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Seasonality and pollution effects on water quality based on phytoplankton and physicochemical variables in the Duhok Dam Lake

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Duhok Dam is a key multipurpose reservoir in northern Iraq that is increasingly exposed to ecological pressures arising from rapid population growth, climate variability, and localized anthropogenic pollution. In this study, we investigated the seasonal and spatial variability of phytoplankton communities and associated physicochemical variables to evaluate water quality conditions and to assess the reliability of phytoplankton communities as bioindicators of environmental stress. The samples were collected six times over nine months in 2021; 36 samples were collected from six sampling stations representing different pollution sources, across four distinct seasons. Multivariate analyses (PCA) combined with statistical testing revealed pronounced seasonal differentiation in both biological and physicochemical variables (ANOSIM, $p < 0.0001$). Spring conditions were shaped by precipitation-driven nutrients. This favored mixotrophic phytoplankton, especially *Euglena* sp. Conversely, summer thermal stratification promoted warm-adapted, pollution-tolerant taxa, such as *Oscillatoria* sp. and *Peridinium cinctum*. There was also marked spatial heterogeneity across the reservoir. Sites with untreated domestic wastewater had elevated COD_{SMn} and NO_3-N concentrations and were dominated by pollution-tolerant diatoms like *Nitzschia acicularis*. Areas impacted by natural sulfur springs hosted distinct phytoplankton assemblages, including *Merismopedia* sp. and *Navicula* sp., highlighting the influence of local geochemical conditions. Overall, our results demonstrate that the phytoplankton community structure responds rapidly and sensitively to both anthropogenic and natural stressors, highlighting its value as an integrative bioindicator of reservoir water quality. This study provides a conceptual basis for incorporating phytoplankton-based biological monitoring into sustainable reservoir management and water quality assessment frameworks in semi-arid regions.

KEYWORDS
anthropogenic activities, biomarkers, PCA, physicochemical variables, phytoplankton, sulfur springs, water quality

1 Introduction

Dams rank among the most significant human interventions in the natural water cycle, constructed to secure reliable water supplies for drinking, irrigation, and recreation, while mitigating flood and drought risks (Altinbilek, 2002; Berg et al., 2005; Hassany et al., 2012; Ghafur and Abdulrahman, 2023). Yet, rising population, urban expansion, agricultural intensification, and industrialization have accelerated the deterioration of water quality, undermining drinking water safety and ecosystem services (Altinbilek, 2002). In parallel, natural processes, including precipitation variability, soil erosion, and catchment weathering, further complicate efforts to maintain acceptable water quality standards for potability and multipurpose use (Berg et al., 2005).

Duhok Dam, built in 1988 as an earth-fill embankment on the Duhok River, originally aimed to irrigate surrounding agricultural lands. Today, it is a vital multipurpose reservoir that supplies drinking water, supports recreation, and buffers hydrological extremes in the semi-arid region of northern Iraq (Toma, 2011, 2013; Shekha et al., 2025). In recent decades, however, the reservoir has faced mounting stress: prolonged droughts, overexploitation, and pollution have affected both water quantity and quality (Shekha et al., 2025). Untreated sewage discharges and sulfur springs locally elevate nutrient and sulfate concentrations, driving eutrophication and changing the reservoir's trophic dynamics (Canfield, 2004; Watson et al., 2016; Ma W. et al., 2025). These trends highlight the urgency of continuous water quality monitoring for sustainable management and public health protection (Sommer et al., 2012; Subbiah et al., 2019).

Eutrophication, a gradual process intensified by phosphorus and nitrogen inputs from point and non-point sources, is one of the most critical threats to reservoir water quality worldwide (Leng et al., 2023). Excessive nutrient accumulation fuels phytoplankton proliferation and, over time, internal loading from sediments can sustain blooms even when external inputs decrease (Lv et al., 2014). Such blooms affect not only ecosystem function and biodiversity but also impair socioeconomic uses, increase treatment costs, and pose health hazards through cyanotoxin production and the formation of disinfection by-products (Drobac Backović et al., 2020; Pedregal-Montes et al., 2024). Phytoplankton, as primary producers at the base of aquatic food webs, are widely recognized bioindicators of water quality due to their rapid and measurable response to environmental change (Reynolds, 2006; Yusuf, 2020; Dembowska, 2021; Yaqoob et al., 2021; Salmi, 2023; Sahoo et al., 2024; Erlangga et al., 2025). Community composition and biomass directly reflect nutrient enrichment, thermal regimes, and hydrological variability, and their seasonal succession patterns help infer trophic status and pollution sources (Bicudo et al., 2009; Padisák et al., 2009). Notably, chlorophyll-a concentrations, shifts from diatoms to cyanobacteria or chlorophytes, and the presence of mixotrophic taxa are all useful indicators of eutrophication and organic pollution (Kutlu et al., 2020; Lin et al., 2024).

Semi-arid and water-stressed regions have emerged as critical focal points for limnological research, as the relation between fluctuating hydrological inflows, prolonged droughts, and anthropogenic nutrient loading exacerbates the vulnerability of multipurpose lentic ecosystems. To assess these ecological shifts, recent studies have increasingly used phytoplankton communities as sensitive bioindicators of water quality. For instance, investigations have been conducted across diverse semi-arid landscapes, including Meggarine Lake in Algeria (Manamani and Bensouilah, 2023) and Costa et al. (2016), which focused on shallow lakes prone to water level fluctuations in the semi-arid region of Brazil. Oliveira et al. (2019) investigated reservoirs in the Brazilian semi-arid region during an extreme drought season. Silva and da Costa (2015) evaluated the ecological status and phytoplankton assemblages of the Passagem and Cruzeta reservoirs located in the semi-arid zone of Northeastern Brazil. Polykarpou et al. (2025) analyzed the combined effects of water level fluctuations and land use on phytoplankton communities across 28 reservoirs in the semi-arid environment in Cyprus. Ikbel et al. (2012) examined the seasonal dynamics of plankton communities in relation to environmental variables within the Sidi Saâd reservoir, situated in a semi-arid region of Tunisia. Pereira et al. (2024) investigated the hidden diversity of phytoplankton within urban ponds in the semi-arid region of Northeastern Brazil. Geraldes and Boavida (2005) analyzed the limnological implications of seasonal water level fluctuations on phytoplankton dynamics in two Mediterranean semi-arid characteristic reservoirs in Portugal.

Within this context, reservoir-based studies that combine physicochemical variables with biological indicators, particularly phytoplankton community structure and trophic dynamics, are increasingly recognized as essential for assessing ecosystem resilience, drinking water safety, and adaptive water management. By addressing eutrophication processes and phytoplankton responses under compounded climatic and anthropogenic pressures, the present study contributes to this growing body of research seeking transferable insights into sustainable reservoir management under changing environmental conditions.

In this study, we aimed to (I) assess seasonal variations in phytoplankton composition and physicochemical parameters in the Duhok reservoir; (II) evaluate the influence of anthropogenic and natural pollution sources on water quality; and (III) explore the reliability of phytoplankton as bioindicators to support sustainable reservoir management.

2 Materials and methods

2.1 Study area

The study has been conducted at the Duhok dam, situated about 2 km north of the city of Duhok, between latitudes 36°52′35 ″ and 36°54′21″N, and longitudes 42°59′51″ and 43°00′40″E (Figure 1A). The dam is an earth-fill embankment on the Duhok River and was completed in 1988 with the primary purpose of providing water for irrigation and the city of Duhok, but it has recently been used for recreational activities as well. The dam is 60 m high, with a capacity of 52 million cubic meters of water and a maximum discharge of 81 m^3. The reservoir is about 4 km long and 1.7 km wide; the total catchment area is 135 km^2 (Shekha et al., 2013). There are sulfur effluents (sulfur springs) that appear on the limit in the tail of the reservoir; their discharges vary seasonally in the sampling points 5 near Krmava sulfur spring 1 and sampling point 6 near Krmava sulfur spring 2 (Figure 1A). The geological structure of the catchment consists mainly of dolomite, limestone, siltstone, clay marls, and gypsum from Eocene deposits (Mohammed, 2010). The reservoir was affected by untreated sewage discharge from Kari Qasrok village, Pirummara village, and a small resort at sampling points 3, 4, and 1, respectively. During the

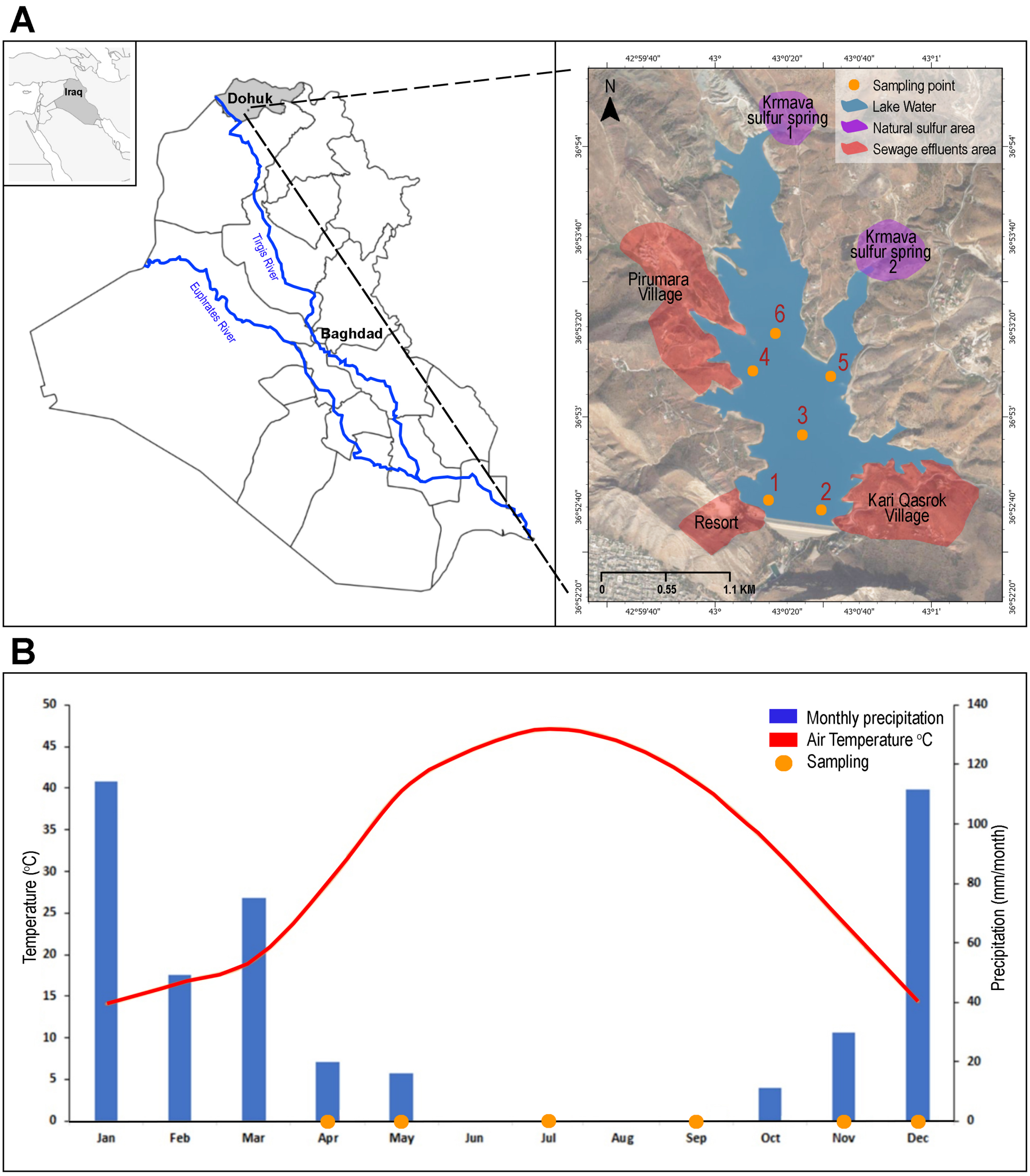

FIGURE 1
(A) Map of Duhok Lake showing locations that affect water quality and two sulfur springs. Sample 1: affected by a sewage pollution source from a small resort. It also served as a drinking water source for Duhok city. Sample 2: affected by sewage pollution from the Kari Qasrok village. Sample 3: is the middle area where there is no direct pollution effect. Sample 4: affected by sewage pollution from Pirummara village. Samples 5 and 6: affected by sulfur effluents (sulfur spring area). **(B)** Figure showing average temperature (°C) in orange line, accumulated monthly precipitation (mm/month) in blue columns, black line for water level (meters), and sampling times in red rectangle in the studied area during the study period.

study period, the lake was used for domestic water supply in Duhok city, with water pumped from sampling location 1 from May 11, 2021, to October 27, 2021.

2.2 Sample collection

During the research, we collected a total of 36 samples from the Duhok Lake (1st of April, 6th of May, 15th of July, 26th of September, 17th of November, and 27th of December) in 2021, covering four seasons. The samples were taken from a boat between 10 a.m. and 12 p.m. under the same weather conditions: clear weather and no winds. Sampling was carried out from the lake surface (25 cm depth).

The investigated period was characterized by high variation of precipitation and water temperature. The selected sampling months were intentionally chosen to represent key hydroclimatic periods within the annual cycle (early and late spring, summer peak, and different phases of autumn–winter transition). April represents early spring, precipitation is high, and the water temperature is around 16 °C. May represents late spring; precipitation decreases, and water temperature is around 21 °C. July is the month of summer and dry weather, when water temperatures peak at around 28 °C. September represents early autumn, with no precipitation and a water temperature around 24 °C. November represents late autumn; precipitation starts with low density, and the water temperature is around 16 °C. December represents winter; precipitation was high, and water temperature dropped to around 10 °C.

During our study, phytoplankton and physicochemical variables were investigated. Samples for chemical analysis and phytoplankton samples were collected with a weighted plastic bottle at each sampling point. At the time of sampling, 500 mL water samples were taken for algal analysis and 1000 mL for physicochemical analysis.

At each sampling location in the field, water temperature (WT, °C), transparency using a Secchi disk (SD, cm), and dissolved oxygen (DO, mg/L) were measured directly with a digital portable ADWA AD630 dissolved oxygen meter (Adwa Instruments, Szeged, Hungary). pH was measured using a digital portable ADWA AD132 pH meter, total dissolved solids (TDS) were measured using a digital portable ADWA AD31 TDS meter, and turbidity (NTU) was measured using a Hach DR2010 device (Hach, Loveland, CO, USA). The data on precipitation, air temperature, and water level were obtained from the Directorate of Duhok Dam.

During the laboratory work, we measured (NO_3-N µg/mL, NO_2-N µg/mL, PO_4-P µg/mL, NH_4-N µg/mL, Cl^- mg/L, COD_{sMn} mg/L, chlorophyll-a mg/L, total suspended solids TSS mg/L, HCO_3 mg/L, and BOD_5 mg/L) according to the analytical standards of the Hungarian water quality monitoring service (Hungarian National Standards, MSZ 12749:1993).

The phytoplankton samples were immediately fixed in the field with Lugol's iodine for subsequent phytoplankton counting with the Utermöhl inverted microscope technique. Sedimentation chambers were used for microscopic analyses during counting. Their volumes were 5 cm^3, 10 cm^3, and 15 cm^3 depending on the amount of algae in the water sample. The microscopic investigation was done with an Olympus-IX73 (Olympus, Tokyo, Japan) inverted microscope and an Olympus-BX53 microscope using phase-contrast and Nomarski-contrast techniques. The investigation was conducted at 400 and 1000 magnification. The taxonomic identification of phytoplankton species was carried out using standard taxonomic keys and monographs widely accepted in phycological research. Taxonomic classification and nomenclature followed the AlgaeBase database to ensure up-to-date and consistent taxonomy, in addition to primary references and identification (Bellinger and Sigee, 2015; Rosen, 2025; Wehr et al., 2015; John et al., 2021; Komarek, 1998; Krammer and Lange-Bertalot, 1997; Krammer and Lange-Bertalot, 2000).

2.3 Data analysis

The phytoplankton data are counted as individuals/liter (ind. L^{-1}). A multivariate approach was used for statistical analysis to illustrate patterns of biotic and abiotic change and correlations between environmental parameters and phytoplankton distribution.

Logarithm transformation was used to linearize the dataset. Both phytoplankton and physiochemical data were normalized (log+1) before being used as PCA outputs. The phytoplankton data (cell density) were analyzed using variance–covariance matrix PCA, and species with a relative abundance greater than 1%. The correlation matrix PCA was used for the physicochemical variables and applied using the R programming language and the FactoMineR package. ARCGIS Pro for creating the map. To test significant differences in the entire phytoplankton community and physicochemical variables during different sampling periods, an analysis of similarities (ANOSIM) was performed. Kruskal–Wallis is used to test for significant differences of single phytoplankton species and single physicochemical variables during different sampling periods. To obtain the correlation coefficients, we used Pearson's correlation calculation on the log+1 transformed data.

3 Results

3.1 Temporal variation of phytoplankton and environmental variables in the investigated months

Based on the principal component analysis (PCA) of both phytoplankton communities and physicochemical variables (Figures 2a,b), three groups distinguished during the investigation period, sampling points April and May was in group I representing spring season, sampling points of Jully was in group II representing summer season, sampling points of September, November, and December in group III which representing autumn and winter seasons.

The phytoplankton composition PCA (Figure 2a) showed marked temporal variation across the months investigated. PCA1 explained 50.9%, and PCA2 explained 24.8% of the total variance. Interestingly, phytoplankton community composition showed significant seasonal dissimilarity (One-way ANOSIM: $R = 0.938$, $p < 0.0001$). Based on the PCA results, *Euglena* sp. showed the highest abundance in groups I and II with a significant seasonal variation (Kruskal–Wallis test; $p < 0.05$). Group II was strongly separated from the other groups based on the phytoplankton composition. *Peridinium cinctum, Desmodesmus* sp., *Oscillatoria* sp., and *Scenedesmus acutus* reached their peak abundance in group II and showed a significant seasonal variation (Kruskal–Wallis test; $p < 0.05$). Furthermore, group III was characterized by diatom abundance, represented by *Cyclotella* sp., *Navicula* sp., and *Nitzschia acicularis,* with a significant seasonal variation (Kruskal–Wallis test; $p < 0.05$).

Moreover, physicochemical variables showed significant seasonal dissimilarity (One-way ANOSIM: $R = 0.988$, $p < 0.0001$). Based on the physicochemical PCA results (Figure 2b), group II was strongly separated from other groups based on the physicochemical variables over the months investigated. PCA1 explained 41.9%, and PCA2 explained 21.8% of the total variance. Group II, characterized mainly by high water temperature and high BOD_5 activity, showed a significant seasonal variation (Kruskal–Wallis test; $p < 0.05$). Group I, characterized by high concentration of precipitation, DO, NO_2-N, NO_3-N, NH_4-N, PO_4-P, CO_3, and high SD, showed a significant seasonal variation (Kruskal–Wallis test; $p < 0.05$). Group III, characterized by high concentration of precipitation, DO, TDS, Cl-, HCO_3, COD_{sMn}, SO_4^{2-}, chlorophyll-a, and high turbidity, showed a significant seasonal variation (Kruskal–Wallis test; $p < 0.05$).

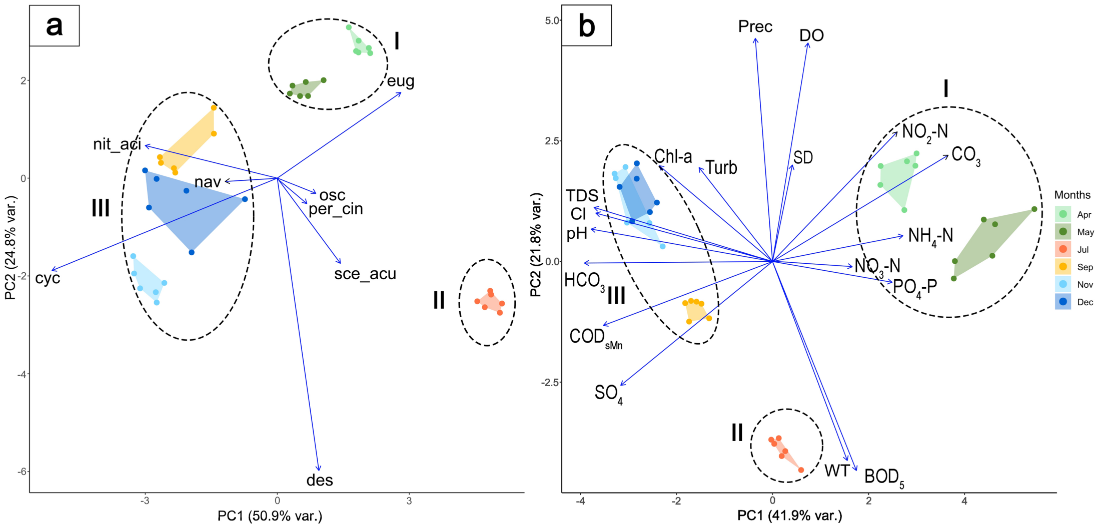

FIGURE 2

(a) Principal component analysis (PCA) graph of phytoplankton within the investigated months in Duhok Lake. **(b)** Principal component analysis (PCA) graph of physicochemical variables within the investigated months in Duhok Lake, whereas cyc, *Cyclotella* sp.; des, *Desmodesmus* sp.; sce_acu, *Scenedesmus acutus*; nav, *Navicula* sp.; eug, *Euglena* sp.; osc, *Oscillatoria* sp.; nit_aci, *Nitzschia acicularis*; per_cin, *Peridinium cinctum*; Apr, April; May, May; Jul, July; Sep, September; Nov, November; Dec, December; Ch-a, chlorophyll-a; Turb, turbidity; WT, water temperature; DO, dissolved oxygen; SD, Secchi depth; Prec, precipitation.

3.2 Spatio-temporal variation of phytoplankton composition

Phytoplankton community composition exhibited marked spatial and temporal variation across six seasonal sampling periods. Principal Component Analysis (PCA) was employed to elucidate the major gradients in species distribution among sampling stations (Figure 3).

In April (Figure 3a), PC1 accounted for 49.3%, while PC2 represented 31.1% of the total variance. Four groups were distinguished during the April sampling time: sampling points 1 and 4 were in group I, sampling point 2 was in group II, sampling point 3 was in group III, and sampling points 5 and 6 were in group IV. The phytoplankton community structure varied significantly among the sampling stations. *Merismopedia* sp. and *Selenastrum minutum* were predominantly observed at group IV, whereas *Kephyrion littorale* and *Monoraphidium komarkova* were primarily associated with group III. Furthermore, based on the phytoplankton PCA, there were no characterized species in groups I and II.

During the late spring sampling in May (Figure 3b), PC1 and PC2 explained 52.6 and 31.7% of the total variance, respectively. Three groups were distinguished during the May sampling time: sampling point 1 was in group I, sampling points 2 and 3 in group II, and sampling points 4, 5, and 6 in group III. Species distribution revealed *N. acicularis* was characterized in group I, while *Peridinium cinctum* and *Monoraphidium minutum* were characterized in group III. Furthermore, based on phytoplankton PCA, there were no characterized species in group II.

In July (Figure 3c), representing the peak of summer, PC1 and PC2 accounted for 69.5 and 21.7% of the total variance, respectively. Three groups were distinguished during the July sampling time: sampling points 1, 4, and 6 were in group I; sampling points 2 and 3 were in group II; and sampling point 5 was in group III. The phytoplankton community structure varied significantly among the sampling stations. Group II was characterized by *Chroococcus limneticus* and *Pediastrum simplex*, while *Oscillatoria* sp. was characterized in groups I and III.

In early autumn during September sampling, PCA (Figure 3d) revealed that PC1 and PC2 accounted for 41.8 and 36.6% of the variance, respectively, indicating stronger structuring of phytoplankton communities. Three groups were distinguished during the September sampling time: sampling points 1 and 2 were in group I, sampling points 3, 4, and 5 in group II, and sampling point 6 in group III. The phytoplankton community structure varied significantly among the sampling stations. *N. acicularis* was predominantly observed at group I, *Oscillatoria* sp. and *Peridinium cinctum* were characterized in group II, while *Navicula* sp. were primarily associated with group III.

In late autumn during the November sampling period, the PCA (Figure 3e) revealed that PC1 explained 61.9% of the variance, and PC2 accounted for 22.3%. Four groups were distinguished during the November sampling time: sampling point 1 was in group I, sampling point 3 in group II, sampling points 2 and 4 in group III, and sampling points 5 and 6 in group IV. The phytoplankton community structure varied significantly among the sampling stations. *Desmodesmus* sp. were predominantly observed in group I. Group IV was characterized by *Cryptomonas* sp. and *Navicula* sp., whereas groups II and III contained no species.

In the winter during the December sampling period, the PCA (Figure 3f) revealed that PC1 and PC2 explained 73.9 and 16.7% of the total variance, respectively. Three groups were distinguished during the December sampling time: sampling points 1 and 2 were in group I, sampling point 3 was in group II, and sampling points 4, 5, and 6 were in group III. The phytoplankton community structure varied significantly among the sampling stations. Group I was characterized by *N. acicularis,* while *Dinobryon* sp. *and P. cinctum* were characterized in group III. Furthermore, based on phytoplankton PCA, there were no characterized species in group II.

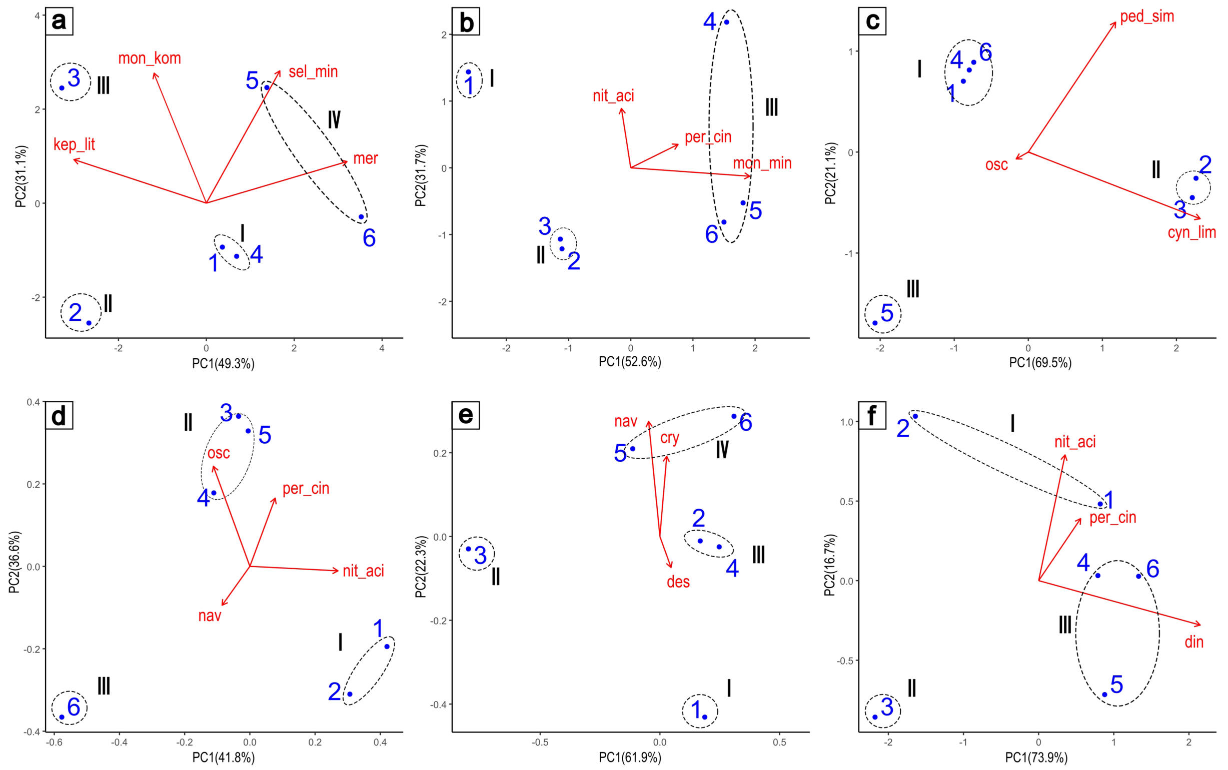

FIGURE 3
Principal component analysis (PCA) for the phytoplankton composition during each investigated month: **(a)** early spring, **(b)** late spring, **(c)** summer, **(d)** early autumn, **(e)** late autumn, **(f)** winter. The numbers from 1 to 6 represented the sampling points, whereas cyc, *Cyclotella* sp.; des, *Desmodesmus* sp.; sce_acu, *Scenadesmus* sp.; nav, *Navicula* sp.; eug, *Euglena* sp.; osc, *Oscillatoria* sp.; nit_aci, *Nitzschia acicularis*; per_cin, *Peridinium cinctum*; kep_lit, *Kephyrion littorale*; mon_kom, *Monoraphidium komarkova*; sel_min, *Selenastrum minutum*; mer, *Merismopedia* sp.; mon_min, *Monoraphidium minutum*; cry, *Cryptomonas* sp.; din, *Dinobryon* sp.; ped_sim, *Pediastrum simplex*.

3.3 Spatio-temporal variation of physical–chemical variables

Principal Component Analysis (PCA) was applied to assess the spatiotemporal variation in physical and chemical parameters across six sampling stations over six distinct periods. The results revealed pronounced spatial heterogeneity in key environmental variables across the reservoir (Figure 4).

In April, the PCA revealed (Figure 4a) that PC1 explained 76.3% of the total variance, and PC2 explained 14.6%. Four groups were distinguished during the April sampling time: sampling points 1 and 4 were in group I, sampling point 2 was in group II, sampling point 3 was in group III, and sampling points 5 and 6 were in group IV. The physicochemical variables varied significantly among the sampling stations. High concentrations of SO_4, NO_3-N, transparency SD, PO_4-P, DO, and chlorophyll-a were observed in group IV. Group III was characterized by DO, chlorophyll-a, and SD. While groups I and II are characterized by high concentrations of NO_2-N, NH_4-N, TSS, BOD_5, Turbidity, and COD_{sMn}.

During the late-spring sampling in May, the PCA (Figure 4b) revealed that PC1 and PC2 explained 59.2 and 20.4% of the total variance, respectively. Three groups were distinguished during the May sampling time: sampling point 1 was in group I, sampling points 2 and 3 in group II, and sampling points 4, 5, and 6 in group III. The physicochemical variables varied significantly among the sampling stations. Groups I and II both exhibited elevated COD_{sMn}, NO_3-N, TSS, and turbidity, with Group I further distinguished by higher PO_4-P. Group III is characterized by higher values of DO, SD, NH_4-N, NO_2-N, and SO_4.

In July, at the peak of summer, the PCA revealed (Figure 4c) that PC1 and PC2 accounted for 51.6 and 17.7% of the total variance, respectively. Three groups were distinguished during the July sampling time: sampling points 1, 4, and 6 in group I; sampling points 2 and 3 in group II; and sampling point 5 in group III. The physicochemical variables varied significantly among the sampling stations. Group I is distinguished by high concentrations of PO_4-P, BOD_5, NH_4-N, COD_{sMn}, NO_3-N, turbidity, and TSS. Group II is distinguished by higher concentrations of chlorophyll-a, NO_2-N, DO, and SD. Group III is distinguished by high DO concentrations and transparency.

In early autumn in September, the PCA revealed (Figure 4d) that PC1 and PC2 accounted for 61.8 and 17.6% of the variance, respectively, indicating stronger structuring of phytoplankton communities. Three groups were distinguished during the September sampling time: sampling points 1 and 2 were in group I; sampling points 3, 4, and 5 were in group II; and sampling point 6 was in group III. Group I is characterized by COD_{sMn}, PO_4-P, BOD_5, turbidity, and TSS at higher concentrations. Group II is characterized by higher concentrations of chlorophyll-a, NO_3-N, DO, and SD. Group III is distinguished by higher concentrations of NO_3-N, SO_4, and NO_2-N.

In the late-autumn sampling period (November), the PCA revealed (Figure 4e) that PC1 explained 63.5% of the variance, and PC2 accounted for 16.8%. Four groups were distinguished during the November sampling time: sampling point 1 was in group I; sampling point 3 was in group II; sampling points 2 and 4 were in group III; and sampling points 5 and 6 were in group IV. Groups I and II were

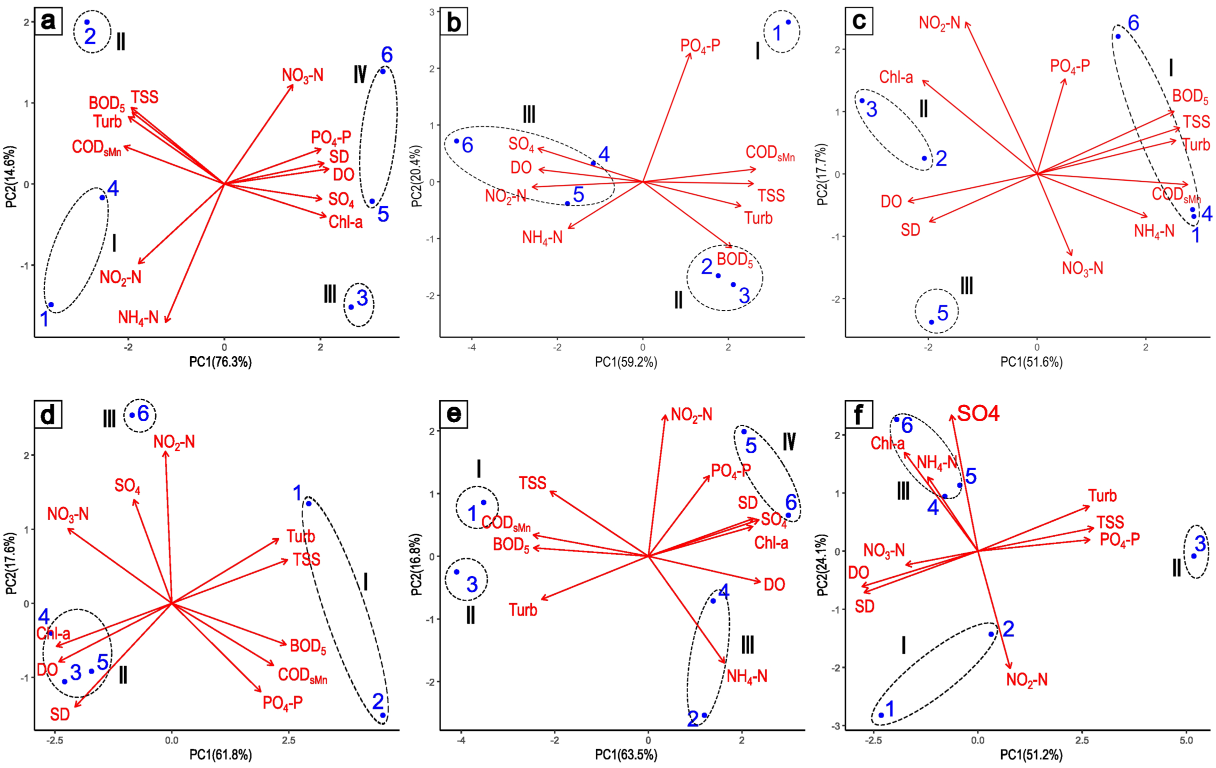

FIGURE 4
Principal component analysis (PCA) for the physicochemical variables during each investigation month. Graph **(a)** early spring, graph **(b)** late spring, graph **(c)** summer, graph **(d)** early autumn, graph **(e)** late autumn, graph **(f)** winter. The numbers from 1 to 6 represent the sampling points. Ch-a, chlorophyll-a; Turb, turbidity; DO, dissolved oxygen; SD, Secchi depth.

characterized by high concentrations of Turbidity, TSS, BOD_5, and COD_{sMn}. Group III is characterized by high concentrations of NH_4-N and DO. While group IV is characterized by high concentrations of PO_4-P, SO_4, SD, chlorophyll-a, and NO_2-N.

In the winter sampling period in December, the PCA (Figure 4e) revealed that PC1 and PC2 explained 51.2 and 24.1% of the total variance, respectively. Three groups were distinguished during the December sampling time: sampling points 1 and 2 were in group I; sampling point 3 was in group II; and sampling points 4, 5, and 6 were in group III. Group I is characterized by high concentrations of NO_2-N, NO_3-N, DO, and SD. Group II is characterized by high concentrations of Turbidity, PO_4-P, and TSS. Group III is characterized by high concentrations of SO_4, DO, chlorophyll-a, NO_3-N, and NH_4-N.

4 Discussion

4.1 Assess seasonal variations in phytoplankton composition and physical–chemical parameters in the Duhok reservoir

Our research revealed that seasonal hydroclimatic variability, especially precipitation and water temperature, was a key factor influencing the dynamics of the phytoplankton community and related physicochemical variables. Principal component analysis (PCA) (Figures 2a,b) suggests that the distribution of the phytoplankton community and the physicochemical variables in the reservoir water was significantly varied among the investigated months. Seasonal changes can have significant effects on both phytoplankton abundance and composition, as well as physical–chemical variables (Vajravelu et al., 2018; Okorie et al., 2024). These changes can be influenced by temperature and seasonal fluctuations in precipitation, which alter light availability, nutrient supply, and mixing depth (Paerl et al., 2001).

Our investigation revealed three distinct groups based on PCA of the phytoplankton community and physicochemical variables (Figures 2a,b). Group I, which represented the spring season, was characterized by precipitation and water temperatures ranging from 16 °C to 21 °C. These conditions, together with elevated turbidity, TSS, CO_3, and increased nutrient concentrations (NH_4-N, NO_3-N, and PO_4-P), reflected substantial watershed runoff and internal nutrient regeneration (Casalí et al., 2008; Rodrigues et al., 2018). Such turbidity and nutrient enrichment often limit light penetration, favoring shade-adapted or mixotrophic phytoplankton. The characterized abundance of *Euglena* sp., a mixotrophic euglenophyte, during April and May highlights its advantage in low-light, nutrient-enriched waters following precipitation events, where heterotrophic feeding enhances photosynthetic efficiency (Kutlu et al., 2020). The species of *Euglena* sp. identified by Faraji et al. (2025) in the Coastal River was characterized as a species during the runoff period in the winter season. Under these eutrophic conditions, opportunistic taxa such as *Euglena* sp. proliferated, benefiting from their mixotrophic capacity and tolerance to fluctuating environmental conditions to thrive in semi-arid areas (Pereira et al., 2024). The dominance of *Euglena* sp. in group I coincided with peak nutrient levels, demonstrating its ability to exploit nutrient pulses and thrive in moderate temperatures (Omar et al., 2016; Wołowski and Grabowska, 2007). Thus, the spring season was dominated by nutrient-driven, mixotrophic communities adapted to variable light and hydrological regimes.

Group II, which represents the dry summer season in the reservoir, exhibited distinct stratification, with the highest water temperature reaching 28 °C, low DO, elevated BOD_5, low pH, and the minimum SD, indicating high microbial respiration and bloom activity (Zwolsman and Van Bokhoven, 2007). The lowest DO coincided with maximum temperature, reflecting reduced oxygen solubility and high biological oxygen consumption (Watson et al., 2016). These physicochemical conditions favored warm-adapted, motile, and buoyant phytoplankton species. Dominant taxa included *Oscillatoria* sp., *P. cinctum*, and green algae such as *Desmodesmus* sp. and *Scenedesmus* sp., all of which are known to thrive under nutrient-rich, warm, and low-oxygen conditions (Xin et al., 2011; Ho et al., 2014). *P. cinctum* reached its highest abundance in July, aligning with its affinity for stratified, nutrient-rich waters (Grigorszky et al., 2006). Our finding was consistent with many researchers who stated that *P. cinctum* is characterized in the summer season (Sharagina et al., 2024; Stanislavskaya et al., 2022). Similarly, *Oscillatoria* sp. flourished under warm and hypoxic conditions, consistent with previous reports linking cyanobacterial blooms to temperature rise and water column stability (Miranda and Krishnakumar, 2015). Other studies also indicated that *Oscillatoria* sp. was a characterized species in the summer season (Stanislavskaya et al., 2022; Faraji et al., 2025), whereas temperatures and increased nutrient concentrations during the warmer months favored the proliferation of these filamentous cyanobacteria (Ikbel et al., 2012). The proliferation of *Scenedesmus* sp. and *Desmodesmus* sp. further reflected the influence of eutrophic and high-temperature conditions, as these taxa display resilience and rapid growth under nutrient-enriched environments (Xin et al., 2011; Yuan et al., 2021; Tang et al., 2026). Moreover, *Euglena* sp. remained abundant during July, demonstrating its ecological adaptability to both nutrient enrichment and hypoxic stress. Its persistence across spring and summer underscores its opportunistic strategy, thriving under diverse and changing physicochemical conditions (Wołowski and Grabowska, 2007; Omar et al., 2016).

Group III, which represented the autumn and winter seasons. This group is characterized by precipitation and water temperature ranging from 10 °C to 24 °C. The reservoir underwent significant hydrological and thermal transitions. In September, the absence of precipitation and moderate temperature (24 °C) led to concentration effects from summer evaporation, elevating ionic strength and COD_{sMn} concentration due to organic matter decomposition (Zhang et al., 2008). Partial mixing began, redistributing nutrients to surface waters and promoting diatom proliferation, notably *Cyclotella* sp., which thrives under improved light and moderate nutrient availability following stratification breakdown (Koçer and Şen, 2012). This finding was consistent with Li et al. (2025) in Poyang Lake, which reported *Cyclotella* sp. in the winter season. By November, late autumn, water temperature declined to 16 °C, and chlorophyll-a reached its maximum, signifying an autumn bloom driven by nutrient mixing from deeper layers (Yan et al., 2023). In December, rainfall resumed, and temperature dropped to approximately 10 °C, with increased CO_3 and TDS indicating runoff inputs. Cold, well-mixed conditions favored benthic diatoms such as *Navicula* sp. and *N. acicularis*, taxa adapted to low-temperature and high-resuspension environments. During this period, phytoplankton growth was limited, but community composition reflected physical resuspension and watershed inputs rather than active production (Luo et al., 2022).

4.2 Evaluate the influence of anthropogenic and natural pollution sources on the reservoir water quality

Duhok reservoir, like many multipurpose reservoirs in semi-arid regions, is under pressure from multiple pollution sources that shape the spatial–temporal distribution of phytoplankton communities and physicochemical variables. The most significant pollution pressures come from untreated domestic sewage discharged near urban areas, bringing high loads of nutrients, especially nitrogen and phosphorus, along with organic matter and suspended solids. This nutrient enrichment accelerates eutrophication, promoting the dominance of pollution-tolerant or opportunistic phytoplankton groups (Albay and Akçaalan, 2003; Chen et al., 2009; Lv et al., 2014). Furthermore, the Duhok reservoir receives sulfur-rich inflows, particularly in its northern part, which locally increase sulfate concentrations. This creates chemically unique conditions that can select for a specialized or tolerant phytoplankton community (Gao et al., 2021). In our study, the sampling sites were strategically selected to represent a gradient of human impact, with sewage impact at sampling points 1, 2, and 4, and the sulfur-rich springs near the sampling points 5 and 6 (Figure 1A).

In early spring, during April sampling time and based on PCA of both phytoplankton and physicochemical variables (Figures 3a, 4a), distinct spatial variations in water quality and phytoplankton structure reflected the combined influence of anthropogenic and natural pollution sources within the reservoir. Group III, situated in the central part of the reservoir and least affected by external inputs, exhibited higher DO, SD, and chlorophyll-a, with *K. littorale* and *M. komarkovae* as representative species. This group reflects a more balanced system, where moderate nutrient availability and good light conditions support diverse algal communities typical of mesotrophic environments (Nielsen et al., 2002). Group IV, influenced by sulfur-rich inflows, was characterized by elevated SO_4^{2-}, NO_3–N, PO_4–P, and DO concentrations, together with high chlorophyll-a concentration. *Merismopedia* sp. and *S. minutum*, which are characterized in group IV, are known for their high tolerance to sulfur and nutrient enrichment due to their physiological adaptability and efficient nutrient assimilation mechanisms. *S. minutum* can regulate nitrogen and carbon metabolism under nutrient stress, enabling it to thrive in waters with elevated nitrate, ammonium, and sulfate concentrations (Elrifi and Turpin, 1986). The presence of *S. minutum* in our study was supported by the positive correlation with DO ($r = 0.96$, $p \leq 0.05$), PO_4-P ($r = 0.98$, $p \leq 0.05$), transparency SD ($r = 0.82$, $p \leq 0.05$), and SO_4^{2-} ($r = 0.94$, $p \leq 0.05$). Furthermore, *Merismopedia* sp., a cyanobacterium, a colonial cyanobacterium, benefits from low grazing pressure and enhanced transparency (Ma Y. et al., 2025). *Merismopedia* sp. possesses flexible metabolic pathways and strong ionic regulation, allowing survival in eutrophic and sulfate-rich environments where other taxa are less competitive (Fawzy, 2016). This was supported by the positive correlation between *Merismopedia* sp. with NO_3-N ($r = 0.95$, $p \leq 0.05$), PO_4-P ($r = 0.72$, $p \leq 0.05$), and SO_4^{2-} ($r = 0.8$, $p \leq 0.05$). A study conducted in the Lake Huron basin of Michigan reported the presence of *Merismopedia* sp. at Great Sulfur Spring, indicating that this species can tolerate these environments (Fray et al., 2024).

Three groups were distinguished during the May sampling time based on phytoplankton and physicochemical variables (Figures 3b, 4b). Group I was mainly influenced by sewage effluents, as evidenced by high concentrations of COD_{sMn}, NO_3-N, TSS, and turbidity—all indicators of organic and nutrient enrichment from domestic wastewater inputs. The dominance of *N. acicularis*, a diatom commonly associated with nutrient-rich and organically polluted waters, supports this interpretation (Yang et al., 2020). Our study supported this finding by the positive correlation of *N. acicularis* with PO_4-P ($r = 0.87, p \leq 0.05$). Elevated COD_{sMn} and nitrate concentrations indicate intense microbial decomposition and nutrient loading, which promote the proliferation of tolerant diatom taxa (Zhang et al., 2008). Group III showed a natural pollution influence dominated by sulfur effluents, as evidenced by elevated concentrations of SO_4, NH_4-N, NO_2-N, and DO, along with high transparency. The presence of *P. cinctum* as a dinoflagellate and *M. minutum* as a chlorophyte indicates adaptation to higher oxygen and nutrient conditions, typical of less disturbed or partially recovered zones (Reynolds et al., 2002). In our investigation, the presence of *P. cinctum* was supported by the positive correlation with DO ($r = 0.91, p \leq 0.05$), NO_2-N ($r = 0.83, p \leq 0.05$), and SO_4 ($r = 0.83, p \leq 0.05$). The higher transparency and DO suggest improved light penetration and reoxygenation, possibly due to reduced organic load compared to the sewage-affected areas. *P. cinctum* negatively correlated with TSS ($r = -0.95, p \leq 0.05$), BOD_5 ($r = -0.9, p \leq 0.05$), and COD_{sMn} ($r = -0.91, p \leq 0.05$). The tolerance of this species to sulfate and variable nutrient regimes has been reported in several studies, showing the ability to persist under mild chemical stress while maintaining photosynthetic efficiency (Gao et al., 2021; Zak et al., 2021).

In the summer season, during July sampling time and based on PCA of both phytoplankton and physicochemical variables (Figures 3c, 4c), three groups were distinguished. Groups I and III were both dominated by *Oscillatoria* sp., a filamentous cyanobacterium that thrives under high-nutrient, sulfur-rich, and organic load conditions. These groups exhibited elevated concentrations of PO_4-P, NH_4-N, NO_3-N, BOD_5, COD_{sMn}, turbidity, and TSS. Such conditions indicate strong anthropogenic influence from sewage and sulfur effluents, alongside natural factors such as evaporation and temperature-driven solute concentration. The persistence of *Oscillatoria* sp. reflects its physiological tolerance to high nutrient and sulfate concentrations, and its ability to regulate buoyancy for light optimization (Sivonen, 1990). These findings suggest that the zones represented by Groups I and III are most affected by combined sewage and sulfur inputs, leading to eutrophic, turbid, and biologically stressed conditions. The dominance of *Oscillatoria* sp. in the polluted waters studied aligns with findings by Reul et al. (2020), who demonstrated that this taxon thrives as a specialist in extreme, chemically stressed environments. Conversely, Group II displayed higher chlorophyll-a, DO, NO_2-N, and transparency, with *C. limneticus* and *P. simplex* as characterized taxa, whereas *P. simplex* correlated positively with NO_2-N ($r = 0.75, p \leq 0.05$). These species typically occur in mesotrophic to moderately eutrophic waters where nutrient enrichment is present but less extreme (Reynolds, 2006). The improved oxygenation and transparency in this group suggest partial mixing and dilution of sewage impacts, likely resulting in more stable photosynthetic activity and intermediate water quality.

The observed differentiation among the three groups in early autumn during the September sampling time, based on the PCA of phytoplankton and physicochemical variables (Figures 3d, 4d), provides valuable insights into the varying impacts of specific pollution types on reservoir ecosystems. Group I, characterized by high concentrations of COD_{sMn}, PO_4-P, BOD_5, turbidity, and TSS, with a prevalence of *N. acicularis*, indicates significant organic pollution primarily from sewage, consistent with conditions often found in meso-eutrophic systems receiving agricultural runoff and domestic wastewater (Yang et al., 2020; Akachukwu et al., 2025). This is further supported by studies demonstrating that nutrient inputs, particularly nitrates from sewage, can significantly influence algal blooms and water quality dynamics (Akachukwu et al., 2025). In our study, *N. acicularis* was significantly correlated with COD_{sMn} ($r = 0.96, p \leq 0.05$) and PO_4-P ($r = 0.7, p \leq 0.05$). This is further supported by studies demonstrating that nutrient inputs, particularly nitrates from sewage, can significantly influence algal blooms and water quality dynamics (Akachukwu et al., 2025). Conversely, the mixed pollution profile of Group II, marked by elevated chlorophyll-a, NO_3-N, DO, and transparency, along with the dominance of *Oscillatoria* sp. and *P. cinctum*, suggests a more complex interaction of organic and inorganic inputs, potentially leading to varied trophic states and phytoplankton community structures (Mohamed, 2002). *Oscillatoria* sp. in our investigation correlated positively with DO ($r = 0.8, p \leq 0.05$) and SD ($r = 0.85, p \leq 0.05$), but negatively with TSS ($r = -0.86, p \leq 0.05$). Group III, primarily impacted by sulfur effluents, was characterized by high concentrations of SO_4^{2-}, NO_3-N, and NO_2-N, reflecting possible nutrient runoff sources. The dominance of *Navicula* sp., a diatom known for its tolerance to high sulfate and nitrate concentrations, suggests adaptation to ionic stress and moderate salinity (Krause et al., 2003; Wen et al., 2017). *Navicula* species are often associated with polluted or slightly brackish conditions where sulfate and oxidized nitrogen dominate (Sayer et al., 2010), as indicated by the positive correlation of *Navicula* sp. with SO_4^{2-} ($r = 0.86, p \leq 0.05$) during our study.

During late autumn in November sampling period and based on the PCA of phytoplankton and physical chemical variables (Figures 3e, 4e), the distinct characteristics of Group I, marked by high turbidity, TSS, BOD_5, and c COD_{sMn}, coupled with the dominance of *Desmodesmus* sp., suggest a strong influence from sewage effluents, which contribute significant organic loading and particulate matter to the reservoir (Akachukwu et al., 2025). This organic enrichment, typical of sewage, fuels the proliferation of tolerant phytoplankton species like *Desmodesmus* sp., which are often indicative of productive aquatic systems (Akachukwu et al., 2025). Conversely, Group IV, characterized by high concentrations of PO_4-P, SO_4, SD, chlorophyll-a, and NO_2-N, and the prevalence of *Cryptomonas* sp. and *Navicula* sp., points toward sulfur effluents (Yang et al., 2020), which was supported in our investigation by the positive correlation of *Cryptomonas* sp. with SO_4^{2-} ($r = 0.83, p \leq 0.05$) and *Navicula* sp. with PO_4-P ($r = 0.8, p \leq 0.05$). The presence of elevated SO_4 and NO_2-N in Group IV, alongside high chlorophyll-a, suggests nutrient enrichment that could support algal blooms, with *Cryptomonas* sp. and *Navicula* sp. being indicators of such conditions (Yaqoob et al., 2023).

Based on PCA of phytoplankton and physicochemical variables (Figures 3f, 4f) from winter sampling time, the observed spatial heterogeneity in phytoplankton community structure and associated physicochemical variables highlights distinct environmental pressures within the reservoir system. Specifically, Group I's dominance by *N. acicularis* alongside elevated NO_2-N, NO_3-N, and DO concentrations strongly suggests an influence from sewage effluents, indicative of nutrient enrichment and potential organic pollution (Akachukwu et al., 2025). This is further supported by studies indicating that elevated nitrate concentrations, often stemming from agricultural runoff and sewage, can lead to algal blooms and shifts in phytoplankton composition (Akachukwu et al., 2025). The presence of *N. acicularis* aligns with a previous report (Salem et al., 2017), which identified this taxon as a significant organic-tolerant bioindicator in the Nile Delta, reinforcing the species' reliability as a diagnostic marker for monitoring anthropogenic enrichment and deteriorating water quality in freshwater ecosystems. Conversely, Group III, characterized by *Dinobryon* sp. *and P. cinctum*, coupled with high concentrations of SO_4, DO, chlorophyll-a, NO_3-N, and NH_4-N, points toward sulfur effluents, often associated with natural sources of sulfur, which can alter water chemistry and foster specific algal blooms (Knöller et al., 2005). Whereas *P. cinctum* exhibited negative correlations with COD_{sMn} ($r = -0.83$, $p \leq 0.05$) and turbidity ($r = -0.82$, $p \leq 0.05$), while *Dinobryon* sp. showed positive correlations with NH_4-N ($r = 0.89$, $p \leq 0.05$) and SO_4 ($r = 0.92$, $p \leq 0.05$).

4.3 Explore the reliability of phytoplankton as bioindicators to support sustainable reservoir management

During our investigation, we focused on how phytoplankton species respond to varying environmental conditions throughout the year and across different locations within the reservoir, which are often influenced by specific pollutants, such as sulfur (natural pollution), sewage effluents, and anthropogenic pollution. The temporal variability in precipitation and water temperature profoundly impacts these phytoplankton communities, with distinct assemblages observed in different seasons (Akachukwu et al., 2025). For instance, high abundances of *Euglena* sp. are typically found in highly turbid waters, while *Pediastrum* sp. and *Scenedesmus* sp. thrive in clearer conditions (Hoffmeister et al., 2004). Conversely, species like *N. acicularis* and *Navicula* sp. often thrive in cooler, nutrient-rich conditions associated with increased precipitation and runoff, making them valuable indicators of these seasonal hydrological changes (Funk et al., 2015). Furthermore, the dominance of certain taxa, such as *Euglena* sp. in organically enriched waters or *Oscillatoria* sp. under specific nutrient regimes, provides critical insights into the trophic status and pollution levels of the reservoir (Akachukwu et al., 2025).

The variability in phytoplankton community structure, therefore, serves as a dynamic, real-time indicator of the complex interplay between different pollution inputs and the reservoir's capacity for ecological resilience (Chandel et al., 2024). The presence of pollution-tolerant genera such as *Oscillatoria* sp. and *Navicula* sp. in zones with elevated organic pollution suggests a shift toward mesotrophic conditions, necessitating targeted management strategies to enhance ecological integrity (Akachukwu et al., 2025; Chandel et al., 2024). The shift in species dominance, for instance, the characterization of *N. acicularis* in Group I during May, September, and December sampling, further emphasizes its role as an indicator for specific environmental perturbations (Chandel et al., 2024). This dynamic response of phytoplankton communities to various environmental conditions, including nutrient availability, water temperature, and light intensity, positions them as highly effective bioindicators for monitoring ecological changes in aquatic systems (Akachukwu et al., 2025).

5 Conclusion

This study provides an integrated assessment of seasonal phytoplankton dynamics and physicochemical variability in the Duhok Reservoir, revealing the combined influence of hydroclimatic variability and pollution inputs on the reservoir's ecological functioning. Seasonal changes in precipitation and temperature emerged as key drivers of nutrient availability, water column structure, and phytoplankton community composition.

Principal Component Analysis (PCA) identified three distinct seasonal regimes corresponding to spring, summer, and autumn–winter conditions. Spring was characterized by increased precipitation, elevated turbidity, and nutrient enrichment, promoting opportunistic and mixotrophic taxa such as *Euglena* sp., which are typical of eutrophic and low-light environments. During summer, thermal stratification, high water temperatures, and reduced dissolved oxygen favored buoyant and warm-adapted taxa, including *Oscillatoria* sp., *P. cinctum*, and *Scenedesmus* sp., reflecting intensified eutrophic conditions and declining water quality. Conversely, autumn and winter mixing events promoted diatom-dominated assemblages, such as *Cyclotella* sp., *Navicula* sp., and *N. acicularis*, indicating enhanced oxygenation and nutrient redistribution following the breakdown of stratification.

The results further demonstrated that both anthropogenic and natural pollution sources significantly influence spatial and temporal variability in water quality across the reservoir. Urban inflows delivering untreated sewage introduce substantial organic and nutrient loads, fostering pollution-tolerant phytoplankton communities, while sulfur-rich inflows modify the ionic composition and support sulfate-tolerant taxa. This spatial heterogeneity highlights the complex interactions among hydrological processes, watershed land use, and external pollution inputs.

Phytoplankton communities proved to be robust bioindicators of environmental change in the reservoir. Shifts in taxonomic composition closely reflected variations in nutrient concentrations, organic loading, and thermal conditions. Indicator taxa such as *Euglena*, *Oscillatoria*, and *Nitzschia* were strongly associated with nutrient enrichment and organic pollution, whereas diatom assemblages signaled mixing-driven recovery phases. These findings confirm the ecological value of phytoplankton-based monitoring for detecting water quality deterioration and ecosystem responses to environmental stressors.

Overall, the seasonal succession of phytoplankton communities reveals a predominantly eutrophic system characterized by recurrent nutrient enrichment, stratification-induced oxygen depletion, and mixing-driven nutrient redistribution. These processes reflect clear trophic dynamics within the reservoir and indicate persistent eutrophication pressure driven by both hydroclimatic variability and external nutrient inputs.

From a management perspective, the study highlights the importance of integrating biological indicators with physicochemical monitoring to improve early detection of eutrophication and pollution impacts. Incorporating phytoplankton-based assessment into reservoir monitoring programs can support adaptive watershed management strategies to reduce nutrient loading, control pollution sources, and maintain the long-term ecological stability of freshwater reservoirs in semi-arid regions.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material; further inquiries can be directed to the corresponding author/s.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

MY: Software, Writing – original draft, Writing – review & editing, Data curation. IS: Writing – review & editing, Visualization. IB: Writing – review & editing, Methodology. BS: Writing – review & editing. KB: Writing – review & editing, Investigation. BH: Writing – review & editing, Investigation. ZI: Writing – review & editing, Supervision. CB: Validation, Writing – review & editing, Supervision. IG: Resources, Writing – review & editing, Writing – original draft.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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