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Seasonal Variation in Water Quality and Plankton Communities in a Eutrophic Tropical Lake (Central, India)

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ABSTRACT

The study was conducted during the year 2024 at Koteshwar Lake, Ramtek, Maharashtra, India to evaluate seasonal variations in water quality and plankton community structure and to determine the trophic status of the lake in relation to monsoon-driven nutrient inputs. Monthly sampling was performed at four representative stations covering inlet, settlement-influenced, open water, and littoral zones. Physicochemical parameters, nutrient concentrations, biochemical oxygen demand, chemical oxygen demand, chlorophyll *a*, and plankton diversity were analysed using standard methods. Statistical analyses included one-way ANOVA, correlation analysis, and principal component analysis. The lake exhibited pronounced seasonal variability, with higher temperatures during the pre-monsoon period and lower dissolved oxygen levels. Nutrient concentrations, biochemical oxygen demand, and chemical oxygen demand increased significantly during the monsoon, indicating strong external nutrient loading. Chlorophyll *a* concentration peaked during the post-monsoon season, reflecting enhanced primary productivity. Multivariate analysis identified nutrient variables as the major factors influencing ecological variation. Phytoplankton diversity remained relatively stable, whereas zooplankton showed marked seasonal fluctuations with greater abundance during the monsoon. The dominance of nutrient-tolerant taxa confirmed eutrophic conditions. The findings demonstrated that monsoon-driven nutrient enrichment and catchment influence strongly regulated the ecological dynamics of Koteshwar Lake and highlighted the importance of catchment-level management strategies for long-term lake conservation.

KEYWORDS: Wate-quality, eutrophication, plankton diversity, nutrient loading, tropical lake

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1. INTRODUCTION

Freshwater lakes are vital yet vulnerable ecosystems that support biodiversity, nutrient cycling, fisheries, and drinking water supplies. However, many freshwater systems are increasingly threatened by eutrophication caused by excessive nitrogen and phosphorus loading, leading to algal blooms, oxygen depletion, and altered aquatic community structure (Mishra and Tripathi, 2023; Ravi et al., 2021; Paerl and Paul, 2012). Small and shallow lakes are particularly sensitive to hydrological fluctuations and nutrient enrichment, often responding rapidly to environmental disturbances (Zhou et al., 2022; Jones and Smol, 2023). In India, lakes and wetlands possess ecological, economic, and cultural significance, yet many are under stress from anthropogenic activities. Studies from different regions have demonstrated the impact of nutrient enrichment on aquatic communities. Zooplankton assemblages in Bhoj Wetland shifted due to agricultural runoff and sewage inputs (Bhat et al., 2015), while protozoan communities in Vembanad Lake reflected varying pollution levels (Radhakrishnan and Jayaprakas, 2015). Similar trends have been reported in Kumaraswamy Lake, where nutrient enrichment altered zooplankton and fish communities (Mohan and Priyadarshinee, 2022). In central India, Ambazari and Futala lakes frequently experience cyanobacterial blooms, and activities such as idol immersion have been shown to significantly affect water quality (Maske et al., 2010; Chatterjee and Lataye, 2020; Belsare et al., 2017). Globally, recent studies further highlight the linkage between nutrient dynamics and plankton ecology. In Dongting Lake, China, dissolved oxygen, nutrient concentrations, and chemical oxygen demand were identified as major factors influencing plankton distribution (Yuan et al., 2024). In northern India, small lentic waterbodies exhibited post-monsoon hypereutrophic conditions associated with elevated nitrogen, phosphorus, and chlorophyll a concentration (Singh and Yadav, 2025). Seasonal studies in Tillari Reservoir also demonstrated the influence of monsoon-driven nutrient pulses on phytoplankton succession (Ahmed et al., 2021). Increasing occurrences of harmful algal blooms (HABs), particularly cyanobacterial dominance under eutrophic conditions, have also been documented in Indian lakes (Savaliya et al., 2026; Maniyar et al., 2022; Prasad and Prasad, 2019). Plankton communities are widely recognized as sensitive indicators of ecosystem health (Zhao et al., 2019; Zhang et al., 2019). Phytoplankton respond rapidly to nutrient enrichment, whereas zooplankton reflect the combined effects of food availability, organic pollution, and predation. Taxa such as *Oscillatoria* and *Brachionus* are considered indicators of eutrophic conditions (Chandel et al., 2023), while diatoms such as *Fragilaria* and *Nitzschia* are associated with moderately nutrient-rich waters (Kuturo et al., 2024; Radhakrishnan and Jayaprakas, 2015). Therefore, integration of plankton analysis with physicochemical assessment provides a comprehensive approach for evaluating trophic status and ecological health. Recent studies also emphasize the importance of combining conventional water-quality analysis with advanced statistical and multivariate approaches for improved ecosystem assessment. Koteshwar Lake, located near the historic Nagardhan Fort in Maharashtra, represents an ecologically sensitive freshwater system influenced by agricultural runoff and domestic discharges. Despite its ecological and socio-cultural importance, limited limnological information is available for this lake. Therefore, the present study was undertaken to establish a baseline assessment of the lake's trophic status using physicochemical characteristics and plankton diversity. The study also aimed to evaluate seasonal variations in plankton communities and identify potential bioindicator taxa associated with nutrient enrichment. It was hypothesized that the lake is undergoing early-stage eutrophication, characterized by the occurrence of pollution-tolerant planktonic species in runoff-affected zones. The findings are expected to contribute to a better understanding of limnological dynamics in small tropical lakes of central India under increasing anthropogenic and climatic pressures.

2. MATERIALS AND METHODS

2.1. Study area and sampling design

The experiment was conducted during the year 2024 at Koteshwar Lake, Ramtek, District, Maharashtra, India, to study seasonal variations in water quality and plankton community structure of Koteshwar Lake and its trophic status in relation to monsoon-driven nutrient inputs. Koteshwar Lake is a small freshwater body located near the historic Nagardhan Fort in Ramtek, Nagpur District, Maharashtra, India (21°20'28''N, 79°18'41''E). The lake is surrounded by agricultural land and human settlements, making it susceptible to nutrient enrichment through surface runoff and domestic inputs.

To capture spatial heterogeneity within the lake, four sampling stations were established: (i) an inlet zone receiving agricultural runoff, (ii) a near-shore region adjacent to village settlements influenced by domestic discharge, (iii) a mid-lake open water (limnetic) zone, and (iv) a macrophyte-dominated littoral zone. The spatial distribution of sampling stations within the lake is illustrated in Figure 1.

Sampling was conducted at monthly intervals over a one-year cycle, encompassing the pre-monsoon, monsoon, post-monsoon, and winter seasons. The study period was categorised into four distinct seasons based on the regional climatic conditions of central India: pre-monsoon (March–May), monsoon (June–September), post-monsoon

Figure 1: Location map of Koteshwar Lake (Maharashtra, India) indicating the four sampling stations: S1 (inlet zone influenced by agricultural runoff), S2 (near settlement zone receiving domestic inputs), S3 (limnetic zone), and S4 (littoral zone with macrophyte domi

(October–November), and winter (December–February). This seasonal framework was adopted to account for hydrological variability known to influence nutrient dynamics and plankton succession in tropical freshwater systems. At each station, samples were collected in triplicate during morning hours (08:00–11:00) to minimise diurnal fluctuations and ensure statistical reliability.

2.2. Physicochemical analysis

Surface water samples (0–0.5 m) were collected using pre-cleaned, acid-washed polyethene bottles. In situ measurements of water temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO) were recorded using a calibrated multiparameter probe (YSI EXO2). Water transparency was determined using a Secchi disc, providing an estimate of light penetration and trophic condition (Wetzel, 2001).

Laboratory analyses were conducted following standard procedures (Anonymous, 2017). Titrimetric methods determined total alkalinity and hardness. Biochemical oxygen demand (BOD) was estimated using the 5-day incubation method, while chemical oxygen demand (COD) was measured using the dichromate reflux method.

Nutrient concentrations were analysed spectrophotometrically: nitrate was determined by the cadmium reduction method, nitrite by diazotisation, ammonium using the phenate method, and total phosphorus following persulfate digestion (Anonymous, 2017; Maske et al., 2010). Chlorophyll a was estimated by filtering known volumes of water through pre-combusted GF/C filters, extracting pigments in 90% acetone, and measuring absorbance using a UV–Visible spectrophotometer. These procedures are widely adopted in limnological studies of tropical lakes (Ahmed et al., 2021; Mohan and Priyadarshinee, 2022).

2.3. Plankton collection and identification

Phytoplankton samples were collected through integrated water sampling (0–1 m depth) using a Van Dorn sampler and preserved immediately with Lugol's iodine solution (final concentration ~1%). Zooplankton were collected using horizontal and oblique hauls with a plankton net of 62 μm mesh size and preserved in 4% formalin.

In the laboratory, phytoplankton were identified and enumerated using an inverted microscope following the sedimentation technique given by Lund et al. (1958). Zooplankton were examined under a stereomicroscope and identified to the lowest possible taxonomic level. Quantitative estimation was carried out using standard counting chambers, and abundances were expressed as cells ml^{-1} for phytoplankton and individuals l^{-1} for zooplankton.

Identification of phytoplankton and zooplankton was carried out using standard taxonomic keys and monographs, complemented by region-specific literature relevant to Indian freshwater ecosystems. Phytoplankton taxa were identified following Desikachary (1959) for cyanobacteria, Anand (1998) for Indian freshwater microalgae, and Prescott (1962) for general algal taxonomy. Zooplankton were identified using Battish (1992) and Wetzel (2001), along with supporting regional limnological studies. The use of these regionally relevant references ensured accurate identification of taxa under tropical Indian conditions, where plankton composition and ecological responses often differ from those reported in temperate systems.

2.4. Diversity indices and bioindicators

To evaluate community structure, diversity indices including Shannon–Wiener diversity (H'), Simpson's dominance, Margalef's richness, and Pielou's evenness were calculated using standard ecological formulas.

In addition, the presence and dominance of key indicator taxa such as *Oscillatoria*, *Microcystis*, *Brachionus*, and *Moina* were examined, as these organisms are widely recognised as indicators of nutrient enrichment and organic pollution in freshwater ecosystems (Chandel et al., 2023; Radhakrishnan and Jayaprakas, 2015; Maske et al., 2010).

2.5. Statistical analysis and trophic classification

All data were expressed as mean±standard deviation (SD) based on triplicate observations. Monthly variations in physicochemical parameters and biological indices were evaluated using one-way analysis of variance (ANOVA), considering month as the main factor. To avoid pseudo-replication, sampling sites were not treated as replicates; instead, mean values across sites were used for statistical comparisons. When significant differences were detected (p<0.05), Tukey's Honestly Significant Difference (HSD) test was applied for post hoc comparisons.

Before analysis, data were tested for normality and homogeneity of variance, and appropriate transformations were applied where necessary. Correlation analysis (Pearson's or Spearman's, depending on data distribution) was performed to examine relationships among physicochemical parameters, nutrient concentrations, chlorophyll a, and plankton abundance.

Multivariate statistical techniques were applied to identify major environmental gradients and their influence on plankton communities. Principal Component Analysis (PCA) was used to reduce the dimensionality of environmental variables, while Redundancy Analysis (RDA) was employed to explore relationships between plankton composition and environmental drivers. These approaches have been successfully applied in freshwater ecological studies to disentangle complex interactions among variables (Yuan et al., 2024).

The trophic status of the lake was evaluated using Carlson's Trophic State Index (TSI), based on Secchi depth, chlorophyll a, and total phosphorus (Carlson, 1977). Additionally, where appropriate, the Trophic Level Index (TLI) was applied to integrate nutrient concentrations and transparency, providing a more comprehensive assessment of trophic conditions in small tropical lakes (Singh and Yadav, 2025).

3. RESULTS AND DISCUSSION

3.1. Physicochemical parameters

The seasonal patterns observed in Koteshwar Lake clearly reflect the influence of the tropical monsoon climate of central India, where alternating dry and wet phases strongly regulate water quality and biological responses. Such seasonality is widely recognised as the primary driver of limnological processes in tropical freshwater systems (Sinha and Michalak, 2022; Kondowe et al., 2022). Koteshwar Lake showed strong seasonal shifts in water quality. As summarized in Table 1a and 1b and Figure 2A–D, water temperature ranged from 24.5±0.5°C (Jan) to 33.5±1.2°C (May), with a significant seasonal effect (p<0.01**). Dissolved oxygen (DO) was inversely related to temperature: lowest in April (4.2±0.3 mg l^{-1}) and highest in winter (6.7±0.5 mg l^{-1} in Dec; p<0.01**). Secchi depth (transparency) was minimal in the late dry season (~1.3 m in June) and maximal (~4.2–5.1 m) in post-monsoon (Nov–Dec). Nutrients and organics peaked with monsoon flow: mean nitrate climbed from 2–5 mg l^{-1} (winter) to ~30 mg l^{-1} (June), and

Table 1a: Monthly variation of physicochemical parameters of Koteshwar Lake

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature (°C)	24.50±0.5^{c}	25.8±0.6^{c}	28.5±0.8^{b}	31.2±1.0^{a}	33.5±1.2^{a}	30.8±1.0^{a}	28.0±0.9^{b}	27.5±0.8^{b}	27.8±0.9^{b}	26.5±0.7^{c}	25.5±0.6^{c}	24.8±0.5^{c}
DO (mg l^{-1})	6.8±0.5^{a}	6.5±0.5^{a}	6.0±0.4^{b}	5.5±0.4^{c}	4.8±0.3^{d}	4.2±0.3^{e}	4.8±0.4^{d}	5.2±0.4^{c}	5.5±0.4^{c}	6.0±0.5^{b}	6.3±0.5^{a}	6.7±0.5^{a}
Turbidity (NTU)	2.80±0.15^{c}	2.68±0.14^{c}	2.40±0.12^{d}	2.10±0.10^{d}	1.80±0.09^{e}	1.34±0.07^{f}	3.50±0.18^{b}	4.20±0.21^{a}	3.80±0.19^{a}	2.90±0.15^{c}	2.75±0.14^{c}	2.85±0.15^{c}
EC (µS cm^{-1})	780±40^{f}	846±42^{f}	1100±55^{e}	1500±75^{d}	1900±95^{b}	2140±107^{a}	1800±90^{c}	1500±75^{d}	1300±65^{e}	1000±50^{e}	900±45^{f}	820±41^{f}
TDS (mg l^{-1})	480±24^{f}	524±26^{f}	700±35^{e}	950±48^{d}	1150±58^{b}	1279±64^{a}	1100±55^{c}	950±48^{d}	820±41^{e}	650±32^{e}	580±29^{f}	500±25^{f}
BOD (mg l^{-1})	6.5±0.5^{f}	7.4±0.6^{e}	10±0.8^{d}	15±1.2^{c}	25±2.0^{b}	33.4±2.6^{a}	20±1.6^{c}	15±1.2^{c}	12±1.0^{d}	9± 0.7^{d}	7.5±0.6^{e}	6.8±0.5^{f}
COD (mg l^{-1})	20± 2^{f}	24± 2^{e}	40± 3^{d}	60± 5^{c}	85± 7^{b}	104±8^{a}	80± 6^{b}	65±5^{c}	50± 4^{d}	35± 3^{d}	28±2^{e}	22±2^{f}
Chlorophyll a (µg l^{-1})	18± 2^{d}	16± 2^{d}	20± 2^{c}	25± 3^{c}	30± 3^{b}	35± 4^{b}	45± 5^{a}	55±5^{a}	50± 5^{a}	35± 4^{b}	25±3^{c}	20±2^{c}

Values are expressed as mean±standard deviation. Different superscript letters within each row indicate statistically significant differences among months (*p<0.05; Tukey's HSD test following one-way ANOVA). Values represent averages across all sampling stations. All analyses were performed using R software (version 4.x)

Table 1b: Monthly variation of additional physicochemical parameters of Koteshwar Lake

Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
pH	8.15±0.12^{a}	8.07±0.11^{a}	8.00±0.10^{b}	7.95±0.10^{b}	7.85±0.09^{c}	7.74±0.08^{c}	7.60±0.07^{d}	7.55±0.07^{d}	7.65±0.08^{c}	7.80±0.09^{c}	7.95±0.10^{b}	8.10±0.11^{a}
Total Hardness (mg l^{-1})	240±12^{f}	252±13^{f}	300±15^{e}	360±18^{d}	420±21^{b}	450±23^{a}	400±20^{c}	360±18^{d}	320±16^{e}	280±14^{e}	260±13^{f}	245±12^{f}
Calcium (mg l^{-1})	58±3^{f}	60.8±3^{f}	75±4^{e}	95±5^{d}	110±6^{b}	117.8±6^{a}	105±5^{c}	92±5^{d}	80±4^{e}	70±4^{e}	62±3^{f}	59±3^{f}
Magnesium (mg l^{-1})	22±1.5^{f}	24.1±1.6^{f}	28±1.8^{e}	32±2.0^{d}	35±2.2^{b}	37.9±2.4^{a}	34±2.1^{c}	30±1.9^{d}	28±1.8^{e}	26±1.7^{e}	25±1.6^{f}	23±1.5^{f}
Alkalinity (mg l^{-1})	185±9^{a}	178±9^{a}	160±8^{b}	140±7^{c}	120±6^{d}	110±5^{e}	130±6^{c}	150±7^{b}	165±8^{b}	175±9^{a}	182±9^{a}	188±9^{a}
Chloride (mg l^{-1})	95±5^{f}	108±5^{f}	180±9^{e}	260±13^{d}	350±18^{b}	424±21^{a}	300±15^{c}	250±13^{d}	200±10^{e}	150±8^{e}	120±6^{f}	100±5^{f}
Sulphate (mg l^{-1})	105±5^{f}	112±6^{f}	120±6^{e}	130±7^{d}	138±7^{b}	142±7^{a}	135±7^{c}	128±6^{d}	120±6^{e}	115±6^{f}	110±5^{f}	108±5^{f}
Iron (mg l^{-1})	0.52±0.03^{b}	0.49±0.02^{c}	0.47±0.02^{c}	0.45±0.02^{d}	0.43±0.02^{d}	0.42±0.02^{d}	0.50±0.03^{b}	0.55±0.03^{a}	0.53±0.03^{b}	0.50±0.03^{b}	0.48±0.02^{c}	0.51±0.03^{b}
Fluoride (mg l^{-1})	0.95±0.05^{c}	1.00±0.05^{c}	1.05±0.05^{b}	1.10±0.06^{b}	1.20±0.06^{a}	1.25±0.06^{a}	1.15±0.06^{b}	1.10±0.06^{b}	1.05±0.05^{b}	1.00±0.05^{c}	0.98±0.05^{c}	0.96±0.05^{c}
Coliform (MPN 100 ml^{-1})	20±3^{a}	18±2^{a}	15±2^{b}	10±1^{c}	5±1^{b}	0^{e}	0^{e}	0^{e}	4±1^{d}	5±1^{d}	12±2^{b}	12±2^{d}

Values are expressed as mean±standard deviation (n=4). Different superscript letters within a row indicate statistically significant differences among months (p<0.05) based on Tukey's honestly significant difference (HSD) test following one-way ANOVA. Values represent averages across all sampling stations. All analyses were performed using R software (version 4.x)

orthophosphate from ~2 mg l^{-1} to ~4.5 mg l^{-1}. Biochemical oxygen demand (BOD) rose to 33.4±2.6 mg l^{-1} in June, and COD to 104±8 mg l^{-1} (Table 1), after which both declined in winter. Chlorophyll-a followed the nutrient pulse, rising from ~16 µg l^{-1} in Feb to ~55 µg l^{-1} in Aug (p=0.002 ANOVA). Based on Carlson's Trophic State Index, the lake falls in the eutrophic range (high chlorophyll, low Secchi). Tukey HSD (monthly) showed significant differences between monsoon and dry months for many variables.

During the pre-monsoon period, elevated temperatures, high solar radiation, and reduced inflow promote thermal stratification and sediment resuspension, resulting in lower dissolved oxygen and increased turbidity, as evident in Figure 2a and 2b. Similar pre-monsoon deterioration in water quality has been reported in several Indian lakes, where evaporation and reduced mixing intensify oxygen depletion and suspended solids concentration.

With the onset of the monsoon, intense rainfall and catchment runoff substantially alter the nutrient regime of the lake. In the present study, nitrate and phosphate concentrations showed a marked increase during June–July, indicating strong external loading. This observation aligns with findings by Sinha et al. (2022), who reported that approximately 68–94% of annual dissolved inorganic nitrogen (DIN) flux in Indian river systems occurs during the monsoon period (June–October). Comparable seasonal nutrient pulses have also been documented in tropical lakes, where rainfall-driven runoff is a dominant source of nutrient enrichment (Kondowe et al., 2022).

The increased nutrient availability during the early monsoon was followed by a pronounced phytoplankton response, with chlorophyll-a concentrations increasing nearly three- to four-fold by August compared to pre-monsoon levels (Figure 3). This strong coupling between nutrient enrichment and phytoplankton biomass is well established in freshwater ecosystems. Tropical lakes are often phosphorus-limited, and increases in phosphorus, together with nitrogen, can significantly enhance primary productivity (Sinha and Michalak, 2022; Paerl and Otten, 2013). Such nutrient-driven blooms, often dominated by opportunistic taxa, are commonly reported from eutrophic water bodies under monsoon influence.

3.2. Plankton community indices

Phytoplankton diversity (H') was uniformly high (1.93–2.12), with no drastic seasonal collapse; evenness remained ~0.90–0.96 and richness 8–9 taxa throughout (Table 2).

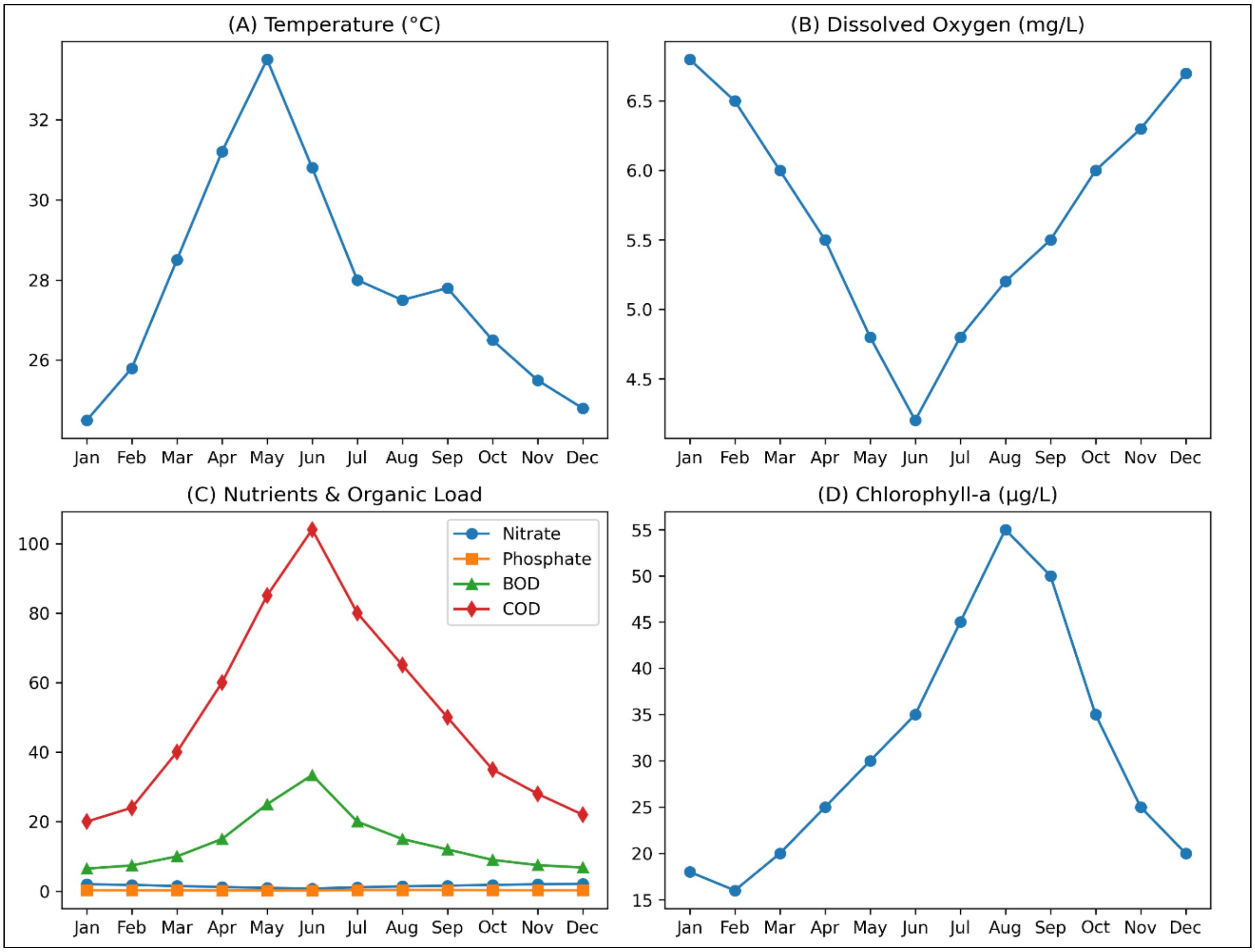

Figure 2: Seasonal variation in key limnological parameters of Koteshwar Lake: (A) water temperature (°C), (B) dissolved oxygen (mg l^{-1}), (C) nutrients and organic load (nitrate, phosphate, BOD, and COD), and (D) chlorophyll-a concentration (µg l^{-1})

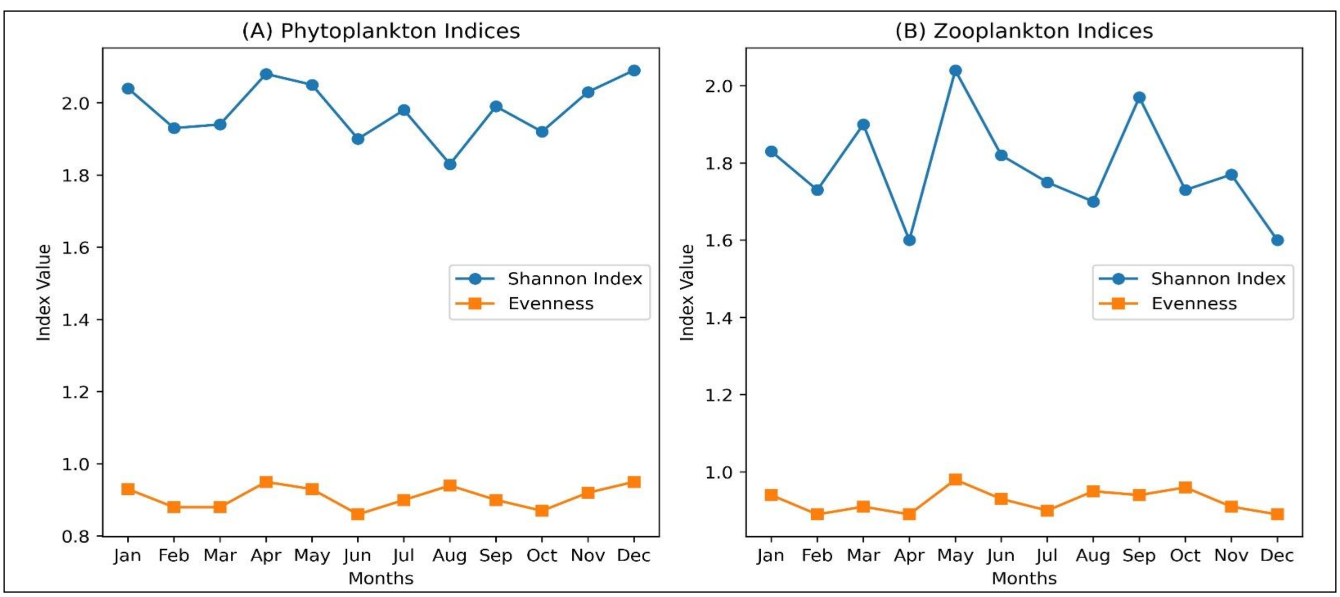

Figure 3: Monthly variation in phytoplankton and zooplankton community indices (Shannon diversity and species evenness) in Koteshwar Lake

Biomass (cells ml^{-1}) peaked in Jan (165±10) and Apr–Jul (≈120–142) and dipped to ≈95–100 in Feb–Mar and Sep–Dec (Table 3 and Figure 3). Zooplankton indices showed stronger seasonality. Rotifer- and cladoceran-dominated zooplankton had H' ranging from 1.64 (Oct) to 2.30 (Jul) and richness of 6–11 species (Table 4, Figure 3). Abundance was lowest in dry-winter (10–12 individuals l^{-1} in Jan–Feb) and highest in late monsoon (26±4 in Aug) (Table 5**)**. ANOVA confirmed significant seasonal differences in zooplankton H' and abundance ($p<0.05^{*}$). In short, phytoplankton maintained relatively steady diversity, whereas zooplankton showed increased diversity and abundance during the nutrient-rich wet season. Indicator taxa of eutrophy were present: cyanobacteria (*Oscillatoria, Microcystis*) and rotifers (*Brachionus, Moina*) – groups commonly reported in high-nutrient lakes.

This physicochemical evidence is strongly supported by the biological response. Plankton community structure reflected nutrient-rich conditions, with abundance and diversity peaks coinciding with high nutrient periods. In particular, rotifer genera *Brachionus* and *Asplanchna* proliferated in summer and early monsoon, raising community diversity (H'). These taxa are classic indicators of eutrophic, organically enriched waters (Sladecek, 1983) and are frequently reported in nutrient-rich tropical lakes. Similarly, the cladoceran *Moina* showed a pronounced summer increase. *Moina* is well-established as a bioindicator of organic pollution and high nutrient load (Gannon and Stemberger, 1978; Janakiraman et al., 2024; Saksena, 1987), so its abundance corroborates elevated organic and nutrient inputs in the lake.

Table 3: Monthly variation in phytoplankton community indices in Koteshwar Lake

Month	Shannon index (H')	Evenness (J)	Species richness (S)	Total abundance
Jan	2.04±0.08^b	0.93±0.02^a	9±1^a	165±10^a
Feb	1.98±0.07^b	0.90±0.03^a	8±1^b	95±8^b
Mar	2.03±0.08^b	0.92±0.02^a	8±1^b	109±9^b
Apr	2.10±0.09^a	0.95±0.02^a	9±1^a	142±12^a
May	2.12±0.09^a	0.96±0.02^a	9±1^a	120±10^a
Jun	2.05±0.08^b	0.93±0.02^a	8±1^b	107±9^b
Jul	2.02±0.08^b	0.92±0.02^a	8±1^b	131±11^a
Aug	1.97±0.07^b	0.91±0.03^a	8±1^b	126±10^a
Sep	2.02±0.08^b	0.93±0.02^a	8±1^b	100±8^b
Oct	2.02±0.08^b	0.92±0.02^a	8±1^b	107±9^b
Nov	1.93±0.07^c	0.90±0.03^a	8±1^b	126±10^a
Dec	1.96±0.07^c	0.89±0.03^a	8±1^b	100±8^b

Values are expressed as mean±standard deviation. Different superscript letters within each column indicate statistically significant differences among months ($^{*}p<0.05$; Tukey's HSD test following one-way analysis of variance). Values represent averages across all sampling stations. Species richness (S) represents the number of taxa recorded per sampling period

Table 4: Monthly variation in zooplankton community indices in Koteshwar Lake

Month	Shannon index (H')	Evenness (J)	Species richness (S)	Total abundance
Jan	1.83±0.05^c	0.94±0.02^a	7±1^c	10±2^d
Feb	1.82±0.06^c	0.93±0.03^a	7±1^c	12±2^c
Mar	1.97±0.07^b	0.94±0.02^a	8±1^b	11±2^c
Apr	2.13±0.08^a	0.95±0.02^a	9±1^a	20±3^a
May	2.03±0.07^b	0.96±0.02^a	8±1^b	10±2^d
Jun	1.97±0.06^b	0.87±0.03^b	7±1^c	14±2^c
Jul	2.30±0.09^a	0.96±0.02^a	11±2^a	14±3^b
Aug	2.06±0.07^b	0.92±0.03^a	9±1^a	26±4^a
Sep	2.06±0.08^b	0.89±0.03^b	10±2^a	19±3^b
Oct	1.64±0.05^c	0.92±0.03^a	6±1^c	11±2^c
Nov	2.20±0.08^a	0.95±0.02^a	9±1^a	20±3^b
Dec	1.71±0.06^c	0.95±0.02^a	6±1^c	14±2^c

Values are expressed as mean ± standard deviation. Different superscript letters within each column indicate statistically significant differences among months ($^{*}p<0.05$; Tukey's HSD test following one-way ANOVA). Values represent averages across all sampling stations. Species richness (S) represents the number of taxa recorded per sampling period

The dominance of cyanobacteria further confirms eutrophic conditions. Bloom-forming cyanobacteria thrive under excess nitrogen and phosphorus, especially in warm tropical waters (Paerl and Otten, 2013; Paerl and Paul, 2012). Their seasonal bloom in Koteshwar Lake is consistent with reports of increasing cyanobacterial blooms in Indian lakes subject to eutrophication (Maniyar et al., 2022; Prasad and Prasad, 2019; Maske et al., 2010).

Despite pronounced seasonal fluctuations in environmental conditions, the plankton community in Koteshwar Lake maintained a moderate to relatively high level of diversity throughout the study period. This pattern suggests that, although nutrient inputs and hydrological changes influenced community composition, they did not lead to prolonged dominance by a single taxon. Similar observations have been reported from tropical and subtropical reservoirs, where seasonal nutrient rhythms, particularly during the monsoon, enhance plankton biomass and alter species composition, but continuous mixing and relatively short

Table 5: Monthly variation in zooplankton species composition (individuals l^{-1}) in Koteshwar Lake across all sampling stations

Species	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Copepoda												
Nauplius	9	6	5	5	4	5	4	8	6	5	6	12
Mesocyclops tenus	8	4	5	4	4	3	4	11	6	6	3	3
Mesocyclops hyalinus	2	3	2	2	2	5	3	8	6	6	5	4
Cyclops vernalis	3	5	3	3	5	9	4	8	4	4	9	3
Diacyclops bicuspidatus	1	2	2	1	6	3	3	9	9	3	7	2
Leptodiaptomus sp.	1	1	1	1	6	8	9	8	2	7	8	1
Cladocera												
Moina macrocopa	7	4	6	9	3	2	7	11	11	10	4	9
Diaphanosoma dentatum	4	7	4	4	3	4	5	4	7	1	1	3
Macrothrix goeldii	2	1	1	1	4	1	2	12	9	7	3	1
Rotifera												
Epiphanes sp.	5	5	5	6	3	2	3	7	7	10	7	6
Brachionus angularis	4	6	4	10	2	2	6	3	4	4	3	5
Brachionus caudatus	3	5	3	6	5	2	1	4	2	0	0	3
Ostracoda												
Cypris sp.	1	1	1	0	6	0	3	6	4	5	5	0
Total abundance	50	50	43	52	53	46	54	99	87	68	61	52

water residence times prevent competitive exclusion (Reynolds, 2006; Wetzel, 2001).

In the present study, diversity did not show a marked collapse during the pre-monsoon or peak summer period, which is often associated with environmental stress in shallow lakes. This relative stability may be attributed to dynamic hydrological conditions, including periodic flushing, catchment-driven inputs, and spatial heterogeneity within the lake. Such mechanisms can maintain community turnover and prevent the establishment of persistent monocultures, even under nutrient-rich conditions. Comparable findings have been reported in tropical lakes of Africa and Asia, where seasonal hydrology, rather than nutrient concentration alone, governs plankton succession (Kondowe et al., 2022; Lewis, 2000).

The data clearly classify Koteshwar Lake as eutrophic. Carlson's Trophic State Index (TSI) places it in the eutrophic range (high TSI) owing to low Secchi depths and high chlorophyll a. Comparable TSI-based assessments have identified many Indian tropical lakes as eutrophic under heavy nutrient loading (e.g., Sheela et al., 2010; Wetzel, 2001). Indeed, shallow warm lakes often transition rapidly to eutrophic or hypereutrophic states under ongoing nutrient enrichment and limited flushing (Wetzel, 2001; Schindler et al., 2016).

However, it is important to note that while seasonal variability influences short-term community structure, the underlying nutrient regime appears to sustain a eutrophic baseline. Continuous inputs from agricultural runoff and nearby settlements likely maintain elevated nutrient concentrations throughout the year, thereby supporting consistently high primary productivity. This interaction between seasonal forcing and chronic nutrient enrichment has been widely documented in tropical systems, where anthropogenic pressures amplify natural climatic effects (Paerl and Otten, 2013; Schindler et al., 2016)

3.3. Statistical analysis

Pearson correlations (Figure 4) revealed strong associations among conductivity, TDS, BOD, and COD ($r \approx 0.97$–0.99), reflecting common runoff origin, and moderate correlations of chlorophyll with TDS and EC ($r \approx 0.54$–0.57). Phytoplankton diversity showed positive correlation with temperature ($r \approx 0.82$) and weak inverse correlation with zooplankton H' ($r \approx -0.35$). Zooplankton diversity was highly correlated with total zooplankton density ($r \approx 0.92$). PCA of environmental variables (Figure 5) separated two main axes: PC1 (≈62.5% variance) aligned with nutrient–algal factors (high nitrate, phosphate, chlorophyll), while PC2 (≈15.8%) aligned with physical conditions (high temperature, low DO). Monsoon months scored high on PC1 (nutrient enrichment), whereas winter months scored

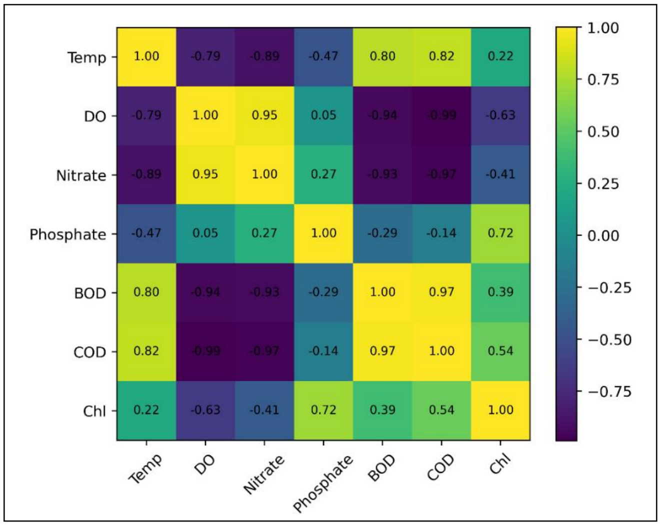

Figure 4: Correlation matrix showing relationships among physicochemical parameters, including temperature, dissolved oxygen, nutrients, organic load, and chlorophyll a in Koteshwar Lake

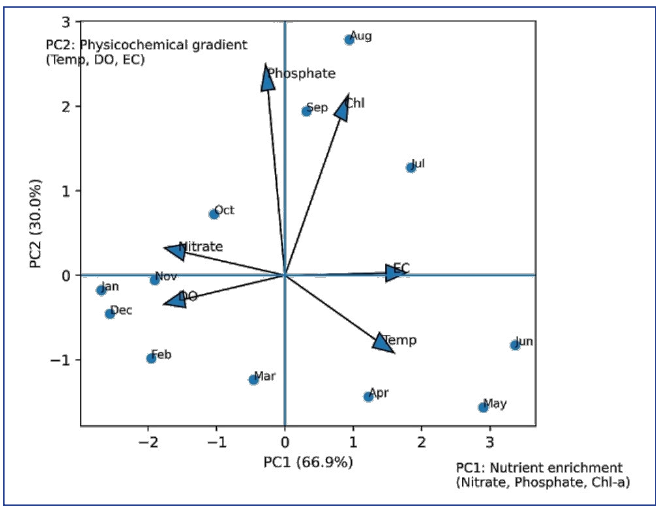

Figure 5: Principal Component Analysis (PCA) showing the distribution of months based on physicochemical variables in Koteshwar Lake. PC1 and PC2 explain the major variability in water quality parameters

high on PC2 (cooler, oxygenated). (RDA linking plankton to environment was also tested: nutrients and clarity were the primary drivers of plankton variation, consistent with past work.)

The PCA and correlation analyses (Figures 4–5) revealed that chlorophyll a and plankton abundance were strongly associated with elevated nitrate and phosphate levels, whereas temperature and dissolved oxygen formed an opposing gradient. This indicates that nutrient enrichment directly supports phytoplankton growth, while higher temperatures and reduced oxygen conditions are characteristic of the dry season. Similar inverse relationships between nutrient availability and dissolved oxygen have been reported in other tropical lakes, where increased biological activity and organic matter decomposition during productive phases lead to oxygen depletion (Kondowe et al., 2022).

4. CONCLUSION

The findings demonstrated that Koteshwar Lake was strongly influenced by monsoon-driven nutrient inputs, which regulated seasonal variations in water quality and plankton dynamics. Elevated nutrient concentrations, reduced transparency, high trophic state index values, and the dominance of nutrient-tolerant plankton collectively indicated a eutrophic condition. Seasonal hydrological processes maintained moderate biological diversity; however, continuous nutrient inflow from agricultural runoff and nearby settlements sustained eutrophication. The study highlighted the importance of catchment-level management practices and regular ecological monitoring for the long-term conservation of tropical freshwater ecosystems.

5. FURTHER RESEARCH

The present study provides a baseline understanding of seasonal dynamics in Koteshwar Lake; however, several aspects require further investigation to improve ecological assessment and management. Long-term monitoring is essential to evaluate interannual variability and to detect trends associated with climate change and increasing anthropogenic pressures. Future studies should incorporate high-frequency sampling during critical periods such as the onset of the monsoon to better capture rapid nutrient influx and short-term ecological responses.

Advanced analytical approaches, including remote sensing and modelling techniques, could be employed to assess spatial variability and predict eutrophication risk under different land-use scenarios. Additionally, detailed nutrient budgeting and source apportionment studies are needed to quantify contributions from agricultural runoff, domestic discharge, and internal loading from sediments.

Further research should also focus on harmful algal blooms, particularly toxin-producing cyanobacteria, to assess potential risks to aquatic life and human health. Experimental studies examining nutrient limitation (nitrogen versus phosphorus) would help in designing targeted management strategies. Finally, integrating higher trophic levels, including fish community dynamics and food web interactions, would provide a more comprehensive understanding of ecosystem functioning and resilience.

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