Assessment of some water quality parameters of Kaptai lake, Bangladesh: a multivariate analysis

Muhammad Sher Mahmud[1] (ID), Sajal Roy[1]* (ID), Kazi Md. Barkat Ali[2] (ID)
and Md. Aktaruzzaman[1] (ID)

A B S T R A C T

The current research was conducted to assess some key water quality parameters of Kaptai Lake (KL). To do this, water samples were collected from seventeen sites in the month of March, followed by laboratory assessment and multivariate analyses. The results revealed that pH, electrical conductivity (EC), temperature, dissolved oxygen (DO), biological oxygen demand (BOD), free carbon di-oxide (CO_2), bi-carbonate (HCO_3^-), chloride (Cl^-), and calcium (Ca^{2+}) varied with the range of 6.58-7.84, 111-127 µS/cm, 25- 26 °C, 9.10-10.20 mg/L, 2.0-5.90 mg/L, 88-180 mg/L, 214-390 mg/L, 89-231 mg/L and 0.25- 0.54 mg/L with mean values of 7.50, 117 µS/cm, 25.36°C, 9.64 mg/L, 4.02 mg/L, 139.06 mg/L, 295.71 mg/L, 159.18 mg/L and 0.31 mg/L, respectively. Water quality parameters exhibited diverse distributions and variability: pH was negatively (-1.49) skewed and EC was positively (1.23) skewed, while temperature and DO were approximately normally distributed with skewness of -0.07 and -0.04, respectively. The BOD, free CO_2, HCO_3^-, Cl^-, and Ca^{2+} showed moderate to high variability with skewness of -0.32, -0.29, 0.57, 0.13 and 2.40, respectively. The inverse distance weighted (IDW) interpolation of each parameter showed almost uniformity across the sampling sites. The hierarchical clustering dendrogram and correlation matrix heatmap revealed distinct groupings among variables: EC was correlated strongly with ionic constituents (HCO_3^-, Cl^-, Ca^{2+}), while BOD, free CO_2, and temperature were inversely correlated with DO and pH. Although most parameters meet the criteria for irrigation and fisheries, relatively high values of BOD at certain locations indicate local anthropogenic impacts. These results emphasize water quality across KL and highlight the need for mitigation measures to ensure sustainable aquaculture and irrigation practices.

Keywords: Dendrogram, Heatmap, Kaptai lake, Physico-chemical indices, Water quality

[1]*Department of Soil Science, University of Chittagong, Bangladesh*
[2]*Department of Geography and Environmental Studies, University of Chittagong, Bangladesh*

*Corresponding author's email: sajal.roy@cu.ac.bd (Sajal Roy)

Introduction

Water is a vital resource in the universe for the sustenance of all living creatures (Versari *et al.*, 2002). Only a small portion (less than 1.0%) of fresh water is accessible for human use in the world (Parvin *et al.*, 2022; Vasistha and Ganguly, 2020). Lakes, rivers, and man-made reservoirs are crucial surface water resources used extensively for domestic, industrial, agricultural, and fish culture purposes (Bhateria and Jain, 2016; Islam *et al.*, 2021; Rubel *et al.*, 2019). Water quality is referred to as the suitability of water in respect of chemical, physical, and biological characteristics. The parameters which reflect water quality include physical: temperature, turbidity, and total suspended solids (TDS); chemical: pH, electrical conductivity (EC), dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD), alkalinity, hardness,

and major dissolved nutrients; microbial: total count of organisms; toxicological; concentrations of heavy metals (Islam *et al.*, 2021; Omer, 2020; Karadeniz *et al.*, 2024).

Bangladesh is a riverine country and is criss-crossed by various large and small rivers and channels. Kaptai Lake (KL) is a major freshwater reservoir in Bangladesh formed by constructing a dam artificially at the site of the Karnaphuli river, primarily for hydroelectricity production in 1962 (Karmakar *et al.*, 2011). As a fresh water reservoir, KL is used for fisheries, tourism, municipal water supply and irrigation in surrounding agricultural lands, particularly in the dry season (Hoque *et al.*, 2021; Lima *et al.*, 2023). The water quality of major rivers and lakes is constantly threatened by deterioration due to natural processes and intensified human activities such as urbanization, industrial discharge, waste dumping, and agricultural runoff (Islam *et al.*, 2021; Karadeniz *et al.*, 2024; Rubel, *et al.*, 2019; Vasistha and Ganguly, 2020). Consequently, the assessment of water quality has become an important issue in recent years globally.

Bangladesh is highly exposed to water quality issues due to the quick development of urban and industrial areas, population pressure, and poor sanitation (Parvin *et al.*, 2022). The extensive network of rivers and other surface water bodies in Bangladesh suffers from widespread pollution, mostly from the discharge of untreated household and industrial wastes into water bodies (Islam *et al.*, 2021; Karmakar *et al.*, 2011). The properties of KL water are also continuously being changed because of a large number of natural and anthropogenic factors, including transport of nutrients from the catchment with heavy rain, input of effluents, thereby affecting aquatic life (Arafeen *et al.*, 2024). In previous studies, several researchers investigated the water quality of KL for its suitability assessment from a physico-chemical and toxicological perspective (Das *et al.*, 2024; Islam *et al.*, 2021). However, the use of multivariate approaches such as inverse distance weighted (IDW) interpolation, hierarchical clustering dendrogram, and correlation matrix heatmap to study the water quality of KL are very scarce in the existing literature. Considering the research gap, the key objective of the present research was to highlight the status of several key physico-chemical water quality parameters of KL through laboratory investigation coupling with multivariate analysis. Therefore, this research would help to visualize the spatial variability and relations among water quality parameters of KL, along with its suitability to take proper management measures to ensure sustainable use of KL water for aquaculture and irrigation purposes.

Materials and Methods

Study area

Kaptai Lake is the largest artificial freshwater lake in Rangamati District, Bangladesh. This lake lies between 22°22′–23°18′ N latitude and 92°00′–92°26′E longitude, experiencing with subtropical monsoon climate where the variations in rainfall and temperature significantly regulate the transport of sediments and nutrients from nearby catchment, affecting the aquatic ecosystem (Arafeen *et al.*, 2024; Das *et al.*, 2024). The area of KL varies depending on season, from approximately 48,300 ha during the dry season to 68,800 ha during the rainy season (Hoque *et al.*, 2021; Islam, 2019). The hydrological and physico-chemical behaviors of the lake are affected by the confluence of Kasalong, Maini, and Karnaphuli rivers (Chakma *et al.*, 2020).

Collection of water samples

Surface water was sampled from 17 sites across the KL in the month of March. The position of the sites from where water was collected is shown in Figure 1. An amount of approximately 500 ml of surface water was collected in plastic bottles for different physico-chemical analyses. After the collection of samples, some parameters were analyzed immediately at the sampling sites, while water samples were brought to the laboratory and preserved appropriately for further analysis of other parameters.

Analysis of water samples

Several parameters, such as pH, EC, temperature, and DO were measured at the time of sampling using a portable pH meter, EC meter, thermometer and DO meter, respectively. The level of BOD and free CO_2 in samples were determined following the standard methods as mentioned in Huq and Alam (2005). The concentration of Cl^- was measured by titration of samples against standard $AgNO_3$ after adding a few drops of $K_2Cr_2O_4$ with water, while the concentration of HCO_3^- was measured by titration of the samples against standard H_2SO_4 after adding 2-3 drops of methyl orange indicators (Gupta, 2001). The content of Ca^{2+} was measured by an atomic absorption spectrophotometer (AAS).
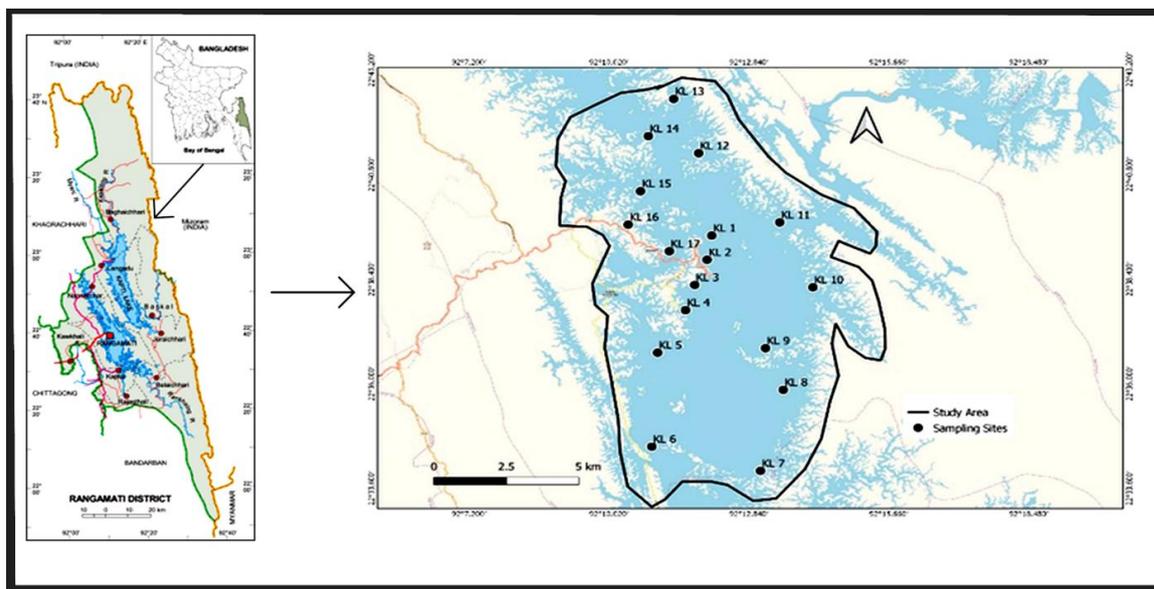
Fig. 1. Sampling sites of KL (right side).

Statistical analysis of data

Initially, measured data were processed and compiled using Microsoft Excel 2010. The descriptive statistics (range, mean, minimum, maximum, standard deviations and skewness) of each variable were calculated by Statistical Packages for Social Sciences (SPSS, version 16). The multivariate analyses, followed by visualization of the figures, were performed using R software (version 4.5.1).

Results and Discussion

Physico-chemical properties of KL water

The states of pH, EC, and temperature across the sampling sites of KL are given in Figure 2. The pH levels across the 17 sampling sites exhibited a range from 6.58 (at site 1) to 7.84 (at sites 8, 12, and 13),

with a mean value of 7.50 indicating neutral to slightly alkaline conditions. The result also showed that the values of the majority of sites clustered between 7.28 and 7.84. The EC values varied from 111 µS/cm (at site 14) to 127 µS/cm (at site 9), with a mean of 117.00 µS/cm, highlighting relatively consistent ion concentrations. The higher values at sites 9 (127 µS/cm), 10 (124 µS/cm), and 17 (121 µS/cm) potentially indicate elevated dissolved solids, whereas lower readings at sites 13 (114 µS/cm), 14 (111 µS/cm), and 15 (113 µS/cm) signify relatively lower ionic concentrations with little deviation among the sampling sites. The temperature values were also found with high uniformity across the sites. The temperature of water samples ranged from 25 °C (at most sites) to 26 °C (at sites 1, 5, 6, 8, and 9), with a mean of 25.36 °C.
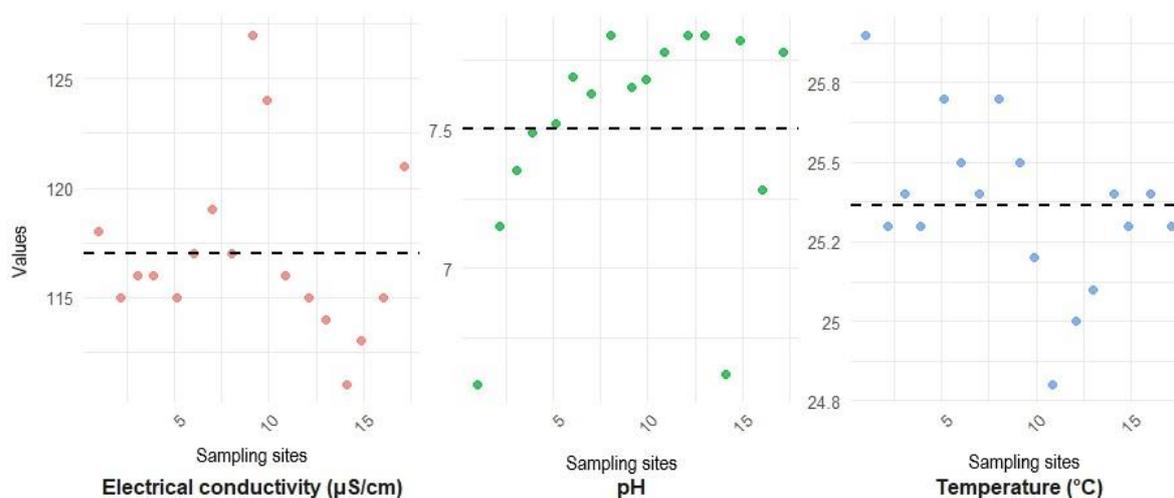

Fig. 2. The levels of EC, pH, and temperature of water samples of KL.

The concentrations of DO, BOD, free CO_2, HCO_3^-, Cl^-, and Ca^{2+} of KL water are shown in Figure 3. The values of DO showed low variability among the sampling sites. The concentrations of DO across the sampling sites ranged from 9.10 mg/L (at site 11) to 10.20 mg/L (at site 1), with a mean of 9.64 mg/L. The values of BOD showed slightly higher variability compared to DO across the sampling sites. The BOD levels varied from 2.0 mg/L (at site 7) to 5.90 mg/L (at site 14), with a mean of 4.02 mg/L. Free CO_2 concentrations ranged from 88.0 mg/L (at sites 2 and 12) to 180.0 mg/L (at site 3), averaging 139.06 mg/L. The levels of HCO_3^- ranged from 214.0 mg/L (at site 12) to 390.0 mg/L (at sites 2 and 15), with a mean of

295.71 mg/L. The concentration of Cl^- varied from 89.0 mg/L (at site 5) to 231.0 mg/L (at sites 2 and 14), averaging 159.18 mg/L, while the concentration of Ca^{2+} ranged from 0.25 mg/L (at sites 2, 6, and 11) to 0.54 mg/L (at site 14), with a mean of 0.31 mg/L. Figure 4 illustrates the spatial variability of key water quality parameters across the study area of KL, highlighting a visual basis for understanding the status of quality parameters. The spatial distribution of each variable is presented using a color gradient to indicate measured concentrations. Warmer colors (yellow/orange) signify upper values, while cooler colors (purple/blue) signify lower values.
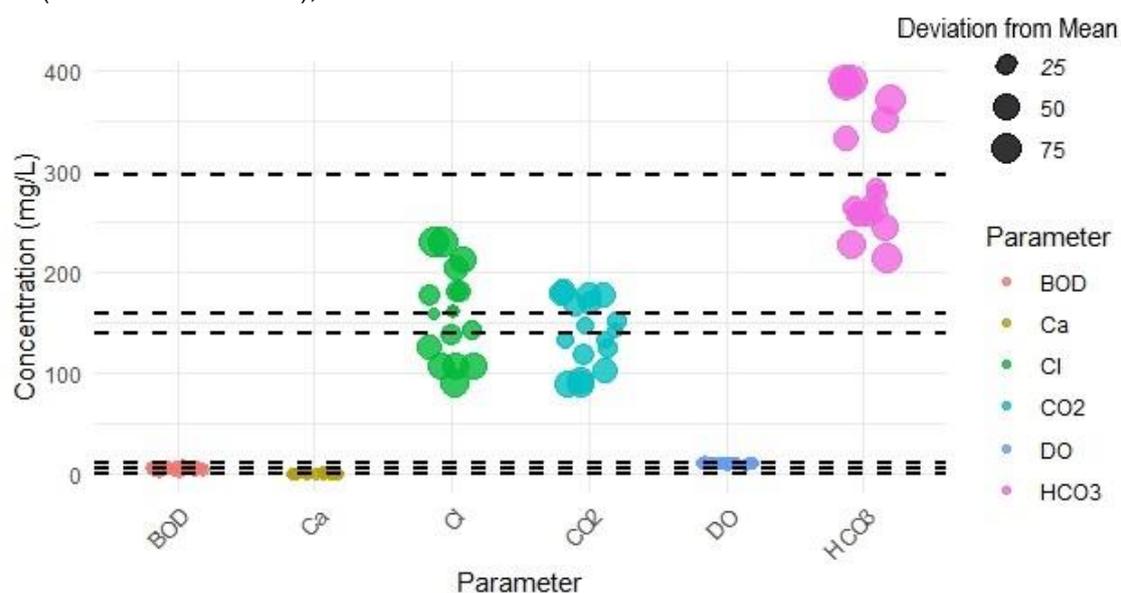

Fig. 3. Concentrations of some key water quality parameters of KL.

From the result, it is clear that pH showed the maximum relative variability, compared to EC and temperature. The higher variability in pH and EC of water samples could likely be due to site-specific influences, dissolved ions from agricultural runoff, industrial discharges, or mineral weathering (Johnson, 2022). On the other hand, remarkably uniform temperature was attributed to even exposure to sunlight and consistent sampling conditions. Smith (2023) also stated that the temperature of a water body is influenced by solar exposure or water flow variations. However, site-specific variations in values of water quality parameters likely arose from a mixture of natural processes and anthropogenic influences. Elevated levels of BOD could be ascribed to organic matter inputs through the disposal of domestic wastes, industrial effluents and intensified microbial activities in warm, favorable water temperature. Similar results were reported by

several authors (Bilal *et al.*, 2023; Zuthi *et al.*, 2020), where BOD was found higher than the expected level. The variations in free CO_2 and HCO_3^- could be due to the dissolution of CO_2 forming carbonic acid during the breakdown of organic wastes by microorganisms. Chloride spikes, such as 231.0 mg/L at sites 2 and 14, could also be linked to the discharge of household wastes or geological sources. Low Ca^{2+} levels may be due to the dilution effect or low mineral weathering and subsequent washing out from the catchment toward the lake. Several authors reported spatial as well as temporal influences on the concentrations of water quality indices of various rivers across Bangladesh (Roy *et al.*, 2020; Saifullah *et al.*, 2012; Uddin *et al.*, 2014). In a study on KL, Islam *et al.* (2021) found that the concentration of ions fluctuated depending on season with higher values in the dry season, and lower values in the wet season.
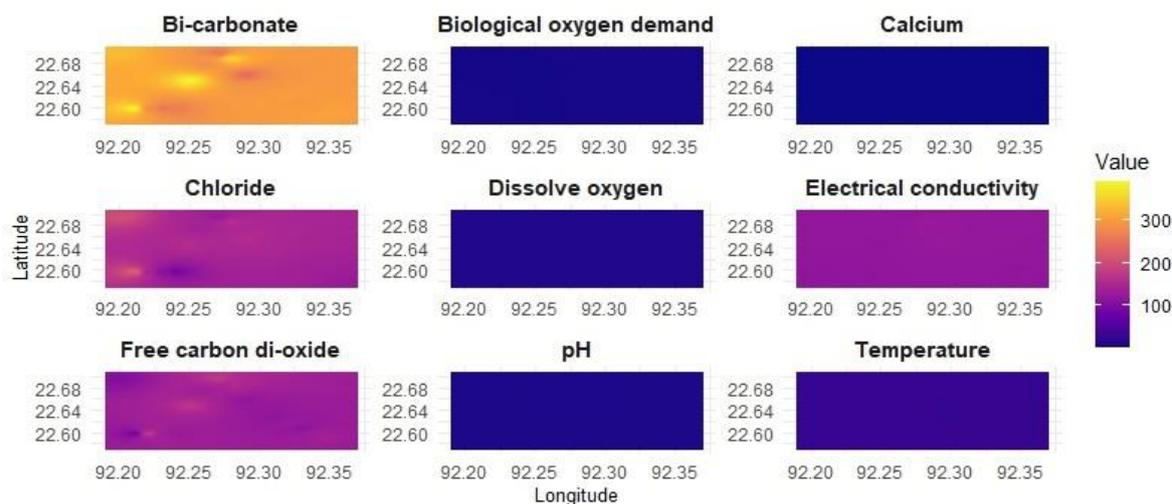
Fig. 4. Spatial variability of water quality indices across the study area of KL.

It is clear from the descriptive statistics given in Table 1 that the pH value showed a negative skewness (-1.49), whereas EC showed a positive skewness (1.23), indicating that most of the observations of pH were clustered at high levels and most of the samples had low EC values. Temperature exhibited an almost symmetrical distribution (-0.07), indicating that the temperature values were fairly normally distributed around the mean and had minimal deviation. The DO had a standard deviation of 0.34 mg/L and a slight skewness (-0.04), indicating an almost normal distribution and low variability. The BOD had a standard deviation of 1.15 mg/L, indicating a higher deviation than DO, while the negative skewness (-0.32) indicated a lower value tail. For free CO_2, the standard deviation was 33.08 mg/L and a slight negative skewness (-0.29) indicating some low outliers. As for HCO_3^- the standard deviation of 60.51 mg/L reflected significant variability, including a positive skewness (0.57). The low skewness (0.13) in the case of Cl^- indicated a symmetrical distribution. For Ca^{2+}, the standard deviation was 0.07 mg/L, indicating moderate relative variability and a strong positive skewness (2.40), indicating a high outlier effect at some sampling points, especially at site 14.

Table 1. Descriptive statistics of some key parameters of KL water.

Parameters	Range	Minimum	Maximum	Mean	Std. deviation	Skewness
pH	1.26	6.58	7.84	7.50	0.39	-1.49
EC (μS/cm)	16.00	111.00	127.00	117.00	3.95	1.23
Temp °C	1.10	24.80	25.90	25.36	0.26	-0.07
DO (mg/L)	1.10	9.10	10.20	9.64	0.34	-0.04
BOD (mg/L)	3.90	2.00	5.90	4.02	1.15	-0.32
Free CO_2 (mg/L)	92.00	88.00	180.00	139.06	33.08	-0.29
HCO_3^- (mg/L)	176.00	214.00	390.00	295.71	60.51	0.57
Cl^- (mg/L)	142.00	89.00	231.00	159.18	44.58	0.13
Ca^{2+} (mg/L)	0.29	0.24	0.54	0.31	0.07	2.40

The hierarchical cluster dendrogram (Figure 5) of water quality parameters revealed distinct clustering patterns. This clustering highlighted the correlations between acidity, conductivity, organic load, and mineral content as key factors shaping water quality dynamics. Overall, the patterns fell into two broad groups: pollution-related variables (temperature, BOD, free CO_2) that positively reinforced each other and negatively influenced oxygen and pH, in contrast to conductivity-driven factors that formed a tightly interconnected subgroup, potentially reflecting ionic concentrations. The correlation matrix heatmap revealed several key insights into the relationships among water quality parameters (Figure 6). Notably, strong positive correlations were observed between EC and ionic components such as HCO_3^-, Cl^- and Ca^{2+}, with deep red shading coefficients indicating likely values greater than 0.8. Similarly, BOD showed a strong positive correlation with temperature and free CO_2 (also deep red). On the other hand, DO showed a clear inverse correlation with temperature, BOD and free CO_2 (dark blue) with co-efficient less than -0.5. The pH also showed a strong positive correlation with DO but negative correlations with temperature, BOD, and CO_2.
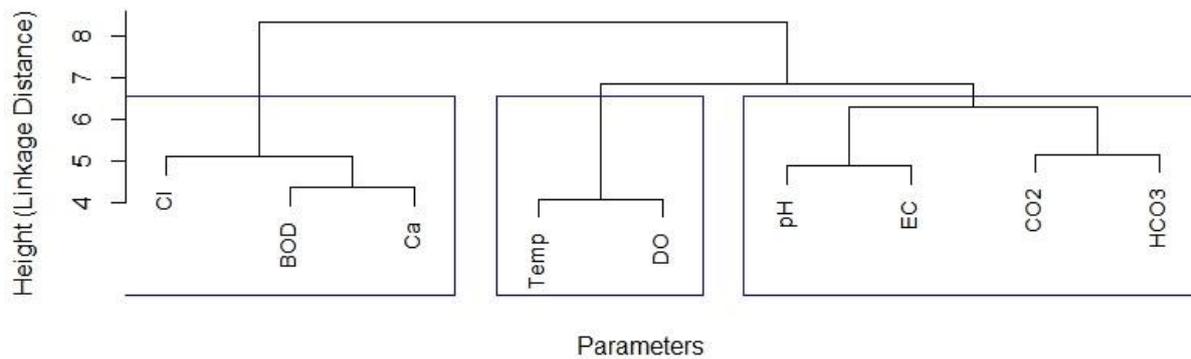
Fig. 5. Hierarchical cluster dendrogram of key water quality parameters of KL.
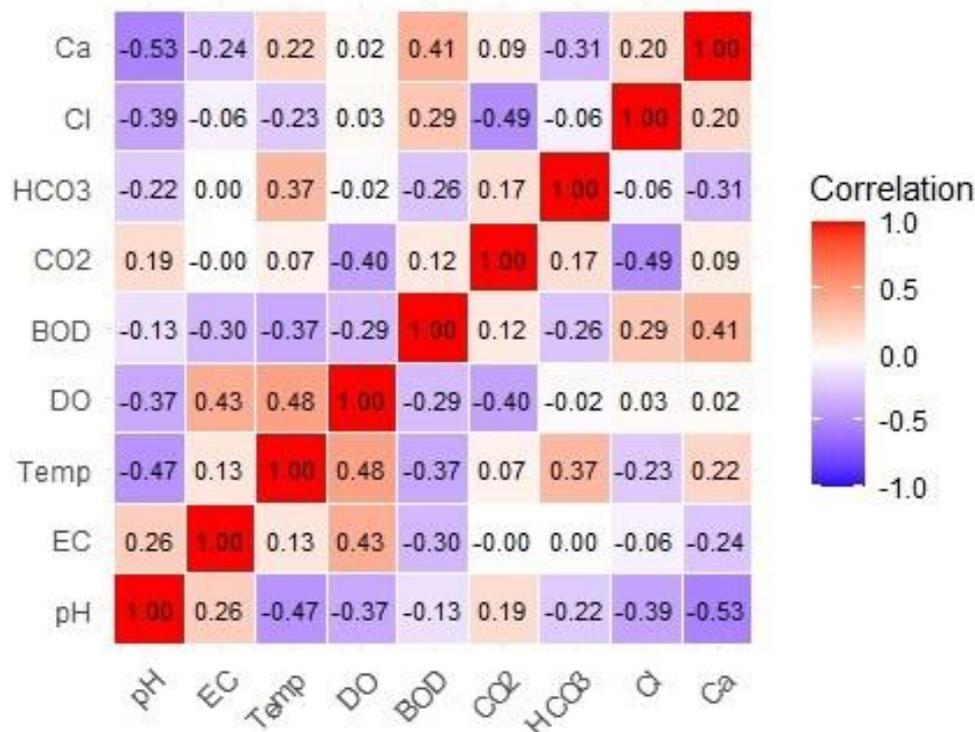

Fig. 6. Correlation matrix heatmap of water quality parameters of KL.

A strong positive relation between EC with that of the ionic components suggested that higher ion concentrations significantly contributed to increased conductivity, which appeared consistent with the previous findings of other researchers (Roy *et al.*, 2020; Islam *et al.*, 2021). Elevated levels of BOD with the increase of temperature and CO_2 could be a reason for exacerbating organic pollution, as these factors often co-occur in degraded aquatic environments (Lee, 2021). The negative correlation of DO with that of the temperature, BOD, and free CO_2 suggested that with increasing BOD, the DO decreases in the aquatic ecosystem. Seo *et al.* (2007) also stated the effect of increased temperature and BOD on the depletion of DO.

Suitability of KL water for irrigation and fisheries

Table 2 shows the suitability of KL water for irrigation and fisheries based on some key water quality parameters. It was evident that most of the parameters were within the suitable range for both irrigation and fisheries. Among the chemical parameters, the mean DO value indicated generally high and healthy conditions for aquatic life. While Ca^{2+} was found suitable both for irrigation and fisheries, the level of HCO_3^- was higher than the expected values suitable for aquatic life. Hossain *et al.* (2019) found that the water quality of KL is greatly affected by urban pollution, which ultimately leads to high ionic concentrations in the reservoir.

Table 2. Suitability of KL water for irrigation and fisheries based on some key water quality parameters.

Parameters (units)	Measured mean	Standard for irrigation	Standard range for fisheries	Suitability for irrigation and fisheries	References
pH	7.5	6.5–8.4	6.5–8.5	Slightly alkaline; Within a suitable range for both uses.	APHA, 2017; Boyd, 1990
EC (μS/cm)	117.0	750-2250	100–2000	Suitable for irrigation and aquatic life.	Ayers and Westcot, 1985; Boyd and Tucker, 2012
Temperature (°C)	36	< 35°C	25–32°C	Within a suitable range for fisheries and irrigation.	Ayers and Westcot, 1985
DO (mg/L)	9.64	–	> 5 mg/L	Indicates suitability for aquatic life.	Boyd, 1990
HCO_3^- (mg/L)	295.71	< 300	60–120	Suitable for irrigation.	Boyd, 1990
Ca^{2+} (mg/L)	0.31	< 400	20–100	Suitable for irrigation and fisheries.	Boyd and Tucker, 2012; Todd and Mays, 2005

The BOD at some sampling points could likely be raised from organic matter inputs through agricultural runoff, waste disposal, or increased microbial function. Several researchers also reported that land use changes due to urban development, and the presence of illegal human settlements, garbage dumping, and silt deposition can reduce the capacity of water channels and increase the pollution load in KL (Bhateria and Jain, 2016; Bilal *et al.*, 2023; Zuthi *et al.*, 2020). In a study on the Jamuna River, Uddin *et al.* (2014) found that the BOD was higher than the standard limit. In another study, Islam *et al.* (2021) reported that while pH, DO, and EC were within the favorable conditions for aquaculture, higher values of alkalinity and hardness were reported in KL. In contrast to our present findings, Chakma *et al.* (2020) reported that the water quality of KL was broadly within acceptable standards for aquatic ecosystems. However, fluctuation in the quality indices of water in the present study could be due to spatial influence.

Conclusion

The assessment of key quality parameters of water in the KL reservoir revealed generally stable temperature and EC and neutral to slightly alkaline pH conditions at the sampling points. The levels of DO supported aquatic life, however; BOD, HCO_3^-, and Cl⁻ concentrations increased at certain points, indicating organic pollution related to agricultural runoff, domestic discharges, or leaching of minerals. The strong positive correlation between EC and ionic components and the negative correlation of DO with temperature and BOD emphasized the influence of nutrient loading and thermal conditions on oxygen dynamics. Clustering analysis further highlighted spatial variation in water quality, distinguishing sites affected by ionic processes. Although, most parameters were found within the suitable range for fisheries and irrigation, HCO_3^- exceeded the standard limit required for aquaculture. Local pollution pressures to some scale suggest that continued monitoring and strategic interventions are essential to mitigate anthropogenic impacts and ensure long-term ecological sustainability and suitability of the lake water for agriculture and aquaculture.

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