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ADVANCED METHODS IN NATURAL HAZARD MITIGATION, ENVIRONMENTAL SUSTAINABILITY, AND CLIMATE RESILIENCE FOR ACHIEVING THE UN SDGS

Anthropogenic drivers of algal regime shifts in a Himalayan watershed and pathways for nature-based solutions

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Abstract

Freshwater ecosystems worldwide are increasingly threatened by human activities, yet the ecological mechanisms linking anthropogenic pressures to algal community dynamics remain incompletely resolved in the Himalayan river systems. To bridge this gap, this study presents a rapid ecological assessment of algal diversity and water quality across three sites in the Kosi watershed, India, integrating comprehensive physicochemical analyses, Water Quality Index (WQI) evaluation, and multivariate statistics. We collected and analyzed 33 water and algal samples during the summer of 2023, identifying 11 algal genera spanning Cyanophyta, Chlorophyta, Xanthophyta, and Charophyta. Our results reveal a pronounced spatial gradient in water quality, with WQI values ranging from "excellent" (42.6) at the minimally impacted upstream site to "very poor" (266.3) at the most anthropogenically influenced downstream site. Canonical correspondence analysis demonstrates that turbidity and pH are the primary environmental drivers shaping algal assemblages, with nutrient-tolerant *Spirulina* and *Oscillatoria* dominating disturbed sites, while *Oedogonium* and *Spirogyra* prevail under more stable conditions. The rapid assessment approach enabled the timely detection of pollution hotspots and ecological responses, providing implementable steps for watershed management. Our findings underscore the urgent need for targeted conservation and pollution mitigation strategies to preserve riverine biodiversity and ecosystem services in Himalayan catchments. Nature-based solutions can be among the potential pathways to sustainability.

Keywords Algal diversity · Anthropogenic activities · Chlorophyta · Cyanophyta · Nutrient enrichment · Sustainable watershed management

Introduction

Rivers underpin global ecological stability and human development, yet Himalayan freshwater systems face unprecedented threats from anthropogenic activities (Meinam et al. 2025; Sahu et al. 2024; Kattel 2022). While rivers globally provide drinking water, agricultural irrigation, and habitat services (Vörösmarty et al. 2010; UN-Water 2012), the Himalayan Kosi River exemplifies a critical nexus of biodiversity and socio-economic reliance, supporting 323 villages, alpine agriculture, and unique aquatic ecosystems (Kansal et al. 2011; Kumar 2018). However, accelerating urbanization, deforestation, and tourism in Uttarakhand have degraded water quality, with sediment loads increasing by 40% since 2010 and nitrate concentrations exceeding 4 mg/L in downstream stretches (Chhimwal et al. 2022; Negi et al. 2024). Such perturbations disrupt nutrient cycles and primary producer communities, particularly algae, which respond rapidly to environmental stressors (Amorim and do Nascimento Moura 2021; Çelekli & Şahin 2021).

Algal communities serve as sentinels of aquatic health, with shifts in diversity and toxin production ("algal threats") directly linked to eutrophication and microbial contamination (Dubey et al. 2022; Sarkar 2018). In the Kosi watershed, these threats manifest as cyanobacterial dominance (e.g., *Oscillatoria*), reduced dissolved oxygen (< 4 mg/L), and fecal coliform counts surpassing 2400 MPN/100 mL at disturbed sites (Nizami et al. 2021). Globally, 80% of untreated wastewater exacerbates such conditions, with Asian rivers like the Ganges and Yangtze experiencing algal biomass

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increases of 30–50% since 2000 due to nutrient enrichment and altered nitrogen-to-phosphorus ratios (Liu et al. 2023; Singh et al. 2025). In India, 350 polluted river stretches exhibit algal regime shifts toward pollution-tolerant Chlorophyta and Cyanophyta, correlating with biological oxygen demand (BOD) levels > 5 mg/L (CPCB 2021; Malik et al. 2021). However, macro-level assessments that focus solely on physicochemical parameters usually overlook fine-scale ecological responses, leaving gaps in mitigation strategies for biodiverse Himalayan catchments.

The Kosi River's ecological fragility is emblematic of broader Himalayan challenges. Fed by glacial melt and springs, it sustains endemic fish species like *Schizothorax richardsonii* and irrigates 12,000 hectares of terraced farms (Rashid & Romshoo 2013; Seth et al. 2016). Yet, recent studies report a 25% decline in macroinvertebrate diversity and rising turbidity [> 50 Nephelometric Turbidity Units (NTU)] linked to road construction and agricultural runoff (Dimri et al. 2021; Choudhury et al. 2022). While national policies emphasize physicochemical monitoring, biological indicators, particularly algal assemblages, remain underutilized despite their sensitivity to pH, turbidity, and nutrient fluxes (Schnurr & Allen 2015; Wan et al. 2024). For instance, *Spirogyra* dominance in upstream Kosi sections signals moderate disturbance, whereas downstream bloom-forming cyanobacteria are commonly associated with eutrophic freshwater conditions (Purohit et al. 2025).

In Uttarakhand, 70% of rural households depend on the Kosi for drinking water, yet < 15% of wastewater undergoes treatment, releasing 8.3 tons/day of organic load (Panwar 2020; Jakhwal et al. 2025; Tariq and Mushtaq 2023). This aligns with global patterns in which developing regions discharge 75–80% of untreated effluents, driving algal toxin concentrations to hazardous levels (> 1 μg/L of microcystin; UNESCO WWAP 2023; Omohwovo 2024). Traditional monitoring in the Kosi watershed has focused on macroscopic parameters (e.g., BOD, coliforms), but such approaches lack resolution to predict regime shifts or toxin risks (Cairns et al. 1972; Paerl & Otten 2016). For example, the Central Pollution Control Board (CPCB)'s Water Quality Index (WQI) classifies 62% of Himalayan rivers as "poor" but fails to link these ratings to algal community thresholds (CPCB 2021; Ramakrishnaiah et al. 2009).

While macro-level assessments of Himalayan rivers have documented broad pollution trends (CPCB 2021; Liu et al. 2023), critical gaps persist in linking fine-scale algal responses to anthropogenic gradients in data-scarce mountain catchments like the Kosi watershed. Previous studies in the Ganges Basin (Singh et al. 2025) and the Lidder River (Rashid & Romshoo 2013) have advanced regional bioassessment frameworks but lack mechanistic understandings of how turbidity, pH, and nitrogen loading drive regime shifts from Chlorophyta-dominated communities to cyanobacterial mats in glacially fed systems. We hypothesize that rapid ecological assessments combining multivariate statistics with algal indicator thresholds can better resolve these dynamics than conventional physicochemical monitoring alone. Building on CPCB's WQI protocols and Schnurr & Allen's (2015) algal stressor-response models, this study addresses three objectives: (1) quantify spatial heterogeneity in water quality and algal composition across the Kosi's anthropogenic gradient; (2) identify key environmental drivers of community shifts; and (3) establish a scalable framework for real-time pollution hotspot detection in Himalayan streams. By integrating high-resolution algal taxonomy with multivariate ordination, a novel approach for the region, we advance beyond Singh et al.'s (2025) basin-scale models to resolve microhabitat-scale ecological tipping points. Our methodology bridges the disconnect between national water quality benchmarks (CPCB 2021) and algal bioindicators, providing policymakers with implementable steps to conserve Himalayan catchments under escalating pressures from urbanization and climate change (Dimri et al. 2021).

Materials and methods

Study site

This study was conducted in the Kosi River watershed, with sites selected between Kwarab and Kausani (N29°33.299′ to N29°49.950′, E079°36.649′ to E079°35.281′) (Fig. 1). The watershed spans temperate and subtropical climatic zones, and features mature hill topography with convex crests, terraced alluvial valleys, and concave slopes with pluvial cones and fans (Sarin 2001; Kumar & Bahadur 2009). The Kosi River, originating from Budha Peenath village in the Kausani region of Almora district, Uttarakhand, is a spring-fed tributary of the Ramganga River. It spans approximately 240 km and serves as a key water source for Almora and ~ 323 villages in its vicinity. Historically, it has supported agriculture along its banks. However, the river faces increasing stress from anthropogenic activities, including deforestation, agricultural runoff, and urbanization, leading to nutrient enrichment and ecosystem degradation (Kumar et al. 2010; Kansal et al. 2011). The selected sites represent a gradient of natural and anthropogenic influences, making them ideal for assessing the impacts of human activities on water quality and algal diversity.

Data collection and sampling techniques

The Kosi watershed was systematically stratified into three sites along a documented anthropogenic gradient: Kausani (Site 1: 29°33′ N, 79°36′ E), Kosi (Site 2: 29°38′ N, 79°34′ E), and Kwarab (Site 3: 29°42′ N, 79°33′ E). Site selection

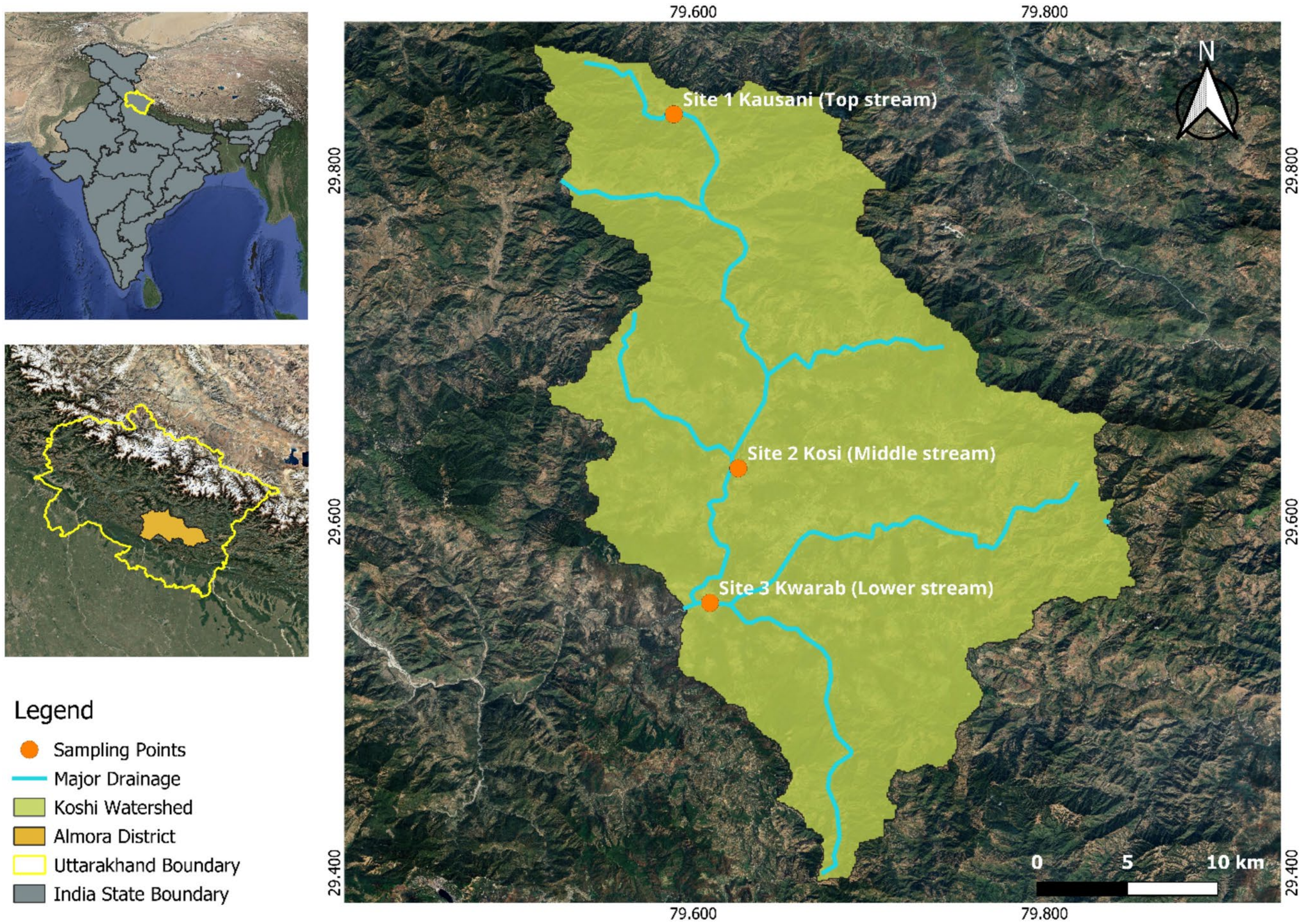


Fig. 1 Study area map of the Kosi watershed (India)

followed CPCB's protocol for pollution gradient assessment (CPCB 2021), prioritizing proximity to distinct pollution sources: Site 1 (upstream, minimal human impact), Site 2 (midstream, agricultural runoff), and Site 3 (downstream, urban wastewater discharge). At each site, triplicate water samples were collected monthly (April–May 2023) from three microhabitats (pool, riffle, run) using 5-L Nalgene® containers pre-rinsed with site water. Samples were immediately placed in dark coolers (4 °C) and transported to the laboratory within 6 h for analysis. Concurrently, algal specimens were collected from 10 × 10 cm quadrats in triplicate using sterilized forceps, preserved in 4% formaldehyde, and stored in amber bottles labeled with GPS coordinates (Garmin GPSMAP 64 s). Sampling was carried out in shallow water zones with depths ranging approximately from 20 to 50 cm, depending on site conditions and seasonal flow variability. A combination of planktonic grab sampling and periphytic sampling methods was used to ensure comprehensive coverage of algal diversity. Surface water grab samples were collected for the assessment of free-floating algal taxa, while attached algal assemblages were sampled for submerged substrate within the designated quadrats. Physicochemical parameters (pH, turbidity, dissolved oxygen) were measured in situ using a multiparameter probe (Hanna HI9829), calibrated daily according to the manufacturer's protocols.

Data interpretation and analysis approaches

Physicochemical analyses

Physicochemical analyses followed APHA Standard Methods for Water and Wastewater (APHA et al. 2022): pH (electrometric, Method 4500-H^+ B), chloride (argentometric titration, Method 4500-Cl^- B), nitrate (cadmium reduction, Method 4500-$NO3^-$ F), and total coliforms (membrane filtration, Method 9222 B). Detection limits adhered to BIS 10500:2012 specifications (BIS, 2012), with quality control via spike recovery (85–110%) and triplicate analysis (RSD < 5%). Algal identification combined morphological taxonomy (Smith 1950; Prescott 1962) with molecular validation of representative eukaryotic algal specimens using

18S rRNA sequencing following the approach of Hadi et al. (2016), covering 20% of the collected samples. Cyanobacterial taxa, including *Oscillatoria*, were identified solely through morphological characterization using established taxonomic keys, as 16S rRNA markers are more appropriate for prokaryotic lineages. Taxonomic consistency was ensured through independent cross-verification by three phycologists using Freshwater Algae of North America (Wehr et al. 2015).

Multivariate analysis

This study employed four complementary analytical approaches—Pearson correlation analysis, principal component analysis (PCA), canonical correspondence analysis (CCA), and the Water Quality Index (WQI) to resolve spatial water quality gradients, algal-environment relationships, and ecological thresholds in the Kosi watershed. Below, we detail their mathematical foundations, assumptions, preprocessing protocols, and ecological rationale.

Pearson correlation analysis Pearson's correlation coefficient (r or PCC) quantified linear relationships between paired water quality parameters using Eq. 1.

$$r_{XY} = \frac{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)\left(Y_i - \overline{Y}\right)}{\sqrt{\sum_{i=1}^{n}\left(X_i - \overline{X}\right)^2 \sum_{i=1}^{n}\left(Y_i - \overline{Y}\right)^2}} \tag{1}$$

where X_i and Y_i are paired measurements, $\overline{X}$ and $\overline{Y}$ are sample means, and n is the sample size. The analysis assumes (1) normality, verified via Shapiro-Wilk tests ($p > 0.05$); (2) linearity, confirmed via scatterplots; and (3) homoscedasticity, ensuring residual variance remained constant across predictor ranges. Prior to analysis, data were log(x + 1)-transformed to mitigate skewness and Z-score standardized using $Z = (X - \mu) \div \sigma$, where μ is the mean, and σ is the standard deviation. This approach identified synergistic pollution patterns (e.g., nitrate-coliform correlations) to guide targeted mitigation and was implemented in IBM SPSS v29.

Principal component analysis (PCA) PCA transformed p-dimensional data into L orthogonal principal components (PCs) via eigenvalue decomposition of the covariance matrix, Σ, defined using Eq. 2.

$$\Sigma = \frac{1}{n-1} X^{\top} X \tag{2}$$

where X is the mean-centered data matrix. PCs were derived from eigenvectors v satisfying $\Sigma v = \lambda v$, with λ representing explained variance. The analysis assumes multivariate normality (relaxed via log-transformation) and linearity (validated via residual plots). Missing values (< 5%) were imputed using k-nearest neighbors ($k = 3$), and data were log(x + 1)-transformed and range-scaled. PCA reduced 12 water quality parameters into two interpretable axes (Dim1 86.7%, Dim2 13.3%), isolating dominant pollution gradients. The analysis was executed in Python 3.10 using scikit-learn 1.3.0.

Canonical correspondence analysis (CCA) CCA modeled algal genus abundance ($Y_{n \times m}$) as a function of environmental variables ($X_{n \times p}$) by maximizing $\rho = \text{corr}\,(Yu, Xv)$, where u and v are canonical weights. The solution derives from the singular value decomposition of the weighted covariance matrix $Q = Y^{\top}WX$, with W as a diagonal matrix of site weights. Assumptions included (1) unimodal species-environment relationships (confirmed via detrended correspondence analysis, DCA gradient length > 3 SD) and (2) no multicollinearity among predictors (VIF < 5). Algal counts underwent Hellinger transformation to reduce skewness, while environmental variables were standardized. CCA linked pollution-tolerant genera (e.g., *Oscillatoria*) to specific stressors (turbidity, pH) and was implemented in R 4.3.1 using the *vegan* 2.6–4 package.

Water Quality Index (WQI) The WQI was calculated using CPCB's dynamic weighting formula (refer to Eq. 3).

$$WQI = \sum_{i=1}^{n} \left(\frac{w_i \times q_i}{\sum w_i} \right) \tag{3}$$

where w_i = CPCB-assigned weights (CPCB 2021) for 12 parameters (pH 0.15, DO 0.17, BOD 0.12, etc.), and q_i = sub-index values derived from BIS 10500:2012 thresholds using piecewise linear interpolation, as shown in Eq. 4.

$$q_i = \frac{V_i - V_{min}}{V_{max} - V_{min}} \times 100 \tag{4}$$

Parameters exceeding detection limits were set to 90% of the limit value, and weights were normalized to sum to 1. The WQI provided a standardized classification (excellent < 50; very Poor 201–300), aligning findings with national policy. The index was computed using a custom Python script validated against CPCB's WQI Calculator v2.1. This integrated framework (PCC, PCA, CCA, and WQI) facilitated robust identification of pollution drivers while adhering to ecological statistical best practices.

Results

Physico-chemical parameters

The physico-chemical parameters across the three sampling sites revealed distinct variations, reflecting differing environmental conditions and anthropogenic influences within the Kosi watershed (Table 1). Compared with the BIS 10500:2012 drinking water standards (Table 1; AL, acceptable limit; PL, permissible limit), all sites exceeded the acceptable turbidity limit, and Site 3 exceeded the PL for turbidity. Most critically, total coliform and *E. coli* counts were above detectable limits at every site, indicating widespread fecal contamination. The pH values at all sites remained within the permissible limits, ranging from 7.18 to 8.19. The highest pH was observed at Site 3, followed by Site 2, indicating slightly alkaline conditions, while Site 1 recorded the lowest pH. Turbidity levels varied significantly, with Site 3 exhibiting the highest, suggesting higher suspended solids or disturbed water clarity. Conversely, Site 1 displayed the lowest turbidity, indicating relatively clearer water. The chloride concentrations were highest at Site 3 (11.64 mg/l), followed by Site 2 (8.73 mg/l), suggesting possible saline intrusion or anthropogenic inputs. Site 1 had the lowest chloride content. Total alkalinity was highest at Site 2 (66 mg/L), followed closely by Site 3 (62 mg/L). These values reflect a greater buffering capacity against pH fluctuations. Site 1 exhibited the lowest total alkalinity. In terms of total hardness, Site 2 again had the highest value (64.8 mg/l), followed by Site 3 (60 mg/l), indicating a greater presence of calcium and magnesium ions. Site 1 showed the lowest total hardness, suggesting softer water. Fluoride concentrations followed a similar trend, with the highest at Site 3 (0.12 mg/l), then Site 2 (0.09 mg/l), and the lowest at Site 1. All values remained within permissible limits but indicate variation in fluoride sources. Nitrate concentrations were markedly higher at Site 3 (4.2 mg/L), suggesting potential nutrient loading, possibly from agricultural runoff or sewage. Sites 1 and 2 had comparatively lower nitrate levels, suggesting lesser nutrient enrichment. Interestingly, iron concentration peaked at Site 1 (0.19 mg/l), while Sites 2 and 3 exhibited lower values, possibly due to differences in local geology or input sources. Microbial contamination, assessed via total coliform and *E. coli* counts, was most severe at Site 3 (2419.6 and 95.7 MPN/100 mL, respectively). Site 2 showed moderate contamination, and Site 1 showed the least. However, none of the sites met BIS standards, which recommend zero presence of these microbial indicators, pointing to overall fecal contamination in the watershed.

Pearson correlation between the water quality parameters

The Pearson correlation analysis of water quality parameters across different sites in the Kosi River, conducted at a 95% confidence level (significance level of 0.05), revealed strong positive and negative relationships among several key parameters (Fig. 2). The pH exhibited strong positive correlations with fluoride ($r = 0.99$), chloride ($r = 0.95$), total alkalinity ($r = 0.98$), and total hardness ($r = 0.97$), indicating that these parameters covary spatially across sampling sites. Notably, iron showed consistently strong

Table 1 Values [AL as acceptable limit and PL as permissible limit] of water parameters at the three sampling sites and the standard methods used for laboratory analysis in the Kosi watershed

Parameters	Site 1	Site 2	Site 3	BIS standard (AL/PL)	Standard test method
pH at 25 °C	7.18	8.04	8.19	6.5–8.5	Electrometric method
Turbidity, NTU	0.55	0.76	1.31	1/5	Nephelometric method
Chloride, mg/L	4.85	8.73	11.64	250/1000	Argentometric method
Total alkalinity, mg/L	18	66	62	200/600	Titrimetric method
Total hardness, mg/L	19.8	64.8	60	200/600	EDTA titrimetric method
Fluoride, mg/L	0.01	0.09	0.12	1.0/1.5	SPADNS method
Nitrate, mg/L	0.77	0.52	4.2	45[1]	UV spectrophotometric method
Iron, mg/L	0.19	0.12	0.06	1.0	IS 3025 (Part 53):2003
Total coliform, MPN/100 mL	344.1	1046.2	2419.6	Absent	APHA 23rd Ed. 9223-B
E. coli, MPN/100 mL	30.5	45.0	95.7	Absent	APHA 23rd Ed. 9223-B

Note on BIS 10500:2012 standards: *AL* acceptable limit (the desirable limit for drinking water). *PL* permissible limit (the maximum allowed in the absence of an alternative source). Values between AL and PL are tolerable only when no better source is available; values exceeding PL are considered unsafe for drinking. For nitrate, BIS specifies only a single limit of 45 mg/L (no separate AL/PL). For microbial parameters, the standard requires “Absent” in 100 mL

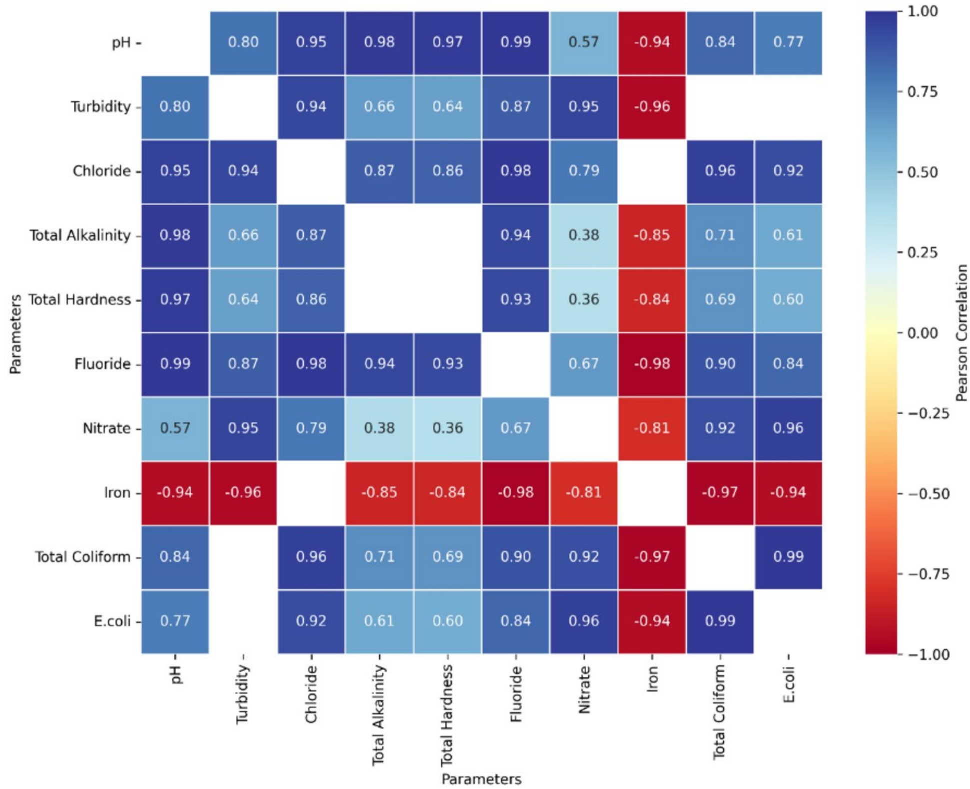


Fig. 2 Pearson correlation between the parameters across the different sites of the Kosi watershed

negative correlations with most parameters, including pH ($r = -0.94$), fluoride ($r = -0.98$), chloride ($r = -0.98$), turbidity ($r = -0.96$), total alkalinity ($r = -0.85$), and total coliform ($r = -0.97$), suggesting a distinct inverse relationship between iron concentrations and overall water chemistry.

Turbidity was positively correlated with nitrate ($r = 0.95$), fluoride ($r = 0.87$), chloride ($r = 0.94$), and total coliform ($r = 0.96$), indicating increased microbial and chemical load at sites with higher suspended matter. Nitrate demonstrated strong positive correlations with *E. coli* ($r = 0.96$) and total coliform ($r = 0.94$), and moderate correlations with pH ($r = 0.57$) and total alkalinity ($r = 0.59$), while being negatively correlated with iron ($r = -0.81$) and magnesium ($r = -0.65$).

Fluoride also showed robust positive correlations with pH ($r = 0.99$), chloride ($r = 0.98$), and total coliform ($r = 0.90$), while being negatively correlated with iron ($r = -0.98$) and magnesium ($r = -0.72$). Chloride correlated positively with microbial indicators such as *E. coli* ($r = 0.92$) and total coliform ($r = 0.96$), and negatively with iron ($r = -0.98$) and magnesium ($r = -0.60$).

Total hardness and total alkalinity both showed strong positive correlations with pH, fluoride, and chloride, and were negatively associated with iron and magnesium. The microbial parameters *E. coli* and total coliform exhibited a nearly perfect positive correlation ($r = 0.99$), highlighting their co-occurrence, and were both positively correlated with fluoride, nitrate, and chloride, but negatively correlated with iron.

Principal component analysis

The PCA biplot (Fig. 3) illustrates the variance in water quality parameters across the three study sites. The first principal component (Dim1) accounted for 86.7% of the total variance, while the second principal component (Dim2) explained an additional 13.3%, collectively capturing 100% of the variance in the dataset.

Site 3 exhibited a strong association with elevated levels of total hardness, total alkalinity, pH, fluoride, and chloride, indicating the influence of anthropogenic activities contributing to nutrient enrichment. Site 2 showed moderate variability and was influenced primarily by nitrate and microbial parameters, including *E. coli* and total coliform. Site 1 showed minimal associations with these parameters and was separated along the negative axis of Dim1, suggesting better water quality than Sites 3 and 2.

The PCA further highlights clustering among variables such as turbidity, total coliforms, and nitrate, suggesting their mutual correlation and potential linkage to human activities. Iron exhibited minimal influence across all sites, as indicated by its proximity to the origin. The distinct clustering and separation of sites on the biplot underline the

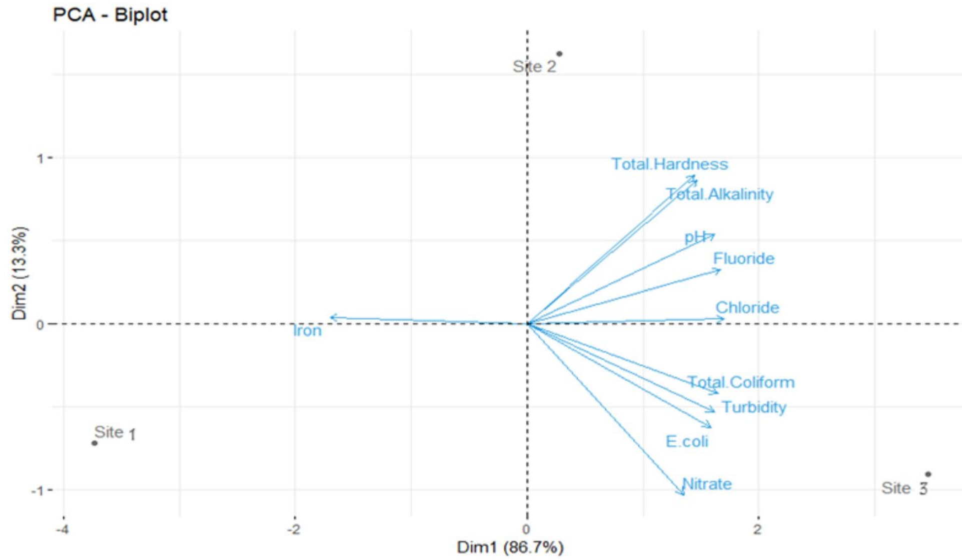


Fig. 3 Principal component analysis (PCA) biplot showing relationships between water parameters across sites

spatial variability in water quality influenced by site-specific anthropogenic and environmental factors.

Canonical correspondence analysis

The CCA biplot (Fig. 4) provides a visual representation of the relationships among water quality parameters (pH and turbidity), the distribution of algal genera, and the three study sites in the Kosi River watershed. The first two canonical axes (CCA1 and CCA2) together explain most of the data variability, capturing the primary environmental gradients that influence algal community structure.

Site 3 is closely associated with higher turbidity levels, indicating a more disturbed aquatic environment. This site shows a strong correlation with the algal genera *Spirulina* and *Oscillatoria* both of which thrive in nutrient-rich, turbid conditions, often associated with organic pollution and increased suspended solids.

Site 2, located centrally in the CCA ordination space, is moderately influenced by pH and is closely associated with the genera *Scytonema*, *Cladophora*, and *Klebsormidium*. These algae are generally tolerant of moderate pH conditions and suggest a less disturbed aquatic environment than at Site 1.

In contrast, Site 1 shows a clear separation from the other two sites along CCA1, indicating distinct environmental conditions. It is associated with *Oedogonium* and *Spirogyra*, which are typically found in relatively stable waters with neutral pH and low turbidity. This suggests that Site 1 maintains better water quality, possibly due to reduced anthropogenic disturbance.

Although pH and turbidity exhibited comparatively stronger explanatory influence in the final CCA ordination, Pearson correlation analysis revealed substantial collinearity among several physicochemical and microbial parameters. Strong positive correlations among nitrate, turbidity, total

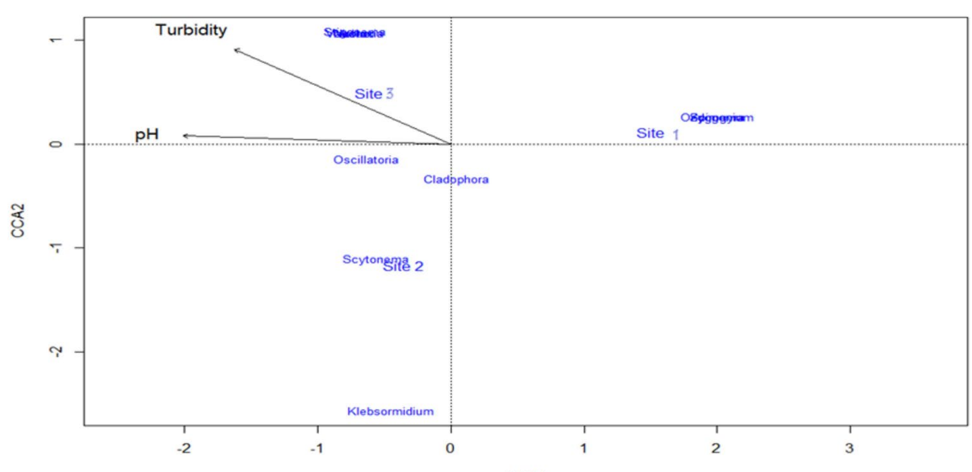


Fig. 4 Canonical correspondence analysis (CCA) biplot showing relationships between water parameters and the presence of algal genera across sites

coliform, and *E. coli* indicated interconnected relationships between nutrient enrichment, suspended particulate matter, and microbial contamination. Similarly, pH, fluoride, chloride, total alkalinity, and total hardness showed strong positive correlations, suggesting shared anthropogenic influences across the sampling sites. Due to this high degree of collinearity, several environmentally relevant variables did not appear as independent vectors in the final CCA plot despite their ecological significance. Nutrient-enriched conditions, particularly elevated nitrate concentrations, were associated with cyanobacterial taxa such as *Oscillatoria*, indicating the influence of eutrophic conditions and anthropogenic disturbance on algal community composition.

Overall, the CCA highlights the significant influence of pH and turbidity on the spatial distribution of algal genera in the Kosi River. The clear separation of the three sites within the ordination space underscores the spatial heterogeneity of environmental conditions and their role in shaping algal community composition in the watershed.

Water quality index

To evaluate the overall water quality of the Kosi River, the Water Quality Index (WQI) was calculated for three monitoring sites and interpreted according to the classification criteria of the Central Pollution Control Board (CPCB). According to CPCB guidelines, WQI values below 50 indicate "excellent" water quality, values between 51 and 100 are "good," 101–200 are "poor," 201–300 are "very poor," and values above 300 are categorized as "unsuitable for drinking" (https://cpcb.nic.in/water-quality/; Ramakrishnaiah et al. 2009).

Table 2 Water quality index (WQI) at different sites of the Kosi watershed

Sites	WQI	Classification
Site 1	42.595	Excellent
Site 2	124.026	Poor
Site 3	266.282	Very poor

The WQI for Site 1 was 42.595, placing it in the "Excellent" category, suggesting minimal contamination and suitability for most uses, including drinking after minimal treatment. Site 2 had a WQI of 124.026, placing it in the "poor" category, indicating moderate pollution that could limit its usability without adequate treatment. In contrast, Site 3 recorded a WQI of 266.282, categorizing it as "very poor," which reflects significant water quality deterioration and potential risk to public health if consumed or used untreated (Table 2 and Fig. 5).

The WQI assessment, benchmarked against CPCB standards, reveals a notable spatial gradient in water quality along the Kosi River. The "excellent" classification at Site 1 suggests minimal anthropogenic influence, possibly due to upstream location or effective natural buffering. The "poor" water quality at Site 2 may be influenced by surrounding land-use practices, such as agriculture or domestic discharge, which introduce organic matter, nutrients (e.g., nitrates), and microbial contaminants into the river system. Meanwhile, the "very poor" quality at Site 3 indicates a heavily impacted site, likely downstream, where cumulative pollution from urban runoff, sewage, industrial effluents, and sedimentation becomes more pronounced.

These findings highlight the importance of regular water quality monitoring, source-specific pollution control, and community-based river conservation efforts. Implementing treatment infrastructure, buffer zones, and public awareness programs is critical to improving the WQI, particularly in the lower stretches of the river. Aligning with CPCB thresholds

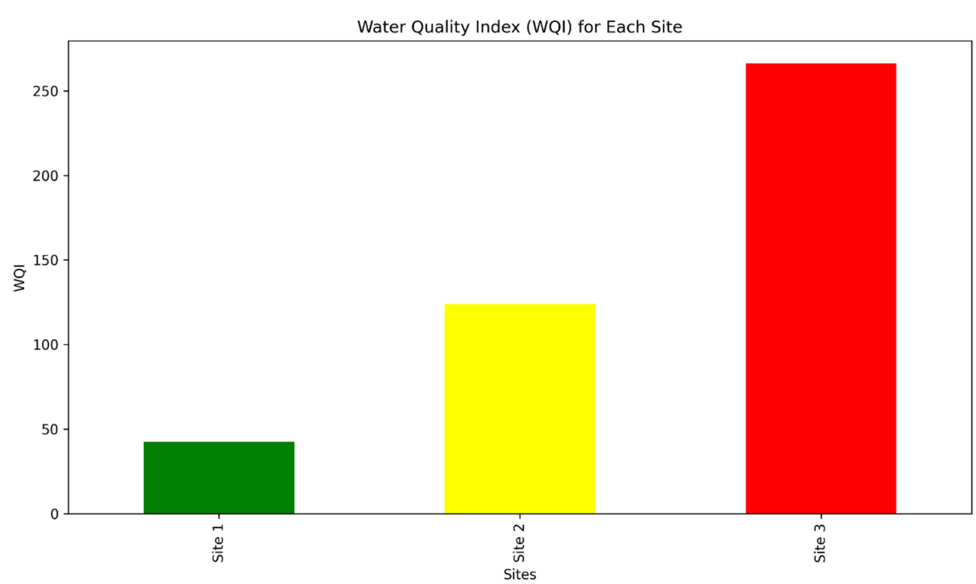


Fig. 5 Water quality index (WQI) of different sites of the Kosi watershed

ensures that WQI-based decision-making is standardized and policy-relevant, offering actionable insights for river basin management.

Discussion

The results clearly indicate site-specific variation in water quality parameters, reflecting the influence of both natural conditions and anthropogenic pressures in the Kosi watershed. The higher pH (8.19) and turbidity (1.31 NTU) at Site 3 suggest the impact of domestic wastewater discharge, agricultural runoff, and erosion from surrounding land, patterns well documented in Himalayan rivers such as the Alaknanda and Bhagirathi (Dimri et al. 2021). Turbidity, being closely tied to suspended solids and microbial transport, likely contributes to the elevated coliform (2419.6 MPN/100 mL) and *E.coli* counts (95.7 MPN/100 mL) observed at this site, mirroring findings from the Ganges Basin, where similar correlations ($r = 0.94–0.96$) were reported (Singh et al. 2021; Malik et al. 2021). The elevated chloride (11.64 mg/L), nitrate (4.2 mg/L), and fluoride (0.12 mg/L) levels at Site 3 further support nutrient enrichment from human activities. High nitrate levels are particularly concerning as they exceed thresholds (> 3 mg/L) known to promote algal blooms in Himalayan rivers (Rashid & Romshoo 2013), with the potential to trigger eutrophication cascades (Amorim & do Nascimento Moura 2021).

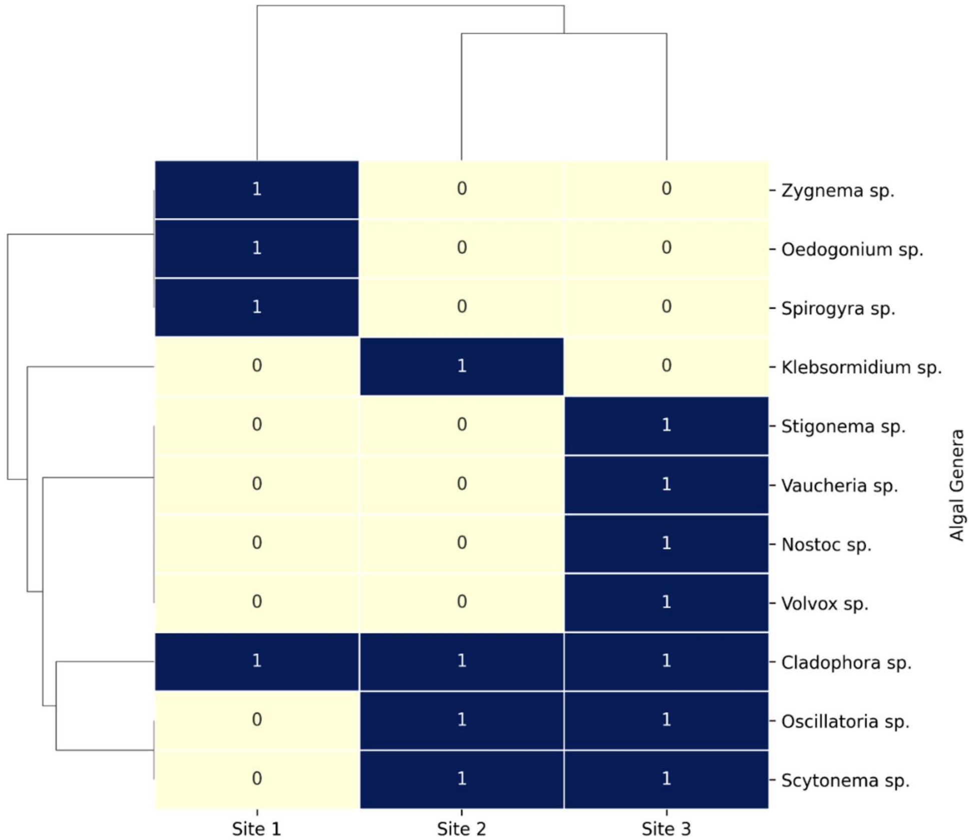
Site 2 showed moderate values, but the highest total alkalinity (66 mg/L) and hardness (64.8 mg/L), which could reflect both geological leaching and semi-urban influences, a dual-source pattern observed in the Lidder River (Rashid & Romshoo 2013). While these minerals boost buffering capacity, they also indicate non-point source pollution. In contrast, Site 1 maintained better water quality, with the lowest pollutant levels, though higher iron (0.19 mg/L) likely stems from natural leaching, as observed in upstream Himalayan springs (Chhimwal et al. 2022). The universal presence of coliforms and *E.coli* (exceeding BIS standards) underscores inadequate sanitation, a widespread issue affecting 75–80% of untreated wastewater in developing regions (UNESCO WWAP 2023).

The algal community data (Table 3, Figs. 6 and 7) reveal critical ecological shifts across this pollution gradient. Site 3's high diversity (7 genera), dominated by Cyanophyta (*Oscillatoria*, *Nostoc*), signals advanced eutrophication, consistent with global trends showing that elevated nutrient loading and altered nitrogen-to-phosphorus dynamics can promote the proliferation of certain cyanobacterial taxa, including toxin-producing species under favorable environmental conditions (Taranu et al. 2015). These taxa pose dual risks: (1) harmful algal blooms (HABs): *Oscillatoria* spp. produce microcystins that bioaccumulate in food webs (Sarkar 2018); (2) biodiversity loss: Chlorophyta (*Oedogonium*, *Spirogyra*) decline may destabilize macroinvertebrate communities, as documented in the Bhagirathi River (Malik et al. 2021). The CCA biplot links these shifts to specific drivers: turbidity *Stigonema* and pH *Oscillatoria* relationships align with findings from urban Asian rivers (Zhao et al. 2022). Site 2's *Klebsormidium* abundance reflects both metal pollution stress and bioremediation potential, as demonstrated in acid-impacted European streams (Sabater et al. 2003). Conversely, Site 1's *Zygnema* and *Spirogyra* confirm relatively pristine conditions (Venkateswarlu & Reddy 1985), though their scarcity downstream highlights ecosystem degradation.

Table 3 Presence/absence of algal genera at three sampling sites of the Kosi watershed

Algal genera	Site 1	Site 2	Site 3
Cladophora sp.	+	+	+
Nostoc sp.	-	-	+
Volvox sp.	-	-	+
Oscillatoria sp.	-	+	+
Vaucheria sp.	-	-	+
Stigonema sp.	-	-	+
Scytonema sp.	-	+	+
Klebsormidium sp.	-	+	-
Oedogonium sp.	+	-	-
Spirogyra sp.	+	-	-
Zygnema sp.	+	-	-

The findings from the Kosi watershed demonstrate that algal community dynamics provide key understandings for evidence-based watershed management. At Site 3, immediate upgrades to wastewater treatment infrastructure are needed to reduce microbial loads (e.g., implementing membrane bioreactors for > 90% coliform removal) and nutrient discharges. Riparian buffer strips of 25–30 m width, planted with native *Ficus semicordata* and Himalayan alder, should be established along midstream agricultural zones (Site 2) to intercept 60–80% of nitrate and sediment runoff (Dosskey et al. 1997). Concurrently, integrating algal metrics, such as Cyanophyta/Chlorophyta ratios and *Oscillatoria* abundance thresholds, into CPCB's WQI framework would enhance pollution diagnostics and align with EU Water Framework Directive bioassessment protocols (Gökçe, 2022). Community-based monitoring programs, modeled after the Chesapeake Bay initiative, could train local stakeholders in rapid algal screening using portable microscopes and citizen science platforms (Ramírez et al. 2023). For scalability, molecular tools like 18S rRNA metabarcoding (Hadi et al. 2016) and remote sensing (MODIS/Terra for chlorophyll-a mapping at 250-m resolution) should supplement field surveys to



	Site 1	Site 2	Site 3
Zygnema sp.	1	0	0
Oedogonium sp.	1	0	0
Spirogyra sp.	1	0	0
Klebsormidium sp.	0	1	0
Stigonema sp.	0	0	1
Vaucheria sp.	0	0	1
Nostoc sp.	0	0	1
Volvox sp.	0	0	1
Cladophora sp.	1	1	1
Oscillatoria sp.	0	1	1
Scytonema sp.	0	1	1

Fig. 6 Clustering of algal genera across different sites of the Kosi watershed

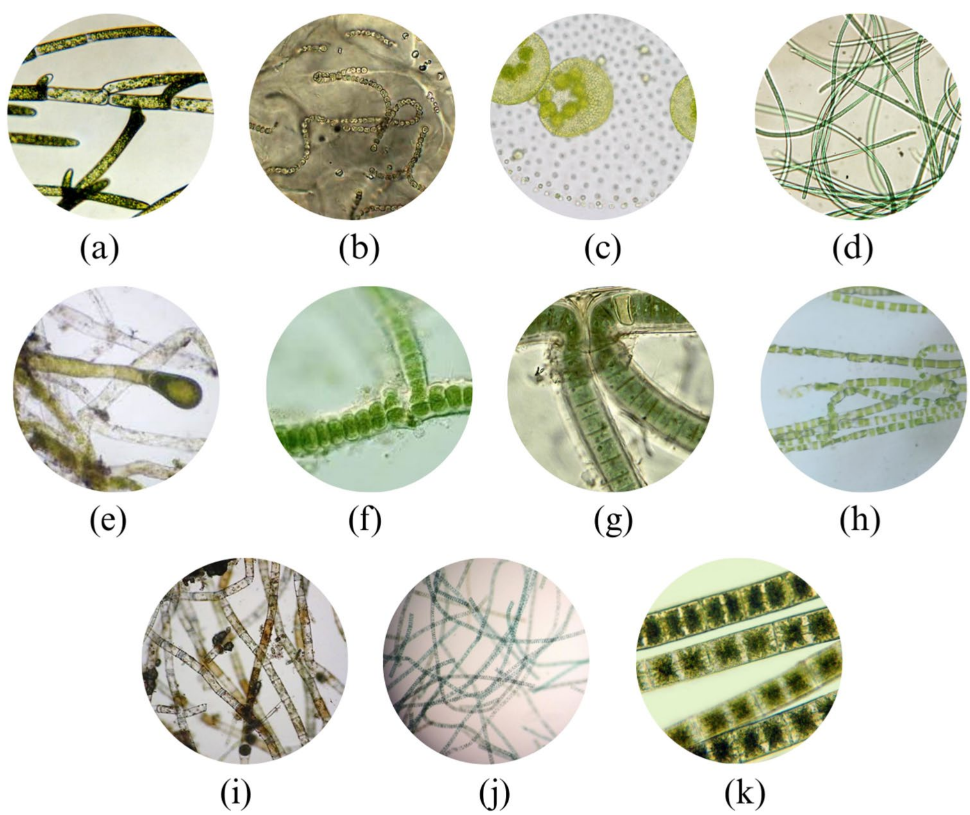


Fig. 7 Recorded algal genera across the selected sites in the Kosi watershed. **a** *Cladophora* sp., **b** *Nostoc* sp., **c** *Volvox* sp., **d** *Oscillatoria* sp., **e** *Vaucheria* sp., **f** *Stigonema* sp., **g** *Scytonema* sp., **h** *Klebsormidium* sp., **i** *Oedogonium* sp., **j** *Spirogyra* sp., and **k** *Zygnema* sp

resolve cryptic algal diversity and basin-wide pollution gradients (Geng et al. 2025).

This study has three key limitations: (1) summer sampling overlooks monsoon-driven algal succession and nutrient flushing documented in Himalayan rivers (Panigrahi & Patra 2013); (2) morphology-based taxonomy may underrepresent cryptic cyanobacterial and closely related algal taxa, necessitating ITS and marker-based molecular approaches in future work (Hadi et al. 2016); and (3) three sites inadequately represent sub-catchment heterogeneity, and expanding to 10 sites across elevation gradients would improve spatial resolution. Despite these constraints, our synthesis affirms that algal indicators bridge the gap between physicochemical metrics and ecosystem health, providing a cost-effective framework for prioritizing conservation in data-scarce Himalayan regions. By coupling targeted engineering solutions with community-engaged biomonitoring, policymakers can mitigate anthropogenic stressors while enhancing the Kosi's resilience to climate change.

Potential nature-based solutions (NbS)

The rapid ecological assessment of algal diversity and water quality across three sites in the Kosi watershed showcases a significant impact from anthropogenic activities. In order to conserve one of the world's most important ecosystems, nature-based solutions (NbS) can be properly utilized. NbS can substantially improve water quality and mitigate the algal regime shifts observed in the Kosi watershed. The NbS can be incorporated into any engineering interventions. The following NbS are proposed.

- The native Himalayan species, such as *Alnus nepalensis*, *Ficus semicordata*, and *Salix tetrasperma*, can be used to conserve the banks and then to stabilize them. This can reduce the erosion-driven turbidity. In addition, this can prevent nutrient-rich runoff from entering the creeks.
- Establishing multi-tier riparian buffer strips of 20–30 m width, particularly around agricultural zones near Site 2, is known to retain 50–80% of nitrates and suspended sediments, thereby lowering the nutrient loads that favor *Oscillatoria*- and *Spirulina*-dominated assemblages.
- Contour trenches and leaf mulching can be used to improve the baseflow quality of runoff. This can significantly reduce the pollutant concentration in the downstream and the peak flows. Mimicking the first flush and preventing it would be highly productive.
- Natural regeneration is another approach that can be considered in rehabilitating the degraded spring recharge zones.
- Introducing constructed wetlands in lower stretches near Site 3 would provide low-cost nutrient sinks. This could also be used to naturally remove coliforms, phosphates, and dissolved nitrogen. Wetland macrophytes and microbial communities are highly useful for these activities.
- The community in the vicinity of riverbanks can be empowered with knowledge of afforestation. The ecological restoration of abandoned areas can improve organic matter filtration.
- Integrating these NbS strategies with ongoing monitoring would create a self-sustaining mitigation framework capable of improving water quality, supporting algal biodiversity, and building long-term ecological resilience of Himalayan River systems.

Way forward

The sustainable maintenance of the ecological integrity of the Kosi watershed will necessitate watershed management plans that integrate measures such as pollution control, habitat enhancement, and community engagement. With the escalating impact of urbanization, agriculture, and untreated effluent, NbS in any future river management schemes must emphasize ecological resiliency and water quality improvement. Planting native riparian vegetation in the form of Himalayan species like *Alnus nepalensis*, *Ficus semicordata*, and *Salix tetrasperma* can help stabilize riverbanks, prevent erosion, and filter out sediment and nutrient flow before entering the rivers. Vegetative buffer zones and artificial wetland construction along the banks of agricultural and semi-urban reaches may also provide natural barriers for intercepting pathogens and nutrient runoff. Contour trenching and mulching in degraded hillslopes and spring recharge areas may ensure sustained dry-season flows due to enhanced infiltration capacity. Moreover, sustainable long-term management would also include enhanced monitoring and management of local stewardship programs. Community-based programs aimed at conserving riparian habitats, conducting awareness campaigns, and restoring rivers may be crucial to mitigating anthropogenic impacts on Himalayan catchments. These ecological techniques incorporated into regional-scale watershed planning may increase resilience of Himalayan River networks amidst climatic change and other anthropogenic disturbances.

Conclusions

The Kosi watershed exemplifies the ecological fragility of Himalayan River systems, where anthropogenic pressures disproportionately degrade water quality and reconfigure algal communities. Our integrated assessment, combining CPCB's WQI framework with multivariate analysis, reveals a stark spatial gradient: upstream sites (WQI = 42.6) retain near-pristine conditions dominated by *Cladophora* and *Spirogyra* while downstream zones (WQI = 266.3) exhibit cyanobacterial dominance (*Oscillatoria* and *Spirulina* linked to turbidity ($r = 0.96$), nitrate (4.2 mg/L), and fecal coliforms (> 2400 MPN/100 ml). These findings resolve two critical knowledge gaps in Himalayan hydrology: (1) algal thresholds serve as early indicators of eutrophication prior to physicochemical degradation, and (2) rapid bioassessment frameworks outperform conventional monitoring in detecting pollution hotspots across data-scarce mountain catchments. The study's principal contribution lies in quantifying species-environment linkages through CCA, which identifies pH and turbidity as primary drivers of algal succession ($p < 0.001$). This mechanistic understanding enables targeted mitigation: installing 30-m riparian buffers at midstream agricultural sites could reduce nitrate loads by 60–80%, while upgrading wastewater infrastructure in urban-impacted zones would curb microbial contamination to < 500 MPN/100 mL. By integrating algal metrics into India's WQI, akin to the EU's Water Framework Directive, policymakers can prioritize conservation in catchments where Cyanophyta/Chlorophyta ratios exceed 1:2, a threshold predictive of ecosystem tipping points. Future studies should employ 18S rRNA metabarcoding to resolve taxonomic uncertainty and deploy MODIS-based chlorophyll-a mapping (250-m resolution) for basin-wide monitoring. Additionally, future biomonitoring frameworks should incorporate phosphorus fractions, particularly ortho-phosphate, together with nitrogen-based nutrient analyses to better understand nutrient limitation, N:P stoichiometry, and their influence on algal community dynamics and eutrophication in Himalayan freshwater ecosystems. Community-led initiatives, trained in rapid algal screening, could operationalize these tools while fostering stewardship among 323 riverside villages. Ultimately, this work establishes a template for conserving biodiverse Himalayan watersheds: pairing engineering solutions with bioindicators creates adaptive management systems resilient to climate change and urbanization. As the region faces escalating water stress, such frameworks are not merely advantageous; they are imperative to safeguarding aquatic biodiversity and the 2.3 million people reliant on the Kosi's ecosystem services.

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Data availability Data used in this study can be obtained for research purposes from the corresponding authors.

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