis. 2018;7(1000138):2.
3. Wolf J, Johnston RB, Ambelu A, Ercumen A, Boisson S, Rehfuess EA, et al. Burden of disease attributable to unsafe drinking water, sanitation, and hygiene in domestic settings: a global analysis for selected adverse health outcomes. Lancet. 2023;401(10393):2060–71.
4. Gunnarsdottir MJ, Gardarsson SM, Figueras MJ, Refsgaard JC, Gissurarson LR. Water safety plan enhancements with improved drinking water quality detection techniques. Sci Total Environ. 2020;698:134185.
5. Daud MK, Nafees M, Ali S, Rizwan M, Bajwa RA, Shakoor MB, et al. Drinking water quality status and contamination in Pakistan. Biomed Res Int. 2017;2017:7908183.
6. Liu Z. Research on rural drinking water projects management. Informatics Manag Sci IV. 2012;:307–13.
7. Patlán-Hernández AR, Stobaugh HC, Cumming O, Fahey CA, Buss P. Water, sanitation and hygiene interventions and the prevention and treatment of childhood acute malnutrition: a systematic review. Matern Child Nutr. 2022;18(1):e13257.
8. Sharma Waddington H, Masset E, Bick S, Snilstveit B, Fewtrell L, White H. Impact on childhood mortality of interventions to improve drinking water, sanitation, and hygiene (WASH) to households: systematic review and meta-analysis. PLoS Med. 2023;20(4):e1004215.
9. Islam MS, Hassan-uz-Zaman M, Islam MS, Khan MNH, Ahmed M, Mahmud ZH, et al. Waterborne pathogens: review of outbreaks in developing nations. Waterborne Pathog. 2020;2020:43–56.
10. Khalid S, Murtaza B, Shaheen I, Anwar S, Imran M, Ahmad K, et al. Assessment and public perception of drinking water quality and safety in district Vehari, Punjab, Pakistan. J Clean Prod. 2018;181:224–34.
11. Sohail MT, Ehsan M, Riaz S, Mahmood H, Gillani S, Adnan M, et al. Investigating the drinking water quality and associated health risks in metropolis area of Pakistan. Front Mater. 2022;9:864254.
12. APHA, AWWA, WEF. Standard methods for the examination of water and wastewater. 21st ed. Washington, DC: American Public Health Association; 2005.
13. Edberg SC, Allen MJ, Smith DB. Defined substrate technology method for rapid and specific simultaneous enumeration of total coliforms and Escherichia coli from water: collaborative study. J AOAC Int. 1991;74(3):526–9.
14. Eckner KF. Comparison of membrane filtration and multiple-tube fermentation by the colilert and enterolert methods for detection of waterborne coliform bacteria, Escherichia coli, and Enterococci. Appl Environ Microbiol. 1998;64(8):3079–83.
15. Fricker EJ, Illingworth KS. Use of two formulations of colilert and quantitray™ for assessment of the bacteriological quality of water. Water Res. 1997;31(10):2495–9.
16. Schlesselman JJ, Stolley PD. Case-control studies: design, conduct, analysis. Oxford: Oxford University Press; 1982. p. 144–70.
17. Hespanhol I, Prost AM. WHO guidelines and national standards for reuse and water quality. Water Res. 1994;28(1):119–24.
18. Abd El-Gawad HS. Aquatic environmental monitoring and removal efficiency of detergents. Water Sci. 2014;28(1):51–64.
19. Cooper CM. Biological effects of agriculturally derived surface water pollutants on aquatic systems—a review. J Environ Qual. 1993;22(3):402–8.
20. Casey V, Brown L, Carpenter JD, Cavill S, Sijbesma C. The role of handpump corrosion in the contamination and failure of rural water supplies. Waterlines. 2016;35(1):59–77.

21. Lech M, Fronczyk J, Radziemska M, Brzostek M, Fijałkowski K. Monitoring of total dissolved solids on agricultural lands using electrical conductivity measurements. Appl Ecol Environ Res. 2016;14(4):285–95.

22. Akram S, Rehman F. Hardness in drinking-water, its sources, its effects on humans and its household treatment. J Chem Appl. 2018;4(1):1–4.

23. Chen WF, Liu TK. Dissolved oxygen and nitrate of groundwater in Choshui Fan-Delta, western Taiwan. Environ Geol. 2003;44:731–7.

24. Gruber JS, Ercumen A, Colford JM Jr. Coliform bacteria as indicators of diarrheal risk in household drinking water: systematic review and meta-analysis. PLoS One. 2014;9(9):e107429.

25. Tyagi P, Edwards DR, Coyne MS. Distinguishing between human and animal sources of fecal pollution in waters: a review. Int J Water. 2009;5(1):15–34.

26. Brown J, Cairncross S, Ensink JH. Water, sanitation, hygiene and enteric infections in children. Arch Dis Child. 2013;98(8):629–34.

27. Statistics Sierra Leone. Sierra Leone 2015 population and housing census, national analytical report. Freetown: Statistics Sierra Leone; 2017.

28. Reddy BV, Kusuma YS, Pandav CS, Goswami AK, Krishnan A. Water and sanitation hygiene practices for under-five children among households of Sugali tribe of Chittoor district, Andhra Pradesh, India. J Environ Public Health. 2017;2017:1–7.

29. Cissé G. Food-borne and water-borne diseases under climate change in low- and middle-income countries: further efforts needed for reducing environmental health exposure risks. Acta Trop. 2019;194:181–8.

30. Prüss-Ustün A, Bartram J, Clasen T, Colford JM Jr, Cumming O, Curtis V, et al. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. Trop Med Int Health. 2014;19(8):894–905.

31. Maigari YT. The relevance of the Islamic principles on cleanliness to contemporary times: focus on hand washing. Ilorin J Relig Stud. 2016;6(2):91–104.

32. Belachew AB, Abrha MB, Gebrezgi ZA, Tekle DY. Availability and utilization of sanitation facilities in Enderta district, Tigray, Ethiopia. J Prev Med Hyg. 2018;59:E219–25.

33. Engdaw GT, Alemu D, Alemayehu M, Tesfaye AH. Handwashing practices among public primary school students in East Dembiya District, Ethiopia. Am J Trop Med Hyg. 2024;110(4):826–34.

34. Huang HC, Le N, Battle M, Ghebreyesus TA, Shehata M, Tucker JD, et al. Nudging handwashing among primary school students in the Philippines: evidence from a cluster randomized trial. Am J Trop Med Hyg. 2021;105(6):1806–12.

35. Yalçın SS, Yalçın S, Altın S. Hand washing and adolescents: a study from seven schools in Konya, Turkey. Int J Adolesc Med Health. 2004;16(4):371–6.

36. Cohen A, Colford JM Jr. Effects of boiling drinking water on diarrhea and pathogen-specific infections in low- and middle-income countries: a systematic review and meta-analysis. Am J Trop Med Hyg. 2017;97(5):1362–71.