



ENVIRONMENTAL STRESSORS AND BIOLOGICAL RESILIENCE IN FRESHWATER ECOSYSTEMS: INTEGRATING WATER QUALITY, MICROBIAL DIVERSITY, AND ECOLOGICAL RESPONSES

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ABSTRACT

Freshwater ecosystems are increasingly affected by interacting physicochemical pressures and microbial contamination, creating a need for integrated approaches to environmental assessment. This research evaluated water-quality conditions and microbial responses across rivers, canals, ponds, and lakes using 120 freshwater monitoring records collected between 2021 and 2023. Temperature, dissolved oxygen (DO), pH, conductivity, biochemical oxygen demand (BOD), nitrate-N, fecal coliform, and total coliform were assessed using descriptive statistics, temporal and water-body comparisons, and Spearman correlation analysis. Mean DO was 6.66 ± 1.73 mg/L, while median fecal and total coliform concentrations were 397.5 and 824 MPN/100 mL, respectively. Median DO decreased from 8.70 mg/L in 2021 to 6.22 mg/L in 2023, whereas total coliform increased from 95 to 1,065 MPN/100 mL. Rivers exhibited the highest median DO, while lakes recorded the highest median microbial indicators. Total coliform was positively associated with BOD ($\rho = 0.458$) and temperature ($\rho = 0.380$) and negatively associated with DO ($\rho = -0.362$) and pH ($\rho = -0.587$). These findings demonstrate the value of combining physicochemical and microbial indicators to identify environmental stress patterns and strengthen freshwater monitoring and ecological assessment.

Keyword: Freshwater ecosystems, Water quality, Environmental stressors, Microbial indicators, Ecological monitoring

Introduction

Freshwater ecosystems supply aquatic biodiversity, nutrient cycling, food production, and a variety of ecosystem services vital to humans. Rivers, lakes, ponds and associated surface waters, in spite of their ecological relevance, are now increasingly subject to various anthropogenic and natural pressures that are interacting with each other. Freshwater environments can undergo changes in their physical, chemical and biological attributes due to urbanization, agricultural runoff, wastewater discharge, nutrient enrichment and hydrological changes. The pollution of the river, in particular, is important due to the fact that pollutants can alter the habitat conditions and the ecology functioning in interconnected aquatic systems (Chakraborty, 2021). Furthermore, freshwater degradation is often caused by a combination of stressors, which may be natural or human-induced, and can have complex ecological impacts (Bănăduc et al., 2024).

Water quality is thus a valuable indicator of environmental stress, and condition of freshwater ecosystems. Physicochemical parameters (temperature, pH, dissolved oxygen (DO), conductivity, biochemical oxygen demand (BOD) and nutrient concentrations) represent various aspects of aquatic environmental quality. They can indicate oxygen depletion, organic enrichment, nutrient pressure, changes in the chemical nature of aquatic habitats, and their interpretation can show these. Water-quality assessment has now become a part of ecological monitoring and environmental management, which is different freshwater environments (Morsy et al., 2020; Perveen, 2023). However, traditional water quality assessments come with methodological restrictions, especially because they can simplify complex environmental situations to a few indicators or into an overall value which does not necessarily reflect ecological impacts (Mikosch et al., 2021).

Biological and microbiological indicators can be used in addition to the physicochemical assessment to give insights into contamination and biological reactions to the environment. The monitoring of bio-indicators is growing in importance as a biological tool for detecting pollution and environmental disturbance as changes occurring in biological characteristics may also reflect environmental pressures not adequately understood based on chemical monitoring alone (Sangwan et al., 2024). Fecal and total coliforms continue to be important indicators of contamination in microbial assessments of water quality. But, microbial indicators should be interpreted with care as they may be affected by environmental factors, contamination sources and methodological factors (Holcomb & Stewart, 2020). The ongoing evolution of traditional and novel microbial indicators also highlights the need for microbiological data to be included in environmental monitoring programmes (Choix et al., 2023).

The correlation between the physicochemical conditions and the microbial pollution is of special significance for an integrated assessment of the freshwater. Environmental variables may affect the detection, survival and distribution of microorganisms in the aquatic environment, as well as the microbial processes. Weather, physicochemical water quality and microbial conditions all interact, and changes in the detection of pathogens have been correlated with these factors, suggesting that microbial

contamination is not always fully understood without considering the environmental context (Weller et al., 2020). Likewise, a combination of physical parameters and fecal indicator bacteria can enhance the understanding of surface-water contamination and possible sources (Tagar et al., 2025). Further investigations have also shown their usefulness in discriminating the water quality conditions in groundwater, surface water and wastewater systems when combined with physicochemical parameters (Debassi et al., 2025).

Such integration is also vital as the quality of fresh water varies both in time and space. Aquatic systems can be quite different depending on the differences in land use, human activity, hydrology, and pollution inputs. The results of studies carried out in tropical karstic areas, for instance, illustrate the importance of surrounding land use for water-quality management and highlight the need to take the environmental context into account when reading the aquatic situation (Marisa et al., 2024). The capacity for monitoring, environmental governance, and public policy responses are also crucial at the community level for effective microbial water-quality management (Anekwe et al., 2025). Thus, it is likely that the simultaneous consideration of combinations of physico-chemical stress and microbial contamination can also be more instructive evidence for environmental management than the consideration of each factor alone.

A focus is therefore growing on indicators that can be integrated to connect ecosystem condition with potential impacts to ecological and human health. Two ways to link environmental condition to more pervasive health risks are aquatic ecosystem indices, though appropriate indicator selection and interpretation are important (De Carvalho et al., 2025). Yet, simple analytical tools to collectively describe physicochemical stressors, microbial indicators, temporal variability and variability between freshwater systems are still needed. These types of analyses help to determine environmental conditions that are related to increased microbial contamination and negate the assumption that individual water-quality variables reflect overall ecosystem conditions.

In this context, the goals of this research were: to describe the temporal and water-body variation of the physicochemical and microbial conditions within freshwater ecosystems; to quantify the relationships between the major environmental stressors and the fecal and total coliform microbial indicators; and to characterize patterns of integrated environmental stress and microbial response pertinent to freshwater ecological assessment. The analysis integrates physicochemical and microbial measurements to give a comprehensive picture of the condition of freshwater environments and can aid in targeting conditions that may need more attention in monitoring and management.

2. Materials and Methods

2.1 Study Design and Data Source

The design of analysis was secondary data analysis for the environmental stress and microbial responses in freshwater systems from 2021–2023. For the purposes of analysis only freshwater forms, such as rivers, canals, ponds and lakes were considered and 120 freshwater records were eligible (Chitloor, 2025). Monitoring records of non-freshwater and wastewater were not included, so as to keep the monitoring records ecologically relevant.

2.2 Environmental and Microbial Indicators

Environmental conditions were evaluated based on the temperature, dissolved oxygen (DO), pH, conductivity, biochemical oxygen demand (BOD), and nitrate-N concentrations; while the microbial conditions were evaluated based on the concentration of fecal coliform and total coliform. Due to missing measurements, the number of valid observations by parameter was different.

2.3 Data Preparation

Data records were checked for eligibility, missing values, numerical consistency and extreme data. A variable-specific complete case approach was implemented for available measurements. Microbial counts and some environmental parameters were highly skewed, so medians were highlighted in the comparisons between water-bodies and time periods.

2.4 Statistical Analysis

Mean, standard deviation, median, minimum and maximum were used as descriptive statistics. The temporal differences were evaluated between 2021–2023, and the freshwater systems were evaluated between rivers, canals, ponds and lakes. Because distributions of the concentrations of fecal coliform and total coliform were non-normal, relationships among the concentrations and the various physicochemical stressors were quantified with Spearman rank correlation.

2.5 Statistical Software and Visualization

All the analyses were conducted in Python, where pandas/NumPy were used for data processing, SciPy was used for statistical testing and Matplotlib was used for visualization. Boxplots, temporal profiles and a correlation heatmap were created to illustrate patterns of the environment and the microbes. Two-sided tests were used for statistical significance with a p-value of < 0.05 .

3. Results

3.1 Physicochemical and Microbial Characteristics

The physicochemical and microbial characteristics are discussed in this section. 120 freshwater records (rivers, canals, ponds and lakes) were examined. As seen in Table 1, the mean dissolved oxygen (DO) was 6.66 ± 1.73 mg/L, the biochemical oxygen demand (BOD) was 3.88 ± 6.91 mg/L, the median counts for fecal coliforms and total coliforms were 397.5 and 824 MPN/100 mL, respectively, and the microbial

indicators were highly variable. The distribution of pH and DO are relatively stable, whereas BOD, conductivity, and microbial contamination are highly variable as shown in figure 1.

Table 1. Descriptive Characteristics of Physicochemical and Microbial Indicators

Indicator	n	Mean $\pm$ SD	Median	Range
Temperature ($^{\circ}$ C)	118	23.83 $\pm$ 5.00	25.00	11.45–31.00
DO (mg/L)	118	6.66 $\pm$ 1.73	6.70	0.70–9.55
pH	120	7.48 $\pm$ 0.39	7.40	6.50–8.40
Conductivity (μ mho/cm)	106	785.75 $\pm$ 2,577.76	240.00	92–23,344
BOD (mg/L)	102	3.88 $\pm$ 6.91	2.30	1.00–51.50
Nitrate-N (mg/L)	105	1.60 $\pm$ 1.61	1.12	0.30–9.90
Fecal coliform (MPN/100 mL)	104	70,725.74 $\pm$ 688,851.44	397.50	2–7,024,500
Total coliform (MPN/100 mL)	105	75,485.31 $\pm$ 722,224.70	824.00	2–7,395,000

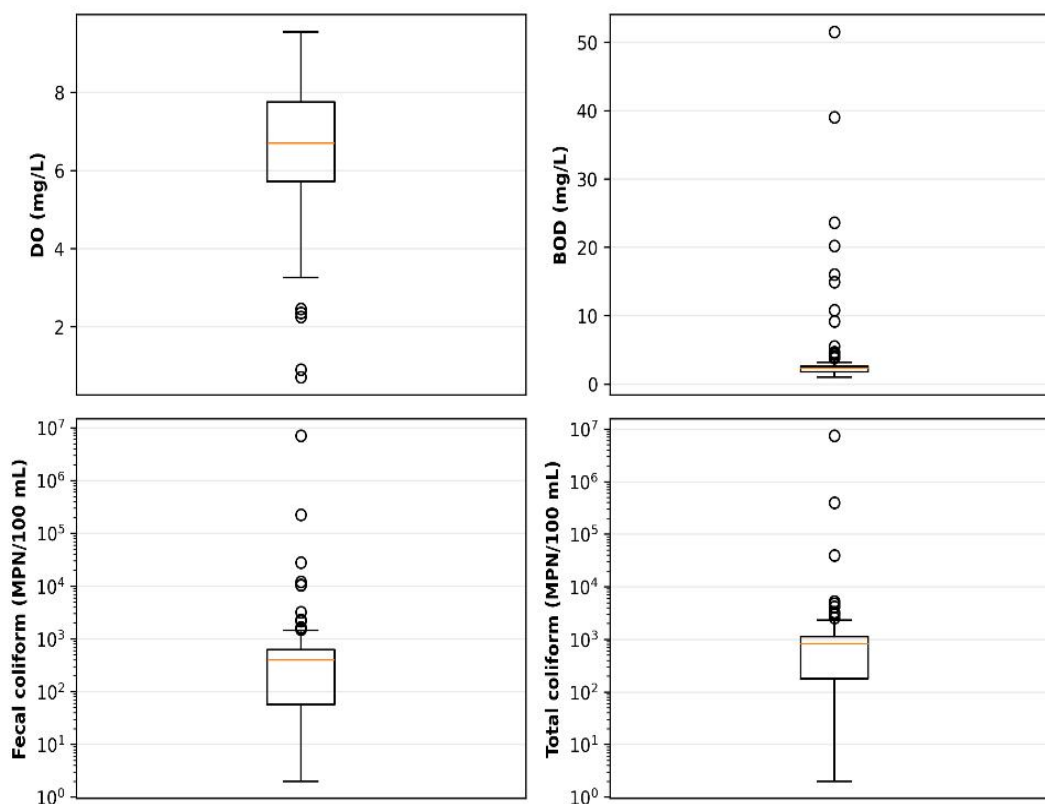


Figure 1. Distribution of Physicochemical and Microbial Indicators in Freshwater Systems

3.2 Temporal and Water-Body Variation

The temporal changes of freshwater are evident in Table 2. Median DO declined from 8.70 mg/L in 2021 to 6.22 mg/L in 2023, while BOD increased from 1.00 to 2.35 mg/L. Total coliform also increased from 95 to 1,065 MPN/100 mL. Least median DO was found in lakes and the highest median fecal coliform and total coliform counts were found in lakes, with the highest median concentration in rivers. The temporal contrast of oxygen conditions, organic load and microbial contamination are shown in Fig. 2.

Table 2. Temporal and Water-Body Variation in Key Freshwater Indicators

Group	DO	BOD	Nitrate-N	Fecal coliform	Total coliform
2021	8.70	1.00	1.00	332.50	95.00
2022	7.70	2.25	1.60	38.50	245.00
2023	6.22	2.35	1.10	460.00	1,065.00
River	7.80	1.68	1.22	115.00	169.00
Canal	5.98	2.72	0.95	25.50	312.50
Pond	6.58	2.35	1.10	460.00	1,060.00
Lake	5.65	2.35	1.17	475.00	1,112.50

Values are medians; DO, BOD, and nitrate-N are expressed in mg/L, and coliform concentrations in MPN/100 mL.

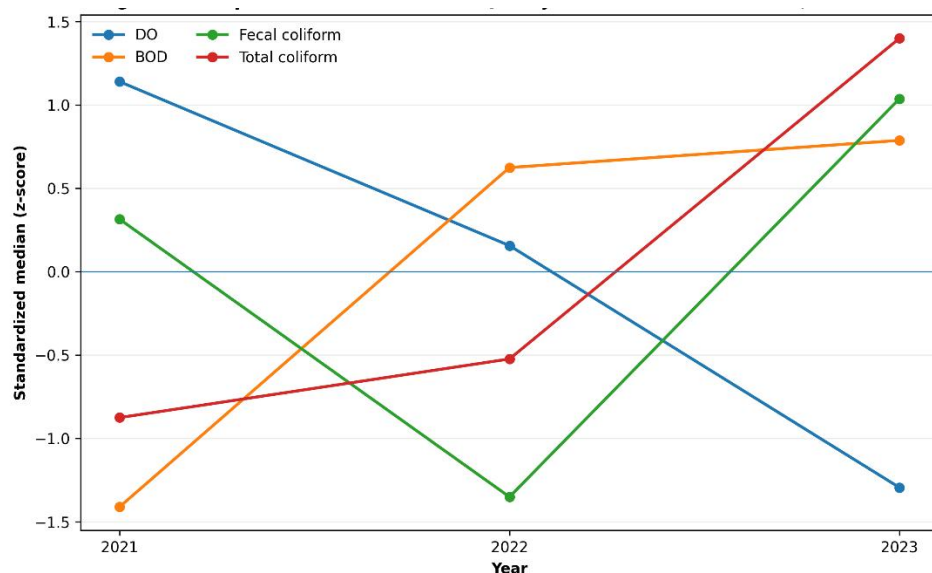


Figure 1. Distribution of Physicochemical and Microbial Indicators in Freshwater Systems

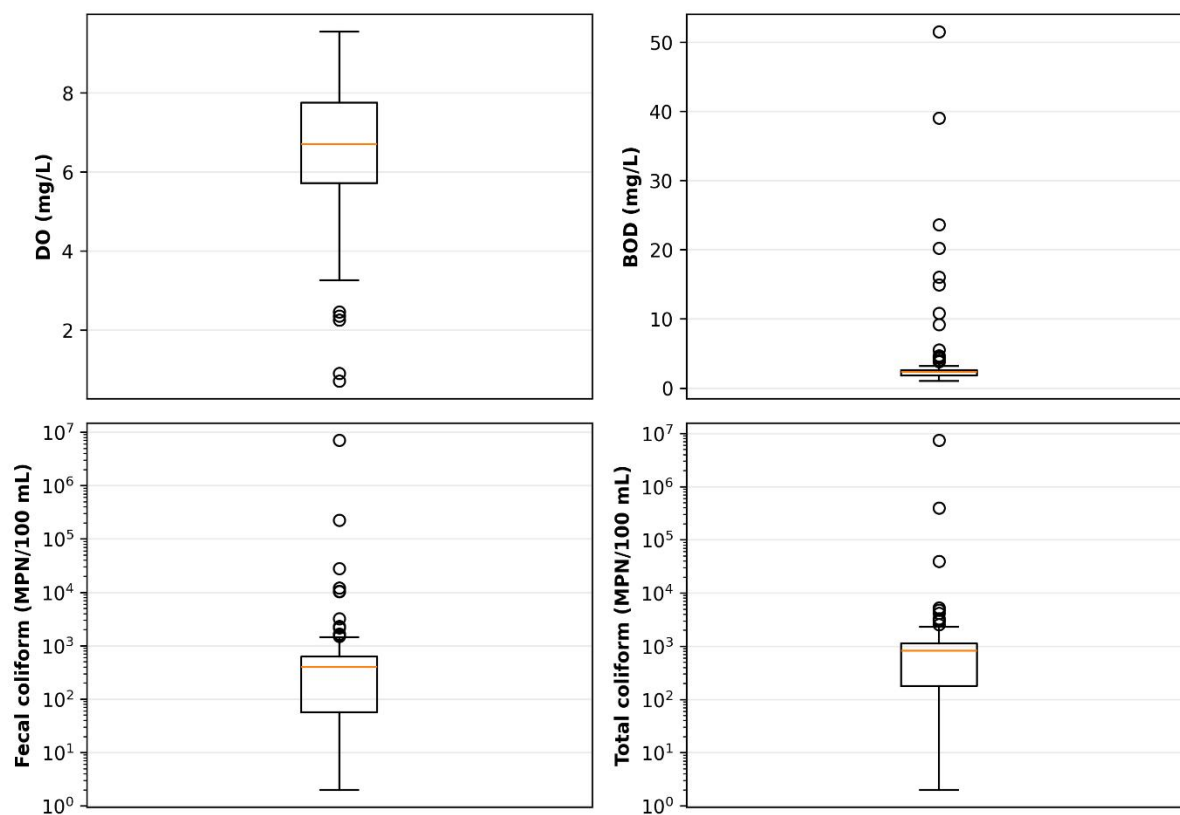


Figure 2. Temporal Variation in Water Quality and Microbial Indicators, 2021–2023

3.3 Environmental Stressor–Microbial Relationships

Table 3 shows that total coliform was positively associated with BOD ($\rho = 0.458$, $p < 0.001$) and temperature ($\rho = 0.380$, $p < 0.001$), but negatively associated with DO ($\rho = -0.362$, $p < 0.001$) and pH ($\rho = -0.587$, $p < 0.001$). Fecal coliform was negatively associated with pH ($\rho = -0.411$, $p < 0.001$) and

nitrate-N ($\rho = -0.242$, $p = 0.014$). The overall correlation structure (Figure 3) indicates that pH and BOD have the highest correlation with microbial contamination.

Table 3. Spearman Correlations Between Environmental Stressors and Microbial Indicators

Indicator	Fecal coliform ρ	p-value	Total coliform ρ	p-value
Temperature	0.099	0.322	0.380	<0.001
DO	0.015	0.883	-0.362	<0.001
pH	-0.411	<0.001	-0.587	<0.001
Conductivity	-0.057	0.564	-0.247	0.011
BOD	0.043	0.688	0.458	<0.001
Nitrate-N	-0.242	0.014	0.026	0.796

Bold values indicate $p < 0.05$.

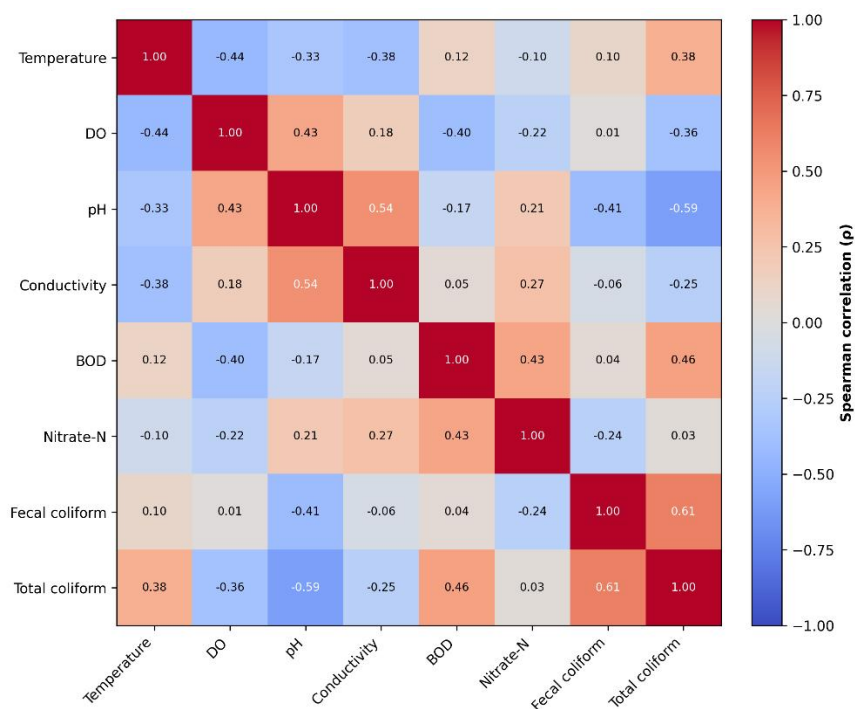


Figure 3. Correlation Heatmap of Environmental Stressors and Microbial Indicators

4. Discussion

Results show significant inter-site variations in the environmental conditions in the freshwater system, especially with respect to BOD, conductivity and microbial parameters. The overall mean dissolved oxygen was relatively high, but varied from 0.70 to 9.55 mg/L with significant differences in oxygen levels between monitoring records. BOD was quite variable and highest value was 51.50 mg/l in the

highly stressed observations. This heterogeneity is in line with the knowledge that the freshwater systems face different pressures from organic pollution, nutrient enrichment, hydrological alteration and other anthropogenic pressures (Bănăduc et al., 2022). The results thus highlight the need for multiple environmental indicators to be considered when assessing the condition of freshwater.

Temporal trends showed a decrease in median DO from 8.70 mg/L in 2021 to 6.22 mg/L in 2023, while BOD median increased from 1.00 to 2.35 mg/L in 2023. The median level of total coliform also significantly increased to 1,065 MPN/100 mL in 2023. The patterns, which occurred concurrently, suggest changes in oxygen conditions, organic loading, and microbial contamination over time, but do not necessarily signify a causal change. Microbial interactions can be altered by environmental stress and microbial networks can be destabilized, impacting ecological functioning (Hernandez et al., 2021). Climate-induced environmental perturbations could also affect the dynamics of the microbial community due to effects on temperature, hydrology, nutrient fluxes, and contaminant release (Huang et al., 2025).

Variations among the freshwater systems were also observed. The median DO was highest in rivers and the median BOD was relatively low in rivers, while the median concentration for fecal coliforms and the total coliforms was highest in lakes. There was also a higher level of microbial contamination in ponds. These differences could be explained by variation in hydrological characteristics, residence time, environmental conditions and pollution inputs of the different types of water bodies. This diversity in the nature of the habitat should help promote freshwater-management that considers the nature of the habitat instead of applying a single interpretation in and across aquatic systems. Incorporating ecosystem health into water-resource management is critical to sustain freshwater ecosystem functions while also using water resources sustainably (Bogardi et al., 2020).

The correlation analysis also revealed that the microbial indicators were related to certain physico-chemical conditions. The results of the study showed that the total coliform was positively correlated with BOD ($\rho = 0.458$) and temperature ($\rho = 0.380$) and negatively correlated with DO ($\rho = -0.362$) and pH ($\rho = -0.587$). The BOD relationship shows that as the organic load increased, the microbial contamination was also higher, and the DO relationship shows that as the total coliform concentration increased, there was a lower DO concentration when compared. The changes in physicochemical environment can significantly affect microbial communities, altering their composition, activity, and interactions in the environment (Kumar et al., 2024). Microbial network organization and stability can also be influenced by environmental stress (Hernandez et al., 2021).

The temperature significantly related with total coliform, but not with fecal coliform, which shows that the responses of the different microbial indicators were not the same. Stress conditions in the environment can cause different responses in the different groups of microorganisms, depending on the conditions of exposure and the physiology of the microorganism (Mohammad et al., 2025). The relationship of pH with both the microbial indicators was negative which also implies that the microbial contamination took place

within a general physicochemical context. These results corroborate the use of integrated monitoring over interpretation of microbial results in the absence of the surrounding environmental conditions.

Combining physicochemical and microbiological indicators to provide a more informative framework for freshwater assessment. Environmental conditions are represented by conventional water-quality variables while microbial indicators are used to indicate biological evidence of contamination. The microbial approach has consequently become increasingly important for monitoring ecological conditions in aquatic environments as microorganisms are able to react quickly to an environmental disturbance (Codello, 2021). Such assessments can be complemented by powerful molecular methods that can reveal shifts in communities or functions of microorganisms in response to environmental stresses, such as wastewater (Esser, 2025).

Concentrations of fecal coliforms and total coliforms, however, should be used as an indicator of microbiological diversity and/or resilience. They are not used to describe the taxonomic diversity, composition or functional diversity of the community or interaction networks among microbes. The use of molecular microbial data in future with the traditional water-quality data would therefore help to better assess biological responses. Biodiversity indicators may also help to link environmental pressures to changes in larger biological communities, and thus to better assessment of environmental condition (De Mello et al., 2025).

The results also have practical applications to freshwater monitoring as the pH, BOD, DO and temperature proved to have significant relationships to microbial contamination. Combining these easily monitored parameters with the microbial parameters may be useful for determining when more detailed environmental monitoring is warranted. A systematic approach to integrating ecological and geographical information can enhance environmental risk assessment and management decisions (Sarker, 2025). These are in line with other more general conservation solutions for freshwater ecosystems that focus on a coordinated approach to the management of environmental pressures, ecological risk, and sustainable utilization of the resources (Bănăduc et al., 2022).

However, there are certain limitations which must be taken into account. Secondary observational data, which have different availability of individual parameters, were used for the analysis and are not suitable for causal relationships. There were no direct indicators of aquatic biodiversity and/or habitat quality or land use, wastewater discharge, rainfall and/or hydrological conditions, and coliform measurements represented microbial contamination, rather than complete microbial community structure. Future research should integrate physicochemical data with microbial sequencing, functional profiling, biodiversity data, and spatial and hydrological data. Such integration would allow the direct assessment of biological response to environmental stress, and would provide more evidence for freshwater ecosystem management and conservation (Bogardi et al., 2020; De Mello et al., 2025; Esser, 2025).

5. Conclusion

The rivers, canals, ponds and lakes examined had significant differences in the physicochemical quality and microbial contamination of the freshwater. Dissolved oxygen changed from a median of 8.70 mg/L in 2021 to 6.22 mg/L in 2023, and BOD and total coliform have increased from 2021 through 2023, suggesting simultaneous shifts in the availability of dissolved oxygen, amount of organic loading, and microbial pressure. The oxygen levels in the rivers were relatively better with higher microbial contamination levels in the lakes and ponds. Microbial contamination was highly correlated with the underlying physicochemical conditions as evidenced by the positive relationship between total coliform and BOD and the negative relationship between total coliform and dissolved oxygen and pH. The results favor the use of microbial indicators in combination with traditional water-quality parameters for freshwater monitoring, and not just for the evaluation of one parameter alone. But coliform levels are only indicators of contamination and not an actual assessment of microbial diversity or ecosystem resilience. Future monitoring should include microbial community profiling, biodiversity, hydrological characteristics, and land use information to allow for a more holistic assessment of biological responses and ecological condition.

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