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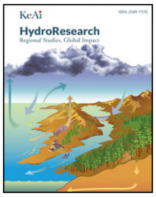

Full Length Article

Investigating drinking water quality, microbial pollution, and potential health risks in selected schools of Badin city, Pakistan

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ABSTRACT

This study investigated drinking water quality in public, private, and religious schools in Badin city, Pakistan. Physicochemical parameters were within limits except for slightly elevated pH and turbidity. The microbial analysis showed that T.C., and F.C., were found in all samples, and *E. coli* in 55% of the smaples, with significant differences in quantities. Microbial contaminants correlated positively with pH, turbidity, and each other, linking them to sewage, runoff, and waste. Bacterial counts exceeded WHO guidelines, and the pollution load index (PLI) demonstrated declining water quality. The water quality index (WQI) rated samples as 30% "very good," 35% "good," and 35% "poor "; none were "excellent" or safe to drink. Subpar water quality poses health risks to children, potentially causing diarrhea, hepatitis A, and typhoid. To mitigate risks, infrastructure improvements, education initiatives, and public awareness campaigns are necessary for securing safe water access to support the well-being of school children and the community.

1. Introduction

Water is crucial for life on Earth, serving as a fundamental solvent, supporting chemical reactions, and regulating temperature. Its importance underlines the need for careful conservation and sustainable use of water resources to protect our planet's future health. (Jat Baloch et al., 2023; Rangasamy and Muniyandi, 2024; Zikirov and Zikirov, 2022). Sustainable water resource management is thus recognized as a fundamental initiative to ensure environmental sustainability and global prosperity (Jimoh et al., 2023; Qadri et al., 2020). Safe, clean drinking water is essential for public health and is recognized by the United Nations as a basic human right. This highlights water's crucial role in supporting life and society's development. (Mititelu et al., 2023). Over 663 million people worldwide lack safe water, risking their health. The problem is acute in developing regions, where 579 million struggles for clean water (Lunegova et al., 2022).

Global collaboration is imperative to address water scarcity and improve water quality, affirming the right to clean water as essential (Alver, 2019; Mazer et al., 2020). Water security, a key element of sustainable development, enables communities to access adequate and safe water, crucial for livelihoods, well-being, socio-economic progress, and ecosystem preservation, all within a context of peace and stability (Verma and Loganathan, 2023). Highlighted by UN-Water in 2013, the journey towards water security is challenged by scarcity, contamination, and water-related hazards (Marcal et al., 2021). Addressing these issues requires a balanced approach to providing safe water and protecting water environments, with a focus on combating contamination, improving infrastructure, and employing integrated water management strategies (Assefa et al., 2019). Ultimately, the aim is to ensure that every person, especially the vulnerable, has access to clean and safe drinking water (Pichel et al., 2019).

However, providing adequate and equitable access to safe drinking water remains a persistent challenge across many South Asian countries like Bangladesh, Nepal, Bhutan, Sri Lanka, and Pakistan (Barathi et al.,

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Abbreviations: AGI, Acute Gastrointestinal Illness; ANOVA, Analysis of Variance; CFU, Colony-Forming Units; *E. coli*, *Escherichia Coli*; F.A, Factor Analysis; F.C., Fecal Coliform; PCA, Principal Component Analysis; PLI, Pollution Load Index; T.C., Total Coliform; WHO, World Health Organization; WQI, Water Quality Index.

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2019; Price et al., 2019). Recent evidence suggests that the drinking water supply in schools often has alarming levels of microbial contamination, putting children at risk of waterborne diseases like diarrhea, typhoid, cholera, and gastroenteritis (Ahmed et al., 2020; Kristanti et al., 2022). In Bangladesh, the detection of microbial contaminants, including T.C., F.C., and *E. coli*, in potable water sources has elicited significant health-related apprehensions. This issue is particularly acute among school-aged children, a group that exhibits heightened vulnerability to waterborne diseases (Hasan et al., 2019). A study in Nepal reported significant contamination in the drinking water sources of schools due to improper water system maintenance and sanitation facilities, with similar findings reported in Tokha Municipality, Kathmandu, where almost all water samples from schools exceeded WHO guidelines, indicating unsafe drinking water (Shrestha et al., 2022). Evidence from Bhutan indicates widespread fecal contamination in rural school drinking water sources, underscoring a regional challenge across South Asia (Roy et al., 2022). In Sri Lanka, only 30% of 657 surveyed schools had access to safe drinking water facilities, highlighting a critical gap in ensuring safe drinking water in schools (Verma and Rai, 2021).

Water quality in Pakistan is severely compromised by microbial and fecal contamination across various sources, posing health risks nationwide. A study in Karachi found 96% of water samples contained total coliform, leading to a high incidence of waterborne diseases like diarrhea, vomiting, and skin issues among residents (Amin et al., 2019). Similarly, in district Mansehra, 92% of water samples were identified positive for pathogenic bacteria, with *E. coli* and Salmonella spp. Being the most prevalent, indicating serious threats to human health (Mian et al., 2020). In Lahore, the microbial contamination of drinking water was evaluated, showing that 95% of water samples were contaminated with fecal coliforms, and 27% of the samples showed the presence of *E. coli* (Javed et al., 2021). Moreover, a comprehensive assessment in district Vehari, Punjab, found microbial contamination of *E. coli* and coliform in water samples, underscoring the need for improved water treatment and sanitation practices (Alsalme et al., 2021). The contamination is not limited to specific areas; studies have also reported the presence of parasitic contamination in inland recreational freshwaters of Quetta, with several parasitic elements identified as potential human pathogens (Luqman et al., 2022).

The World Health Organization estimated that only 20% of the population in Pakistan has access to safe drinking water (Razi et al., 2021). Key factors contributing to persistent water contamination include inadequate water treatment and disinfection, cross-contamination from poor drainage and sewerage facilities, unregulated discharge of industrial effluents, and overexploitation of water resources (Baloch et al., 2020; Talpur et al., 2020). However, contaminated drinking water poses severe health concerns to the population, such as acute and chronic symptoms (Iqbal et al., 2021; Jat Baloch et al., 2021). In polluted water resources, pathogens such as T.C., F.C., and *E. coli* are typically found. These bacteria are the primary reason for diarrhea, typhoid, shigella, and cholera in the local communities (Akram, 2020; Hora et al., 2021; Suardiana and Yadnya Putra, 2020). Over the last few decades, diarrhea claimed the lives of countless youngsters, making up to 3.6% of the world's disease burden (Charoenwat et al., 2022; Manetu et al., 2021).

This study presents novel insights into the microbial contamination of drinking water in educational institutions across Badin City, Pakistan, an area previously underexplored in the literature. Unlike existing research, which broadly addresses water quality in residential or unspecified settings, our work specifically targets public, private, and religious schools, uncovering the unique challenges and health risks faced by students in these environments. By employing a comprehensive array of physicochemical and microbial analyses combined with advanced statistical tools, this investigation not only delineates the extent of contamination with unprecedented precision but also correlates specific water quality parameters with potential health outcomes. Furthermore, through the application of the PLI and WQI, our study quantitatively assesses the suitability of drinking water in a manner specifically tailored to the context of educational institutions. This approach not only advances our understanding of microbial pollution sources and their health implications but also sets a benchmark for future studies in similar socio-environmental settings. The findings underscore the urgent need for targeted infrastructure improvements, educational initiatives, and public awareness campaigns to ensure safe water access, thereby contributing significantly to the global pursuit of sustainable water management and public health enhancement in vulnerable communities.

2. Methodology

2.1. Study area

Badin city is located at 24°40′N 68°49′E in the Sindh province of southern Pakistan Fig. 1. The climate is predominantly mild, moderated by sea breezes from March to October, leading to a temperate environment compared to other regions. The summer season stretches from March to November, with winters from December to February, and an average annual rainfall of 233 mm (Talpur et al., 2020).

2.2. Sample collection

The selection of sampling sites in Badin city was strategically based on the assessment of potential exposure to drinking water among the student cohorts at selected schools, including both public, private, and religious schools. The primary source of drinking water analyzed was the municipal water distribution system connected to the Kaziya canal, as shown in Fig. 1, which serves the educational areas. Following rigorous standardized sampling protocols, a total of twenty water samples, each with a volume of 500 mL, were systematically collected in triplicate from each of the three sources at each site, including tap water, cooler water, and kitchen water. This procedure was implemented to enhance the strength of quality assurance. The collection utilized pre-cleaned Nalgene bottles from predetermined schools, specifically chosen for their compatibility with water quality assessment protocols.

2.3. Analysis of water matrices

The water samples underwent thorough examination for various water quality markers, employing an array of analytical tools and techniques. Turbidity was measured using a HI 93703 Portable Microprocessor Turbidity Meter. The pH levels were determined with an Info Lab pH 720 Laboratory pH Meter from the WTW Series, Germany. The Electrical Conductivity (E.C.) and Total Dissolved Solids (TDS) were evaluated using a CON 110 Conductivity/TDS/Temperature/RS232C Meter certified by EUTECH Singapore ISO 9001. The concentrations of Alkalinity, Calcium (Ca^{2+}), Magnesium (Mg^{2+}), and Bicarbonate (HCO_3^-) were measured through Volumetric Titration methods. Chloride (Cl^-) levels were determined using Volumetric Titrations with Silver Nitrate according to the Standard Method. Water Hardness was analyzed through EDTA Titration, following the Standard Method 1998. Sodium (Na^+) and Potassium (K^+) concentrations were measured with a Flame Photometer 360 from Sherwood, UK. Sulphate (SO_4^{2-}) and Nitrate ($NO_3 - N$) levels were determined using a Colorimeter DR-2800 (HACH) and an Ultraviolet Spectroscopic Screening Method, respectively. Field parameters like turbidity, pH, E.C., and TDS were measured on-site, while the rest of the analyses were conducted in a laboratory setting. Microbial contamination levels for T.C., F.C., and *E. coli* in 500 ml water samples were assessed using the Membrane Filtration Technique (MFT), following the American Public Health Association standard procedures (Ekbal and Khan, 2022). All these analyses were performed at the Pakistan Council of Research in Water Resources (PCRWR) laboratory in Badin, Sindh, Pakistan.

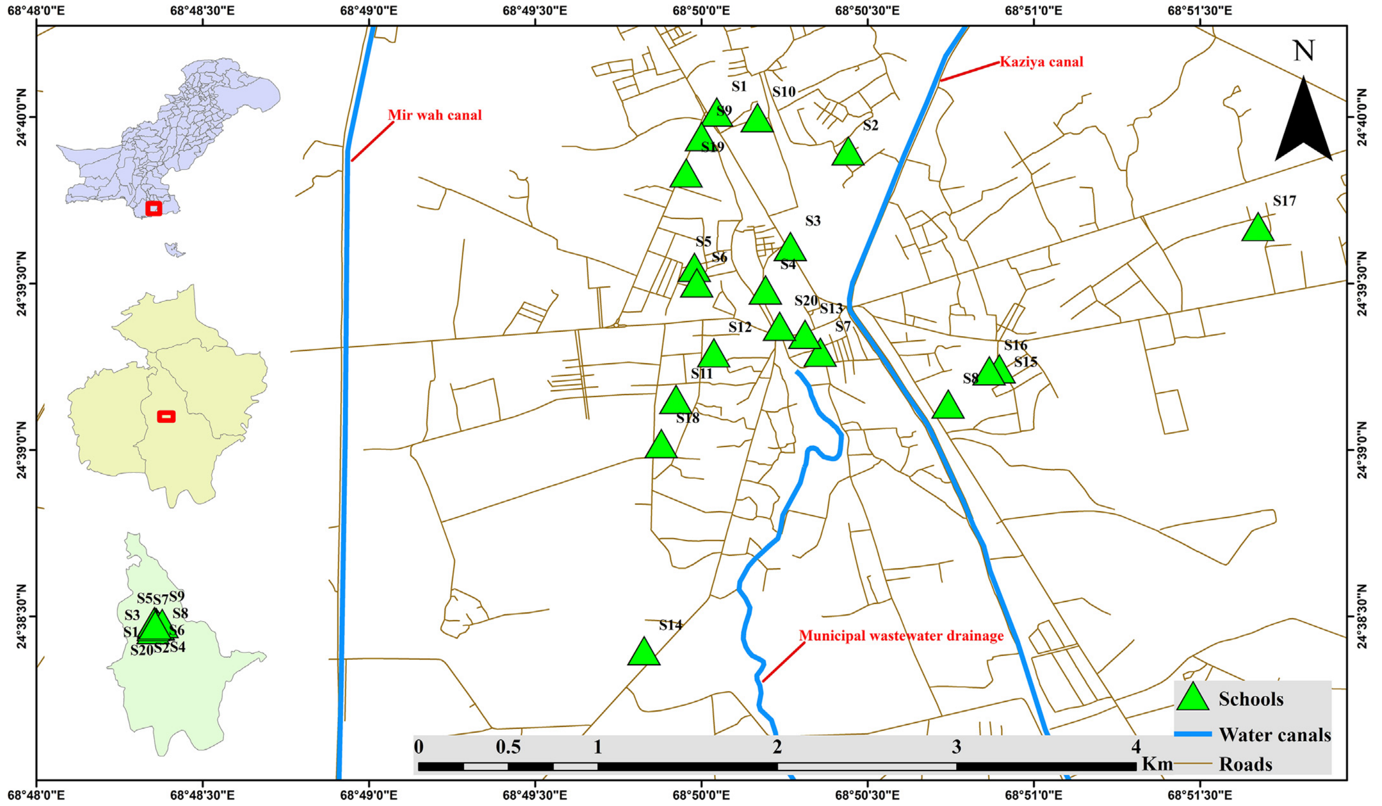


Fig. 1. The sampling locations of selected schools in Badin city, Pakistan.

2.4. Statistical analysis and visualization

Statistical analyses were conducted utilizing the R programming language, encompassing calculations of mean, standard deviation, minimum, and maximum values, alongside Pearson's correlation matrix, Factor Analysis (F.A.), and one-way Analysis of Variance (ANOVA). Additionally, the ArcMap 10.8 assisted with spatial representations, including maps of sampling locations, pollutant dispersion, and the water quality index (Fahimah et al., 2023).

2.5. Standard indices for pollution and water quality assessment

To quantify the extent of microbiological pollution and assess the suitability of drinking water, two principal indices were applied: the Pollution Load Index (PLI) (Khattak et al., 2021) as defined in Eq. (1), and the Water Quality Index (WQI) (Shalumon et al., 2021; Tarawneh et al., 2019) encompassed by Eqs. (2), (3), and (4).

$$\mathrm{PLI} = \frac{C_w}{C_r} \tag{1}$$

where (C_W) denotes the microbiological concentration of T.C., F.C., and *E. coli* in the water sample, and (C_r) represents the minimum observed microbiological concentration of T.C., F.C., and *E.coli* across all analyzed samples.

$$Wi = \frac{w_i}{\sum_{i=1}^{n} C_r} \tag{2}$$

$$Sli = W_i \times q_i \tag{3}$$

$$WQI = \sum_{i=1}^{n} Sl_i \tag{4}$$

Initially, a weight (Wi) is assigned to each indicator based on its importance. Subsequently, the relative weight (Wi) is determined, followed by the calculation of the WQI and the sub-index ($\mathrm{SI_i}$) in the final phase.

3. Results and discussion

3.1. Physicochemical parameters

The physicochemical characteristics of the water samples are presented in Table 1 and compared to the WHO guidelines (World Health Organization, 2011). Turbidity ranged from 0.8 to 5.7 NTU, indicating erratic pollution levels from suspended materials. Alkalinity went from

Table 1
Descriptive statistical analysis of water samples from the selected schools in Badin city.

Variables	Min	Max	Mean±StDev	WHO limits
Turbidity (NTU)	0.8	5.7	3.2 ± 1.5	5
Alkalinity (mg/L)	2.0	4.2	2.8 ± 0.5	N/A
Hardness (mg/L)	128.3	223.3	170.1 ± 34.5	500
TDS (mg/L)	277.0	618.3	423.0 ± 84.3	1000
EC (μS/cm)	432.7	966.7	656.2 ± 126.6	1000
pH	7.3	8.3	8.0 ± 0.3	8.5
Ca^{2+} (mg/L)	20.7	46.0	30.8 ± 6.9	200
Mg^{2+} (mg/L)	15.7	32.7	22.2 ± 5.3	150
Na^{+} (mg/L)	39.7	124.0	67.2 ± 19.3	200
K^{+} (mg/L)	5.3	13.3	7.9 ± 1.6	12
Cl^{-} (mg/L)	41.7	150.7	87.3 ± 26.8	250
SO_4^{2-} (mg/L)	46.0	102.0	62.3 ± 13.6	250
HCO_3^{-} (mg/L)	101.7	205.0	134.0 ± 21.8	500
NO_3–N (mg/L)	2.3	4.9	3.8 ± 0.6	10
T.C. (per ml)	2.0	72.3	11.1 ± 14.9	0
F.C. (per ml)	2.0	52.0	7.2 ± 10.9	0
E. coli (per ml)	0.0	33.0	2.2 ± 7.1	0

Table 2
Mean and standard deviation of microbial contaminant levels in drinking water samples from private, public, and religious schools in Badin city.

	N	T.C		F.C.		*E.coli*	
		Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Private schools	24	6.45	±3.95	3.70	±3.02	0.541	±0.77
Public schools	24	14.41	±4.64	7.54	±2.88	2.45	±1.93
Religious schools	12	22.58	±4.66	13.50	±4.64	6.75	±3.25

2.0 to 4.2 mEq/L. Hardness varied from 128.3 to 223.3 mg/L, classifying the waters as hard to very hard. Electrical conductivity (EC) was found within the safe range, from 432.7 to 966.7 μS/cm. The pH ranged from 6.5 to 8.5, with an average of 8.0, meeting the WHO standards. Total dissolved solids (TDS) varied between 277.0 and 618.7 mg/L, below the threshold. Major cations such as Ca^{2+}, Mg^{2+}, and Na^{+} were found to be within permissible limits set by WHO, while K^{+} was slightly elevated at 5.3 to 13.3 mg/L. Additionally, significant anions such as Cl^{-}, SO_4^{2-}, HCO_3^{-}, and NO_3–N were also found within acceptable limits.

3.2. Microbial parameters

Bacterial analysis was conducted for T.C., F.C., and *E. coli* and compared to the WHO drinking water quality standards from (World Health Organization, 2011). Religious schools showed higher levels of microbial contamination than public and private schools. All water samples contained microbial colonies ranging from 1.0 to 33.0 colony-forming units per milliliter (CFU/mL). 50% of the samples exceeded health-based guidelines, with mean values of 11.1 CFU/mL for T.C., 7.2 CFU/mL for F.C., and 2.2 CFU/mL for *E. coli*.

One-way analysis of variance (ANOVA) was employed to evaluate differences in T.C., F.C., and *E. coli* levels between school types (Ntumi, 2021). The Shapiro-Wilk test ($p < 0.05$) established that T.C. results were normally distributed across schools, meeting the assumption for ANOVA. The non-parametric Kruskal-Wallis test was applied because F.C. and *E. coli* results violated the normality assumption. The null hypothesis (H_0) was that mean contaminant levels do not differ between school types. The alternative hypothesis (H_A) was that means are unequal for at least one school type. Significant differences were detected between school types for all parameters at ($p < 0.05$) as shown in Table 2. Pairwise comparisons revealed that microbial contamination followed the trend: religious schools > public schools > private schools Fig. 2.

3.3. Relationship between water quality parameters

Pearson's correlation analysis at 99% confidence levels revealed distinct relationships between the water quality parameters, as illustrated in Fig. 3. Microbial quality is a critical indicator of potable water safety. T.C., F.C., and *E. coli* are bacterial groups utilized to assess fecal pollution in drinking water (Gunter et al., 2023). Pearson analysis in this study revealed significant positive correlations between T.C., F.C., and *E. coli*, implying a common origin - likely from sewage discharge, agricultural runoff containing animal feces, or cross-contamination during

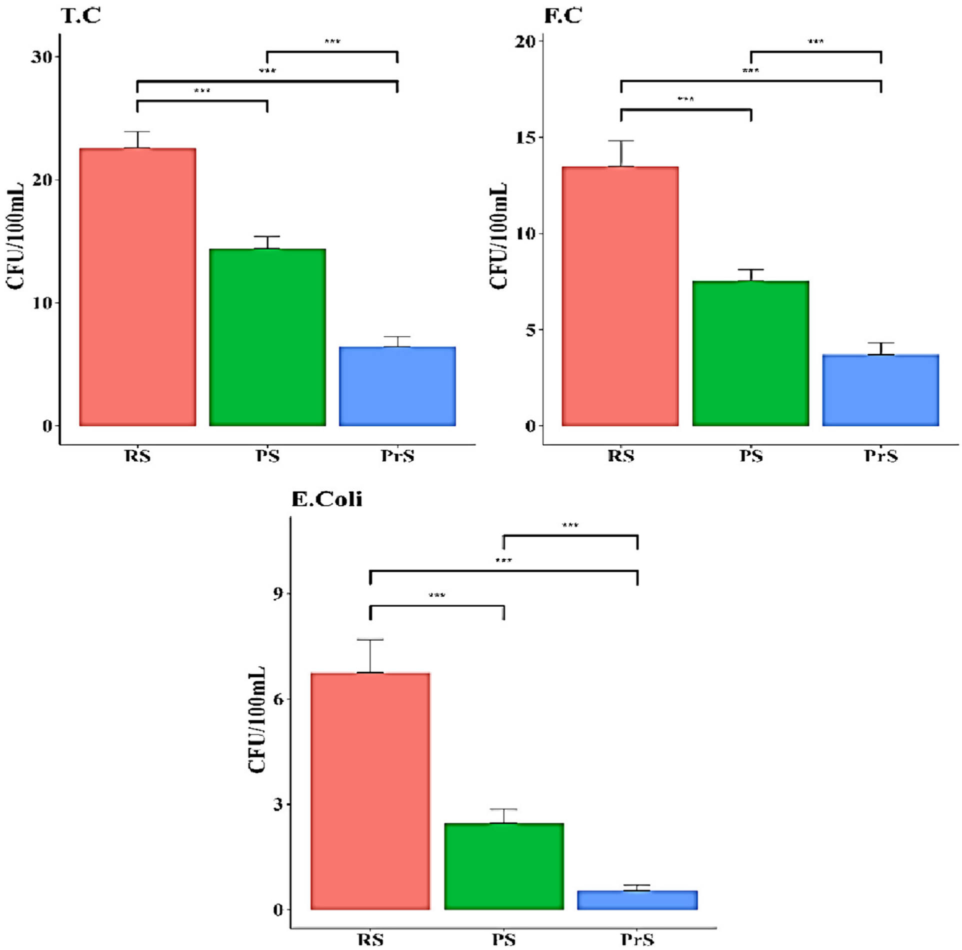
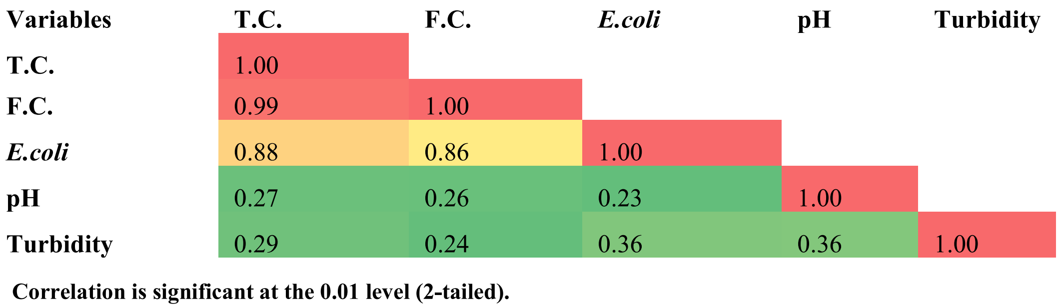


Fig. 2. Comparative analysis of religious schools (RS), public schools (PS), and private schools (PrS) in Badin City: Statistical evaluation of differences with a significance level of α = 0.05, revealed $p < 0.05$, indicating notable differences."



Variables	T.C.	F.C.	*E.coli*	pH	Turbidity
T.C.	1.00				
F.C.	0.99	1.00			
E.coli	0.88	0.86	1.00		
pH	0.27	0.26	0.23	1.00	
Turbidity	0.29	0.24	0.36	0.36	1.00

Correlation is significant at the 0.01 level (2-tailed).

Fig. 3. Pearson's correlation matrix for drinking water quality parameters.

transportation/storage, which allows interspecies microbial transfer (Senkbeil et al., 2019; Sorensen et al., 2021; Sruthi et al., 2022). Consumption of water contaminated with enteric pathogens can cause gastrointestinal illnesses, including cholera, typhoid, diarrhea, and dysentery (Khabo-Mmekoa et al., 2022; Loyola et al., 2020). These diseases present an enormous health burden, causing nearly 829,000 global deaths annually, significantly affecting developing countries (Prüss-Ustün et al., 2019).

Additionally, significant positive relationships were observed between microbial contaminants and both pH and turbidity. Alkaline pH between 7 and 8.5 promotes optimal conditions for enteric bacterial growth and proliferation (Acciarri et al., 2023; Krishna et al., 2021). Turbidity shields microorganisms from disinfection processes and depletes chlorine residuals and provides increased chances of survival. Particulates can also act as nutrients, enhancing microbial growth (Ding et al., 2019; Léziart et al., 2019). Increased turbidity has been implicated in higher acute gastrointestinal illness (AGI) (Muoio et al., 2020). Proper monitoring of turbidity and pH ensures optimized disinfection and restricted pathogen proliferation. The positive correlations between fecal indicators, pH, and turbidity show their collective impact in heightening microbial hazards in drinking water (Aram et al., 2021; Saalidong et al., 2022).

3.4. Source identification

Factor analysis was utilized to elucidate the predominant sources influencing water quality characteristics. Three significant factors accounted for 72.12% of the cumulative dataset variance Table 3.

Table 3
Factor Analysis of drinking water quality parameters from the selected schools in Badin city.

Variables	F1	F2	F3
Turbidity (NTU)	−0.351	0.263	0.124
Alkalinity (mg/L)	0.757	0.191	0.194
Hardness (mg/L)	0.835	0.162	−0.164
TDS (mg/L)	0.951	0.212	0.028
EC (µS/cm)	0.956	0.239	0.049
pH	−0.608	0.137	0.374
Ca^{2+} (mg/L)	0.835	0.015	−0.429
Mg^{+} (mg/L)	0.593	0.270	0.112
Na^{+} (mg/L)	0.800	0.226	0.022
K^{+} (mg/L)	0.080	0.344	0.791
Cl^{-} (mg/L)	0.900	0.225	0.075
SO$_4^{2-}$ (mg/L)	0.606	−0.112	−0.497
HCO$_3^-$ (mg/L)	0.817	0.313	0.319
NO$_3$–N (mg/L)	−0.305	0.013	0.252
T.C. (per ml)	−0.594	0.761	−0.238
F.C. (per ml)	−0.584	0.766	−0.234
E.coli (per ml)	−0.555	0.728	−0.312
Eigenvalue	8.235	2.352	1.673
Variability (%)	48.441	13.838	9.843
Cumulative %	48.441	62.279	72.122

Factor 1, explaining 48.44% of the variance, was heavily loaded with physicochemical parameters indicating water mineralization and hardness, including alkalinity, hardness, TDS, EC, TDS, EC, Ca^{2+}, Mg^{2+}, Na^{+}, Cl^{-}, SO$_4^{2-}$, and HCO$_3^-$. This signifies Factor 1, represents geochemical processes controlling drinking water hydrochemistry. Microbial contaminants and pH, turbidity and NO$_3$-N displayed strong negative associations under this factor.

Factor 2 described 13.84% of the variance, with dominant loadings from turbidity and microbial indicators including T.C., F.C., and *E. coli*. This denotes their common fecal pollution origin and interdependent behavior. Elevated turbidity impedes disinfection, promoting pathogen survival (Khedikar et al., 2021). Turbidity also signals contamination with particulate matter, which microbes utilize as nutrients (Bright et al., 2020). Thus, turbidity and indicator bacteria loading suggest sewage/agricultural waste contamination (Kaetzl et al., 2019).

Factor 3, explaining 9.84% of the variance, constituted favorable pH, potassium, and nitrate-nitrogen loadings, implying influence from fertilizers, pesticides, and municipal discharge containing elevated nutrient levels in water (Hao et al., 2020; Li et al., 2020). Factor analysis enabled the identification of significant sources of contamination and geochemical processes governing the portability and safety of drinking water supplies.

3.5. Pollution load index (PLI)

The PLI quantified the level of microbial contamination in the investigated drinking water supplies. T.C. demonstrated a PLI range of 1.0–36.0, with a mean of 5.5, and a standard deviation of ±7.6. F.C. showed a PLI span of 0.9–74.0, an average of 9.9, and standard deviation of ±15.9. *E. coli* exhibited values between 0 and 33, a mean of 2.2, and a standard deviation of ±7.2. Alarmingly, over 75% of samples for all indicator organisms had PLIs surpassing 1, denoting contamination above permissible limits. T.C. were detected in 99% of samples, F.C. in 95.5%, and *E. coli* in 75% - indicating widespread fecal pollution. The cumulative pollution loads attributable to microbial contaminants in a set of 20 samples, quantified in terms of T.C., F.C., and *E. coli*, were observed to be 31%, 57%, and 12%, respectively. Given the frequent PLI limit infringements and indicator organism prevalence, children consuming this water at schools across Badin City face substantial risks of contracting dangerous waterborne diseases like cholera, typhoid, diarrhea, and dysentery (Ahmed et al., 2020). Immediate remediation is imperative to safeguard child health by supplying safe drinking water at educational institutions lacking adequate resources for treatment and contaminant removal.

3.6. Water quality index (WQI)

The WQI is an effective methodology for evaluating overall supply potability for human consumption based on key physicochemical and biological parameters (Asomaku, 2023; Talpur et al., 2020). Computed WQIs were mapped across the studied area Fig. 4 and ranked across

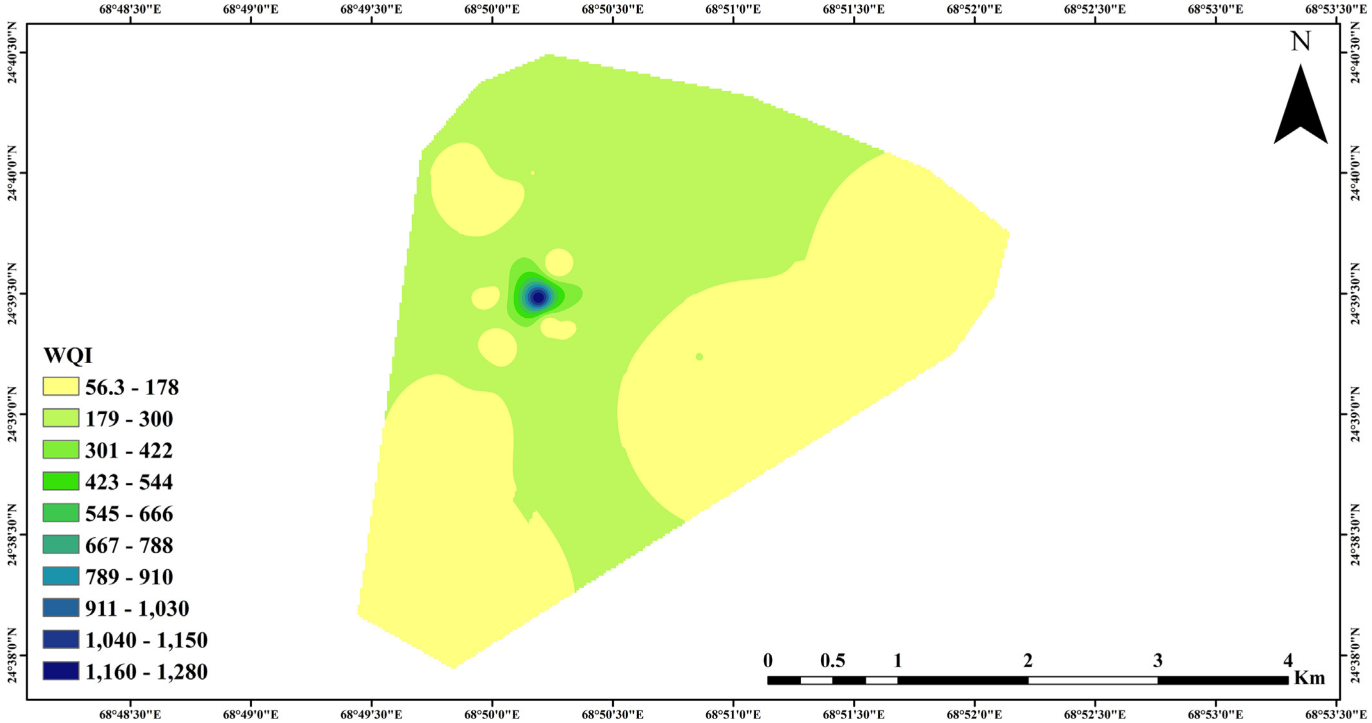


Fig. 4. WQI for water samples collected from the selected schools in Badin City.

five quality designations as follows: excellent (<50), good (50–100), poor (100−200), very poor (200−300), and unsuitable for drinking (>300) (Kumar et al., 2024; Rahman and Habiba, 2023). Susceptibility to waterborne diseases rises with higher WQIs (Ali and Ahmad, 2020).

However, of the 20 composite samples analyzed from public ($n = 8$), private (n = 8), and religious ($n = 4$) schools, among them 3 public, 3 private and 1 religious school supplied "good quality" water per WHO guidelines (World Health Organization, 2011). Two public, 1 religious, and 5 private schools provided "poor quality water" exceeding acceptable limits for certain parameters. Three public schools, 2 religious' schools, and no private schools exhibited "very poor-quality water". Alarmingly, 30% of samples demonstrated high WQIs indicating urgent mitigation to prevent student health risks.

3.7. Possible microbial health risks

The spatial distribution of microbial contaminants across the sampling sites highlights the alarming degree of drinking water contamination in Badin City Fig. 5. High levels of T.C., F.C., and *E. coli* were detected, posing severe health risks, especially for children. A previous study demonstrated that poor drinking water quality increases the risk of waterborne infections and diseases (Miraji et al., 2023). This is particularly concerning in developing regions like Badin, where drinking water treatment and sanitation infrastructure is often inadequate.

Badin lacks proper wastewater treatment and solid waste management systems (Talpur et al., 2020). As a result, untreated sewage and waste frequently contaminate local water sources. This contamination can promote the spread of infectious diseases, including hepatitis A/E, diarrhea, typhoid, and gastroenteritis. Our findings reveal severe microbial contamination across all sampled sites, with 100% testing positive for T.C. and F.C. and 45% positive for *E. coli*. This indicates a high risk of waterborne disease for residents, especially school children who lack access to safer drinking water alternatives. Religious schools appear to be the most vulnerable on this front.

With poverty levels high in Badin, providing children with bottled water on a regular basis poses financial challenges for most families. Children under 5 years old face the most significant health risks if they consume unsafe water over extended periods. Diarrheal diseases attributed to poor water and sanitation are responsible for nearly 10% of deaths in this age group worldwide (Malebatja and Mokgatle, 2023). The 2019 Prüss-Ustün et al. study shows that in 2016, inadequate WASH contributed to 829,000 diarrheal deaths (60% of all cases) and was especially severe among children under 5, causing 297,000 deaths (5.3% of deaths in this group). Overall, WASH deficiencies resulted in 1.6 million deaths and 104.6 million DALYs globally, underscoring their significant effect on health, especially in young children. (Prüss-Ustün et al., 2019). Inadequate hygiene practices in local schools further exacerbate this public health threat (Shehmolo et al., 2021). Therefore, failure to address Badin's drinking water contamination could jeopardize the health and lives of many children in these communities. Implementing safety measures to provide access to clean and safe drinking water is imperative.

3.8. Recommendations

1. Implement a regular water monitoring program that collects and tests samples across Badin, particularly during rainy seasons when contamination risks are higher. Repair leaking pipes on an urgent basis before the next rainfall. Construct water treatment plants that filter and purify canal/river supply prior to distribution.
2. Invest in upgrading sewage and waste management systems across Badin. Construct modern wastewater treatment plants with the capacity to treat all industrial and urban effluents to meet environmental discharge standards before release. This will significantly reduce the pollution of local water bodies.
3. Develop public health education programs that raise awareness on the prevention of waterborne illnesses, safe hygiene practices, and household water treatment options. Schools and colleges would be ideal venues for workshops and disseminating pamphlets to the broader community.

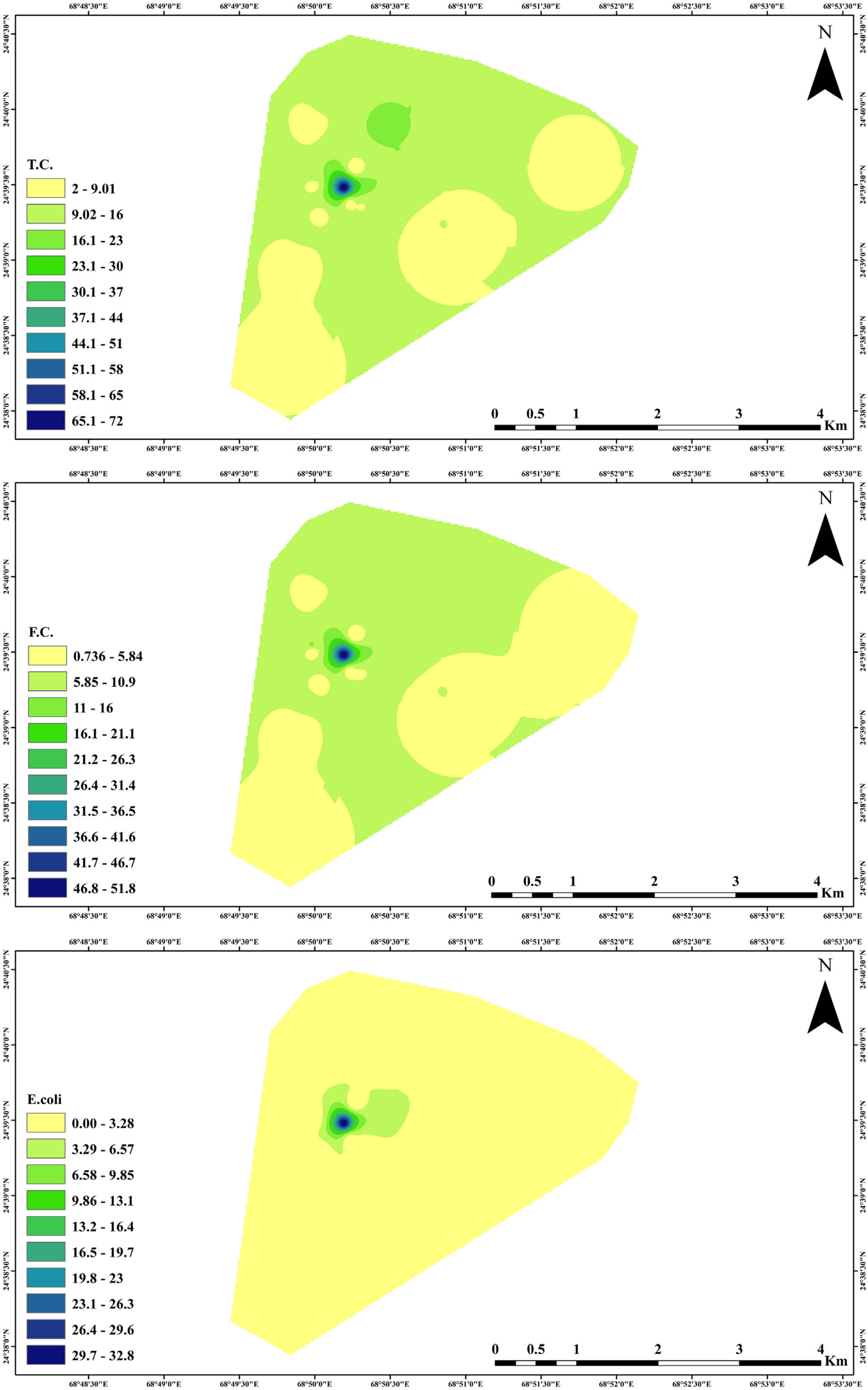


Fig. 5. Interpolation of T.C., F.C., *E.coli*. Contaminants in drinking water samples from selected schools in Badin city, including.

4. Provide grants and subsidies to install small-scale water purification systems, including filters, solar disinfection units, and chlorine tablets, in schools and households lacking access to safe municipal water. Increase budget allocation for water and sanitation infrastructure - an integral long-term investment.
5. Enforce stronger anti-pollution regulations on industries, setting definite effective limits and penalties for violations. Commission further investigative studies on Badin's surface and groundwater resources, identifying pollution hotspots and quantifying environmental and health impacts. In addition, encourage collaboration among government agencies, non-governmental organizations, and local communities to effectively implement the proposed measures and ensure the sustainability of interventions.

4. Conclusion

In this comprehensive study of drinking water quality in public, private, and religious schools across Badin City, Pakistan, our analyses present concerning data on microbial contamination levels. The study highlights the detection of T.C. and F.C., in each sample and *E. coli* in 55% of water samples, respectively. Notably, the levels of these contaminants significantly exceeded WHO guidelines, underlining a critical public health issue. Religious schools were found to have the highest contamination levels, followed by public and private institutions. The PLI further underscored the severity of contamination, with over 75% of samples exceeding safe limits for all microbial indicators. Specifically, the PLI for T.C. ranged from 1.0 to 36.0 (mean of 5.5), for F.C. from 0.9 to 74.0 (mean of 9.9), and for *E. coli* from 0 to 33 (mean of 2.2). This widespread contamination presents a substantial risk of waterborne diseases, particularly among children in the studied schools. WQI assessment revealed that 30% of water samples were classified as 'very poor', with none achieving an 'excellent' rating, indicating the urgent need for remediation. This study shows that the drinking water supplied to the selected schools poses significant health risks, particularly gastroenteritis, due to microbial contamination. It further reveals the urgent need for action to improve the poor drinking water quality in the schools of Badin city. Highlighting significant health concerns and contamination sources, it stresses the importance of immediate infrastructure upgrades, education, and public awareness to secure safe water for students and the wider community. The findings of this study have the potential to significantly impact water quality management and public health in Badin city and similar regions. Implementing the recommended measures can reduce waterborne diseases, improve quality of life, and contribute to the global effort to ensure access to safe drinking water.

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CRediT authorship contribution statement

Hafeez Ahmed Talpur: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Shakeel Ahmed Talpur:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Amanullah Mahar:** Supervision, Project administration. **Gianluigi Rosatelli:** Writing – review & editing. **Muhammad Yousuf Jat Baloch:** Writing – review & editing. **Aziz Ahmed:** Writing – review & editing, Visualization, Validation, Software, Resources. **Aqib Hassan Ali Khan:** Writing – review & editing, Writing – original draft, Validation, Software.

Declaration of competing interest

All the authors declared no competing interest.

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