



Ecoregional assessment of Turkish lakes using phytoplankton metrics and multimetric approaches

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Abstract

The aim of this study was to investigate how environmental gradients influence the ecological status (ES) of four lake ecosystems located in different ecoregions of Türkiye using integrated physicochemical and multimetric bioassessments. Four lakes differing in salinity, nutrient levels, and morphometric features were sampled across distinct ecological contexts. Canonical correspondence analysis revealed that phytoplankton communities varied significantly among the lakes. Species composition, primarily shaped by key environmental factors such as electrical conductivity (EC), total organic carbon (TOC), total phosphorus (TP), total suspended solids (TSS), pH, nitrate (NO_3^-), and temperature, had a strong association of 98.8%. Lake Gölbaşı was related to relatively high temperature and NO_3^- levels, conditions which favor species such as *Lepocinclis fusiformis*, *Lepocinclis acus*, *Euglena agilis*, *Phacus caudatus*, and *Dolichospermum* sp. Lake Burdur was associated with high EC, TP, TOC, TSS, and pH, supporting taxa like *Lagerheimia ciliata*, *Lagerheimia genevensis*, and *Microcystis flos-aquae*. Lake Dalyan, a brackish ecosystem, was separated in the ordination, with species such as *Phacus limnophilus* var. 'swirenkoi', *Gymnodinium discoidale*, and *Pseudanabaena* sp. preferring relatively high EC levels. According to bio-assessment based on the Modified Phytoplankton Trophic State Index, Lakes Gölbaşı and Dalyan have a good ES while Lakes Salda and Burdur have moderate and poor ES, respectively. Using the Biological Condition Gradient model, Lake Burdur was categorized with a bad ES and the other three studied lakes were categorized with a good ES. The multimetric Aquatic Biotic Omnimetric Zenith Index (chemical assessment) classified Lake Burdur as the most degraded system. These results highlight the value of combining biological and chemical indicators to achieve a more comprehensive understanding of lake health and highlight the need for adaptable assessment frameworks that can account for both local conditions and broader ecological patterns.

Keywords Alkaline lakes · Ecoregion · Environmental gradient · Phytoplankton dynamics · Surface waters

Introduction

Ecoregions are geographically distinct areas characterized by relatively homogeneous environmental conditions, including climate, geology, and ecological traits, which

serve as a valuable framework for understanding biodiversity patterns and ecosystem functions (Omernik 1995; Loveland and Merchant 2004). By shaping key environmental drivers—such as nutrient availability, thermal conditions, and hydrological regimes—ecoregions play a fundamental role in regulating lake productivity, community composition, and trophic dynamics (Çelekli et al. 2020). Lake systems are intricate and dynamic ecosystems affected by various environmental, biological, and human-induced factors. One of the key influences of lake systems is the ecoregion in which the lake is located, as it significantly shapes its physical, chemical, and biological properties.

The relationship between ecoregions and lake ecosystems is critically important for understanding and managing freshwater resources. Differences in climate, land use, and geology across ecoregions result in varying inputs of

This paper is dedicated to the memory of Dr. Colin S. Reynolds, an undisputed leader in aquatic sciences, whose pioneering contributions and guidance have profoundly shaped the field of phytoplankton ecology.

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nutrients, organic matter, and pollutants, which directly affect water quality and ecosystem health (Carpenter et al. 2011). For example, lakes in forested ecoregions often receive inputs rich in organic matter, while those in agricultural regions are more prone to nutrient enrichment and eutrophication (Wurtsbaugh et al. 2019). Similarly, climatic factors such as temperature and precipitation, which vary significantly across ecoregions, influence the thermal stratification and mixing regimes of lakes, with profound implications for their ecological dynamics. Despite the well-recognized influence of ecoregions on lake ecosystems, a comprehensive understanding of these interactions remains incomplete. The diversity of lake types and their responses to regional environmental drivers necessitate a holistic approach to the study of these systems. Ecoregional factors significantly influence the ecological dynamics and nutrient relationships in lakes. These factors include land use, geology, catchment characteristics, climate, and hydromorphological conditions, all of which affect nutrient levels, algal biomass, and water quality.

The European Union's Water Framework Directive (WFD; European Parliament and the Council of the European Union 2000) highlights the importance of monitoring and managing aquatic ecosystems, with emphasis on the use of biological indicators to evaluate ecological status (ES). The WFD emphasizes the importance of using phytoplankton metrics to evaluate the ecological health of lakes. Phytoplankton metrics (e.g., phytoplankton trophic indices, total phytoplankton and cyanobacterial biovolume, chlorophyll-*a* concentrations, among others) are effective indicators of water quality and ecosystem health, reflecting changes in nutrient levels, pollution, and environmental factors covered under the WFD (Carvalho et al. 2013; Thackeray et al. 2013). Phytoplankton metrics are crucial instruments for evaluating the ES of freshwater ecosystems, providing valuable information on ecological conditions through the analysis of community composition, abundance, and diversity (Carvalho et al. 2013; Çelekli and Özpınar 2021; Qin et al. 2023). Indices that evaluate species based on their ecological preferences along a trophic gradient determined by total phosphorus (TP) are crucial for understanding ecosystem dynamics and health (Phillips et al. 2013). These indices often focus on changes in species richness, biodiversity, and community composition in response to varying phosphorus levels (Jeppesen et al. 2023). Indices like the PhyCoI (Phytoplankton Community Index; Katsiapi et al. 2016), PTI (Phytoplankton Trophic Index; Phillips et al. 2013), IPLAC (Phytoplankton Index for Lakes; Laplace-Treytore and Feret 2016), and the TSI (Trophic State Index; Ptacnik et al. 2009) have been developed and rely on phytoplankton data specific to certain regions. In Türkiye, the modified PTI (MPTI) (Çelekli and Lekesiz 2021) and the Phyto-Tr Index (Çetin

2023) were designed to evaluate the ES of lakes and reservoirs based on the trophic gradient of TP.

A comprehensive understanding of the factors mentioned above is essential for developing effective strategies for the management of water quality, nutrients and eutrophication tailored to specific ecoregions. The ecoregional approach helps address spatial heterogeneity and ensure the protection and sustainability of lake environments. We hypothesize that ecoregional differences significantly influence lake ES primarily through region-specific physicochemical drivers, such as salinity and nutrient enrichment in semi-arid regions and nutrient enrichment and temperature dynamics in humid regions, which in turn structure phytoplankton assemblages and trophic conditions. We also propose that multimetric assessment tools differ in their sensitivity to these regional patterns, with the MPTI and Biological Condition Gradient (BCG) integrated into the Aquatic Biotic Omnimetric Zenith (ABOZ). This study aims to (1) investigate how key physicochemical parameters vary across four lakes situated in different ecoregions of Türkiye; (2) examine the composition and structure of phytoplankton communities in relation to these physicochemical gradients, identifying indicator species associated with specific environmental conditions; and (3) assess the ES of lakes using a suite of multimetric indices (MPTI, Phyto-Tr, BCG, and ABOZ), and evaluate their consistency and sensitivity. By integrating biological and chemical data from multiple ecoregions, this study seeks to elucidate the mechanisms through which ecoregions shape lake dynamics and provide insights for effective management and conservation strategies. Therefore, this study serves as a preliminary investigation into how ecoregional environmental factors interact—rather than a definitive attribution of lake differences to ecoregions alone. By integrating biological and chemical assessments, this research provides a valuable starting point for developing regionally sensitive lake monitoring frameworks and highlights the need for more extensive, stratified sampling designs in future studies to disentangle the effects of regional influences on lake ecosystems.

Materials and methods

Study area

The study area comprises four lentic ecosystems, Lake Gölbaşı (*L1*) in the Asi River Basin; Lakes Burdur (*L2*) and Salda (*L3*) in the Burdur Closed River Basin; and Lake Dalyan (*L4*) in the Meriç-Ergene Basin (Fig. 1; Table 1). The Asi and Burdur basins are in the south of Türkiye, whereas the Meriç-Ergene Basin is in the north.

Lake Gölbaşı (*L1*) is a significant geological and ecological feature influenced by tectonic activity and climatic

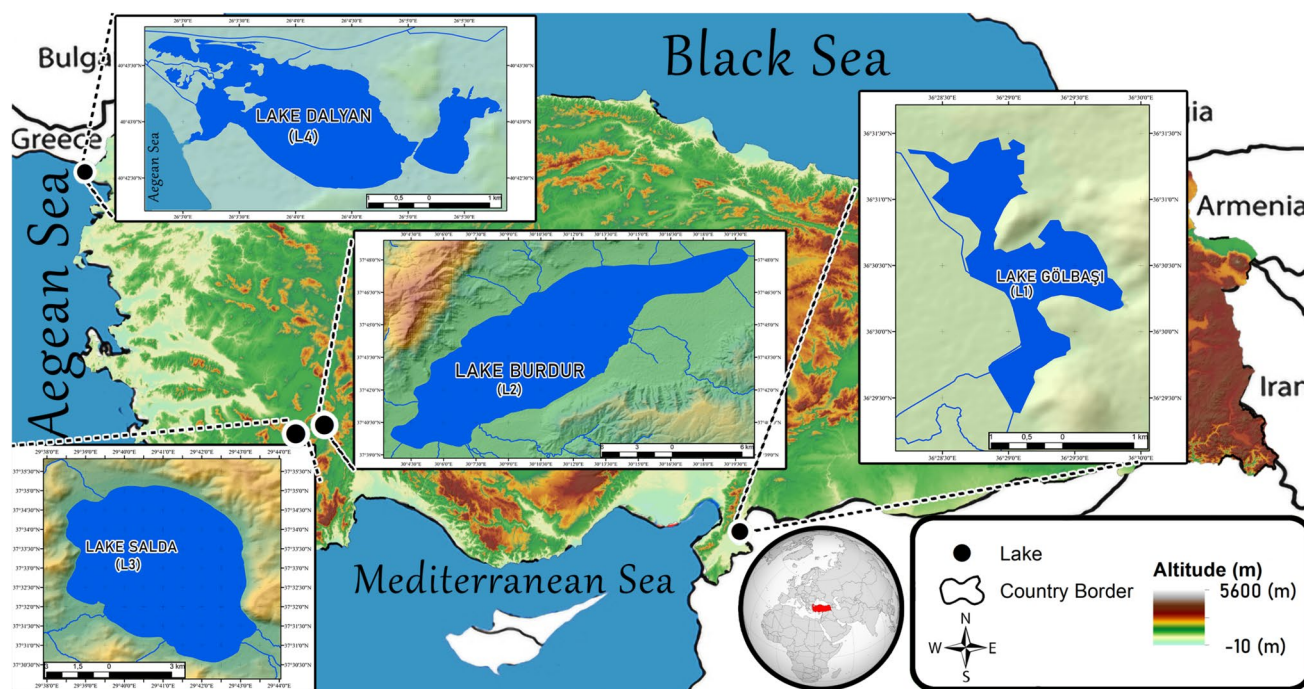


Fig. 1 Locations of lakes under study in the Asi, Burdur, and Meriç-Ergene basins of Türkiye. Codes for the lake ecosystems (L1–L4) and their full names are given in Table 1

Table 1 Code, full name, geographical data (longitude, latitude, and altitude), and surface area of the lakes sampled in the present study

Lake code	Name	Latitude	Longitude	Altitude (m a.s.l.)	Surface area (ha)	Max depth (m)	Ecosystem	Origin
L1	Lake Gölbaşı	36.503787	36.498292	85	82	2	Freshwater	Set
L2	Lake Burdur	37.693737	30.109965	850	15,769	Approx. 100	Saline	Tectonic
L3	Lake Salda	37.564009	29.676151	1145	4446	Approx. 200	Soda saline	Tectonic
L4	Lake Dalyan	40.720181	26.078971	5	36	1.5	Saline	Alluvium

conditions. It is fed by underground water, surrounded by agricultural lands, and its water is used for irrigation. Macrophytes (e.g., *Phragmites*, *Typha*, etc.) cover the shorelines of Lake Gölbaşı. This lake supports diverse aquatic life and serves as a habitat for various bird species, making it a crucial site for biodiversity conservation.

Lake Burdur (L2) is a tectonic-origin, saline, and alkaline lake located in southwestern Türkiye. It is the largest Ramsar site in the country, and is recognized for its ecological significance and biodiversity. The lake's water is brackish with high salinity, which continues to increase due to fluctuations in water levels. The lake's bitter and saline water composition is influenced by these hydrological inputs and evaporation dynamics. Lake Burdur supports a unique ecosystem adapted to saline and alkaline conditions, making it a vital habitat for diverse species, particularly waterbirds. However, ongoing reductions in

water levels and rising salinity pose significant ecological challenges, highlighting the need for conservation efforts.

Lake Salda (L3), located in southwestern Türkiye, is a highly alkaline and saline soda lake with exceptional limnological, geological, and ecological significance. It has gained scientific interest due to its similarities to the Martian Jezero Crater, particularly in terms of hydromagnesite stromatolites and extreme environmental conditions, and is rich in Mg^{2+} and Ca^{2+} (Kaiser et al. 2016; Balcı et al. 2020).

Lake Dalyan (L4) is a coastal lagoon within the Meriç–Ergene River Basin in the Thrace region of Türkiye, where it forms part of the larger Maritza/Evros/Meriç river system, a transboundary watershed shared by Bulgaria, Greece, and Türkiye. This lagoon is shaped by alluvial deposits from the Meriç River and is hydrologically influenced by both fluvial inputs from the Meriç River and marine inflows from the Aegean Sea. Surrounded by

agricultural lands and human settlements, Lake Dalyan is ecologically significant since it lies along a major migration route for water birds within the Meriç River Delta, a designated A-Class Wetland supporting water birds. However, agricultural activities in the Meriç–Ergene Basin have led to water contamination, with elevated levels of arsenic and metal(loid)s, necessitating improved water management strategies to mitigate pollution (Hallı et al. 2014).

The lakes included in this study were deliberately selected to represent contrasting ecoregions and distinct limnological types across Türkiye, thereby capturing variability in climatic, hydrological, and physicochemical conditions. This selection strategy enables a more robust assessment of how ecoregional drivers—such as climate, geology, predominant land use, and catchment characteristics—interact with lake-specific features, including morphometry, salinity, hydrological connectivity, and origin, to shape ES and phytoplankton composition. While morphological differences (e.g., depth, salinity, and lagoon vs. deep lake types) undoubtedly contribute to ecological variation, the inclusion of diverse lake types across distinct ecoregions provides an opportunity to disentangle regional-scale patterns from site-specific effects, thereby improving the interpretability and transferability of multimetric assessment tools.

Water and phytoplankton sampling

Water and phytoplankton samples were collected from the four lakes across different basins (Fig. 1) during the wet season (May 2022) and the dry season (September 2022) using a motorized Zodiac boat. Water samples were obtained using a Hydro-Bios water sampler bottle (Hydro-Bios Apparatebau, Altenholz, Germany), stored in insulated coolers at approximately 4 °C, and transported to the laboratory for subsequent chemical analyses. Sampling was conducted at a total of 11 stations: two stations in Lake Gölbaşı and three stations each in Lakes Burdur, Salda, and Dalyan, during the dry and wet periods. Phytoplankton samples were obtained from the surface at designated sampling stations of lakes following the EN 16698 standard protocol (European Committee for Standardization 2015). Phytoplankton samples were fixed in a Lugol–glycerol solution that was prepared by combining Lugol's iodine mixture with 2–3% glycerol, following the EN 15204 standard protocol (European Committee for Standardization 2006).

Before sampling, environmental parameters—including water temperature, pH, electrical conductivity (EC), and dissolved oxygen (DO)—were measured in situ using a YSI Professional Plus multi-parameter meter (YSI Inc., Yellow Springs, OH, USA). Water transparency was assessed using a 20-cm Secchi disk with black and white quadrants. Additionally, the geographic coordinates of each lake were

recorded with a Garmin eTrex Vista® HCx GPS device (Garmin, Olathe, KS, USA).

Laboratory analyses

The concentrations of total phosphorus (TP), total nitrogen (TN), nitrate (NO_3^-), total organic carbon (TOC), total suspended solids (TSS), and alkalinity in the lake water samples were determined following the standard methods (Rice et al. 2012). Chlorophyll-*a* concentrations were measured after 90% methanol extraction, with absorbance recorded using a UV/VIS spectrophotometer at 665 nm and 750 nm to correct for turbidity (Youngman 1978).

Phytoplankton taxa were identified using an Olympus BX53 light microscope equipped with a DP73 camera and CellSens Version 1.6 software (Olympus Group, Tokyo, Japan), following standard taxonomic references (Komárek et al. 1983; Komárek and Anagnostidis 1998; John et al. 2012; Bey and Ector 2013; Lange-Bertalot et al. 2017). Sub-samples (20–100 mL) were allowed to settle for 24–72 h in Hydro-Bios counting chambers (Hydro-Bios Apparatebau) prior to enumeration. Species enumeration was conducted along two transects at 400–600× magnification using an Olympus CKX41 inverted light microscope (Olympus Group). A minimum of 350 individuals were counted per sample, with each sample analyzed in triplicate, following the EN 15204 standard (European Committee for Standardization 2006). Phytoplankton biovolume was estimated by multiplying cell density by the average biovolume of each taxon (Sun and Liu 2003).

Trophic and ecological status

The Trophic State Index (TSI; Carlson 2007) and eutrophication criteria for lakes (Electronic Supplementary Material S1; Turkey's Surface Water Quality Regulation 2016 [TSWQR 2016], published in the Official Gazette on 10 August 2016) were applied to calculate the trophic states of the four lakes based on TP, TN, chlorophyll-*a*, and Secchi disk depth.

To evaluate the ES of each of these lakes, located in different ecoregions, values of the MPTI (Çelekli and Lekesiz 2021) and the Phyto-Tr (Çetin 2023) indices were calculated using Eqs. 1 and 3, respectively.

$$\text{MPTI} = \frac{\sum_{j=1}^n a_j \times s_j \times i_j}{\sum_{j=1}^n a_j \times i_j} \quad (1)$$

$$t = \sqrt{\left(\sum_{i=1}^n (\log \text{TP} - \text{WA})^2 * a_j \right) / \sum_{i=1}^n a_j} \quad (2)$$

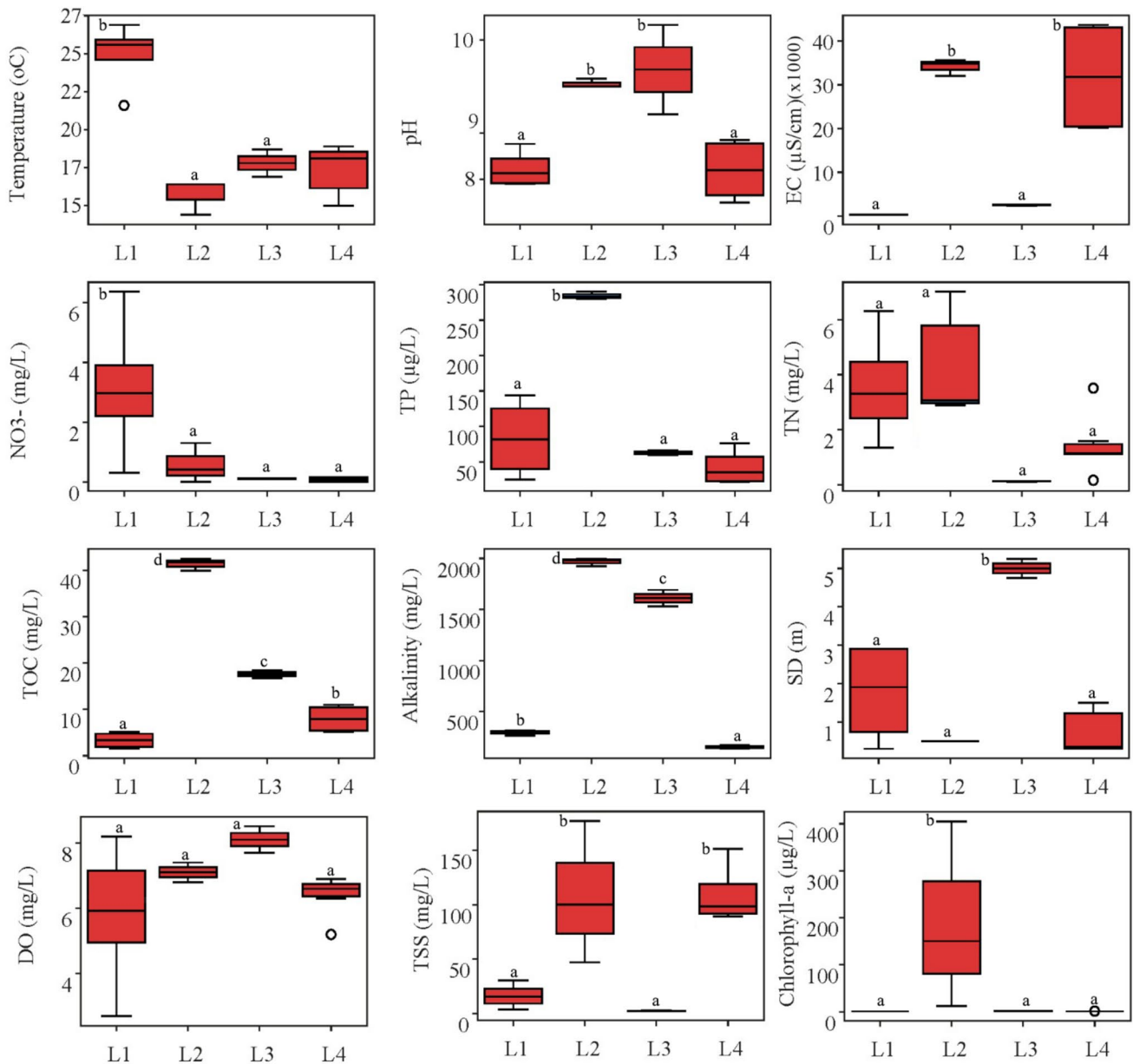


Fig. 2 Boxplots of physico-chemical variables measured in the four lakes (L1–L4) located in different basins. Codes of lakes (L1–L4) with their full names are given in Table 1. For each parameter, different lowercase letters above/beside the boxes indicate statistically significant differences among lakes at the $\alpha=0.05$ level; identical letters

denote no significant difference according to Duncan's multiple range test (95% confidence interval). *DO* Dissolved oxygen, *EC* electrical conductivity, *NO₃⁻* nitrate, *SD* Secchi depth, *TN* total nitrogen, *TOC* total organic carbon, *TP* total phosphorus, *TSS* total suspended solids

In Eq. 1, a_j represents the fractional biovolume, s_j denotes the optimum value for logTP, and i_j corresponds to the species' indicator value.

Weighted average (WA) regression was applied to estimate the optimum logTP value for taxa (Juggins and ter Braak 1992). The tolerance (t) value was calculated using Eq. 2 and was based on the calculated values. For the classification procedure, threshold values of t were used to assign indicator values (i_j) of each species, assigned on

a scale from 1 to 4 as follows: when $t < 0.25$, $i = 4$; when t was within the range $0.25 \leq t < 0.50$, $i = 3$; when t was within the range $0.50 \leq t < 0.75$, $i = 2$; and when $t \geq 0.75$, $i = 1$.

$$\text{Phyto} - \text{Tr} = \sum_{i=1}^n a_j x s_j / \sum_{i=1}^n a_j \quad (3)$$

where a_j exhibits the fractional biovolume and s_j is the optimum of j th species for logTP.

The multimetric approaches of Aquatic Biotic Omnimetric Zenith (ABOZ) and Biological Condition Gradient (BCG) were used to predict the ES of the lakes.

The ABOZ Index integrates multiple environmental parameters into a single, dimensionless indicator of water quality. This index ranges from 0 to 1, with values closer to 1 reflecting higher ecological quality, while those closer to 0 indicate a decline in aquatic conditions. A set of key parameters was chosen based on their well-documented significance in determining ES and overall water quality in lentic ecosystems. This selection was further supported by preliminary statistical analyses, including canonical correspondence analysis (CCA). Given the varying units and scales of these parameters, minimum (min)–maximum (max) normalization (Eq. 4) was applied to standardize raw measurements within a range of 0 and 1 (Mazziotta and Pareto 2022):

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (4)$$

These measurements are prioritized in the weighting scheme of the ABOZ Index, reflecting their influence on overall aquatic ecosystem status. This approach ensured that the transformations (e.g., inverse metrics) applied to negatively correlated parameters accurately represented their relationships with ecological quality. Negatively correlated parameters were converted to an inverse metric, $X_{inv} = 1 - X_{norm}$, as their increase typically indicates a deterioration in water quality. A positively correlated parameter was retained in its normalized state, i.e., DO_{norm} form. The specific minimum and maximum bounds for each parameter were drawn from the dataset's observed ranges or established water-quality thresholds. To account for high inflation factors identified by CCA, each parameter received a predefined weight. In the present formulation, weights were assigned as indicated.

The total sum of these weights equals 12, ensuring that each ABOZ value remains scaled between 0 and 1. The final ABOZ value for each sampling station was calculated using Eq. 5:

$$ABOZ = \frac{(TP_{inv} \times 5) + (EC_{inv} \times 2.5) + (Temp_{inv} \times 2) + 0.25 \times (NO3_{inv} + DO_{norm} + TN_{inv} + TSS_{inv} + TOC_{inv})}{12} \quad (5)$$

A fuzzy logic-based system was developed to assess water quality using four key input parameters: MPTI, TP, EC, and DO. Trapezoidal or triangular membership functions were applied to TP, EC, and DO to ensure comprehensive coverage of their measurement ranges. The evaluation process followed a two-stage rule-based approach. First, a fuzzy inference engine—built using the scikit-fuzzy toolkit in Python—calculated a numerical BCG value ranging from 0, representing a bad ES (ES), to 1, indicating a high ES. A

structured rule set (BCG1 represents high ES-BCG5, indicating bad ES) was designed to link membership functions, variables, and logical operations in the fuzzy logic framework. For example: If TP, MPTI, DO, and EC all belong to BCG1, then the ES is classified as BCG1. In the second stage (merging), additional rules and inference algorithms were applied based on membership functions. The final output was mapped to one of five linguistic BCG classes—bad, poor, moderate, good, or high—using a threshold-based approach. The entire method was implemented in Python 3.9, utilizing the NumPy library for defining universes of discourse and the scikit-fuzzy toolkit for encoding membership functions and inference rules. This fuzzy logic framework effectively integrates the relationship between MPTI and TP.

Statistical analyses

Average values of data across the lakes were compared using analysis of variance (ANOVA) and Duncan's Multiple Range Test (SPSS Statistics for Windows, version 2020; IBM Corp., Armonk, NY, USA). Percentiles for the data were calculated using percentile analysis. To evaluate correlations between the studied metrics and environmental variables, we applied the Spearman rank correlation test. The analysis of similarities (ANOSIM) was used to test the statistical significance of differences in species assemblages across lakes located in different basins. A linear regression analysis was conducted to assess the interaction between logTP and the other metrics (Myers et al. 2012). The sampling stations were categorized into three groups: group I for stations in the Asi Basin, group II for stations in the Burdur Basin, and group III for those in the Meriç-Ergene Basin. ANOSIM compares within-group similarity with between-group similarity to evaluate similarities and differences in species composition. Additionally, SIMPER (Similarity Percentage) analysis was performed to quantify the similarities and dissimilarities among groups. This method

compares within-group similarities to between-group similarities, offering insights into the degree of similarity or dissimilarity in species composition. SIMPER analysis was also employed to identify and quantify the similarities and differences among the identified groups.

Detrended correspondence analysis (DCA) was conducted to determine the gradient lengths of the first two axes, with values exceeding 4.0 confirming the appropriateness of the canonical correspondence analysis (CCA). All predictor

variables, except pH, were log-transformed [$\ln(x+1)$] to reduce skewness and approximate normal distribution (ter Braak and Šmilauer 2002). The complete environmental dataset was subjected to CCA using Canoco version 4.5 software to examine the relationships between phytoplankton species (recorded at least twice during the study) and ecological predictors across the different basins. Forward selection and Monte Carlo permutation tests (999 iterations) were used to identify the key environmental variables influencing phytoplankton distribution at the sampling stations (Lepš and Šmilauer 2003). Finally, WA regression (CALIBRATE program) was applied to determine the optimum levels phytoplankton species for different selected environmental variables that play significant roles in phytoplankton distribution in the CCA (Juggins and ter Braak 1992), and the resulting species optima were visualized using SigmaPlot version 9.0 (Systat Software Inc., San Jose, CA, USA).

Results

Physicochemical variables

Boxplots of the environmental variables obtained in the studied lakes in different ecoregions are given in Fig. 2; all variables exhibited significant spatial variations. Descriptive results of the environmental variables are given in ESM S2. The highest water temperature was recorded in Lake Gölbaşı ($L1 = 26.9^\circ\text{C}$) with a mean of 24.9°C , whereas the lowest value (14.4°C) was observed in Lake Burdur ($L2$) with a mean of 15.7°C . Lakes Salda ($L3$) and Burdur ($L2$) had significantly higher pH values of 9.68 and 9.53, respectively ($p < 0.05$, $F = 25.0$) than those of Lakes Gölbaşı ($L1$) and Dalyan ($L4$). The EC value was the highest in Lake Burdur ($L2 = 34,133\ \mu\text{S/cm}$), followed by Lake Dalyan ($L4 = 31,833\ \mu\text{S/cm}$) and Lake Salda ($L3 = 2510\ \mu\text{S/cm}$); the lowest mean EC value was found in Lake Gölbaşı ($L1 = 337\ \mu\text{S/cm}$). There were significant differences in EC values among lakes ($p < 0.05$).

Nutrient concentrations also varied substantially among the lakes. The highest TP was measured in Lake Burdur ($L2 = 284.3\ \mu\text{g/L}$), whereas the lowest value was recorded in Lake Dalyan ($L4 = 41.8\ \mu\text{g/L}$), followed by Lake Salda ($L3 = 63.0\ \mu\text{g/L}$). Lake Gölbaşı ($L1$) exhibited the highest TN ($3.57\ \text{mg/L}$) and NO_3^- ($3.15\ \text{mg/L}$) concentrations, while the lowest values were observed in Lake Salda ($L3$). Lake Burdur ($L2$) had the highest mean TOC ($41.4\ \text{mg/L}$) and TSS ($108\ \text{mg/L}$), indicating higher organic matter content and turbidity compared to the other lakes. The highest and lowest Secchi depth (SD) was recorded in Lake Salda ($L3 = 5\ \text{m}$) and Lake Burdur ($L2 = 0.5\ \text{m}$), respectively, followed by Lake Dalyan ($L4 = 0.7\ \text{m}$). The highest chlorophyll-*a* value was determined in Lake Burdur ($L2 = 189.2\ \mu\text{g/L}$);

the other ecosystems had low chlorophyll-*a* levels of about $1\ \mu\text{g/L}$.

Phytoplankton assemblage–environmental relationships

A total of 120 phytoplankton taxa were identified across the studied lakes ($L1$ – $L4$), with 91 taxa appearing at least twice during the study period and included in the multivariate statistical analyses (ESM S3). Several species were frequently observed across the sampling stations, including *Cryptomonas ovata*, *Fragilaria capucina*, *Chlamydomonas passiva*, *Cocconeis placentula*, *Gymnodinium discoidale*, *Pantocsekiella ocellata*, *Tetraselmis cordiformis*, and *Gyrodinium aureolum*.

Total phytoplankton biovolume, used as a proxy for biomass, varied among lakes, ranging from $5.14\ \text{mm}^3/\text{L}$ in Lake Burdur ($L2$) to $0.36\ \text{mm}^3/\text{L}$ in Lake Salda ($L3$, Fig. 3). The distribution of phytoplankton biovolume among classes revealed differences in biomass dominance rather than numerical abundance across the lakes. In Lake Gölbaşı ($L1$), Chrysophyceae (37%) was the most abundant class of phytoplankton, followed by Cryptophyceae (21%), and Bacillariophyceae (20%). Lake Burdur ($L2$) was dominated by Chlorophyceae (52%) and Bacillariophyceae (46%), whereas Dinophyceae (71%) contributed the most to total phytoplankton biovolume in Lake Salda ($L3$), followed by Chlorophyceae (17%) and Bacillariophyceae (10%). In Lake Dalyan ($L4$), Euglenophyceae (51%) and Bacillariophyceae (32%) were the dominant contributors to total phytoplankton biovolume. Notably, the highest Cyanobacteria biovolume ($0.014\ \text{mm}^3/\text{L}$) was recorded in Lake Burdur ($L2$), indicating a potential influence of nutrient availability on community structure. These findings highlight distinct phytoplankton compositions and biovolume distributions across the lakes, reflecting their unique environmental conditions.

Stations were categorized into three groups based on their river basins: group I included stations in the Asi Basin, group II included stations in the Burdur Basin, and group III included stations in the Meriç–Ergene Basin. According to the ANOSIM results, a significant difference was found in the species composition among lakes in different ecoregions ($p < 0.05$). The SIMPER revealed dissimilarity values of 97.2% between group I (Lake Gölbaşı) and group II (Lakes Burdur and Salda), 94.3% between group I and group III (Lake Dalyan), and 94.7% between group II and group III. The dissimilarity between group I and group II was due to the presence of *Tetraselmis cordiformis*, *Dinobryon divergens*, *G. attenuatum*, *Navicula cryptocephala*, *Navicula cari*, and *Chlamydomonas passiva*. The species *Phacus limnophilus* var. 'swirenkoi', *D. divergens*, *G. attenuatum*, *Plagioselmis nannoplanctica*, and *Cryptomonas ovata* contributed to the dissimilarity between group I and group III. The

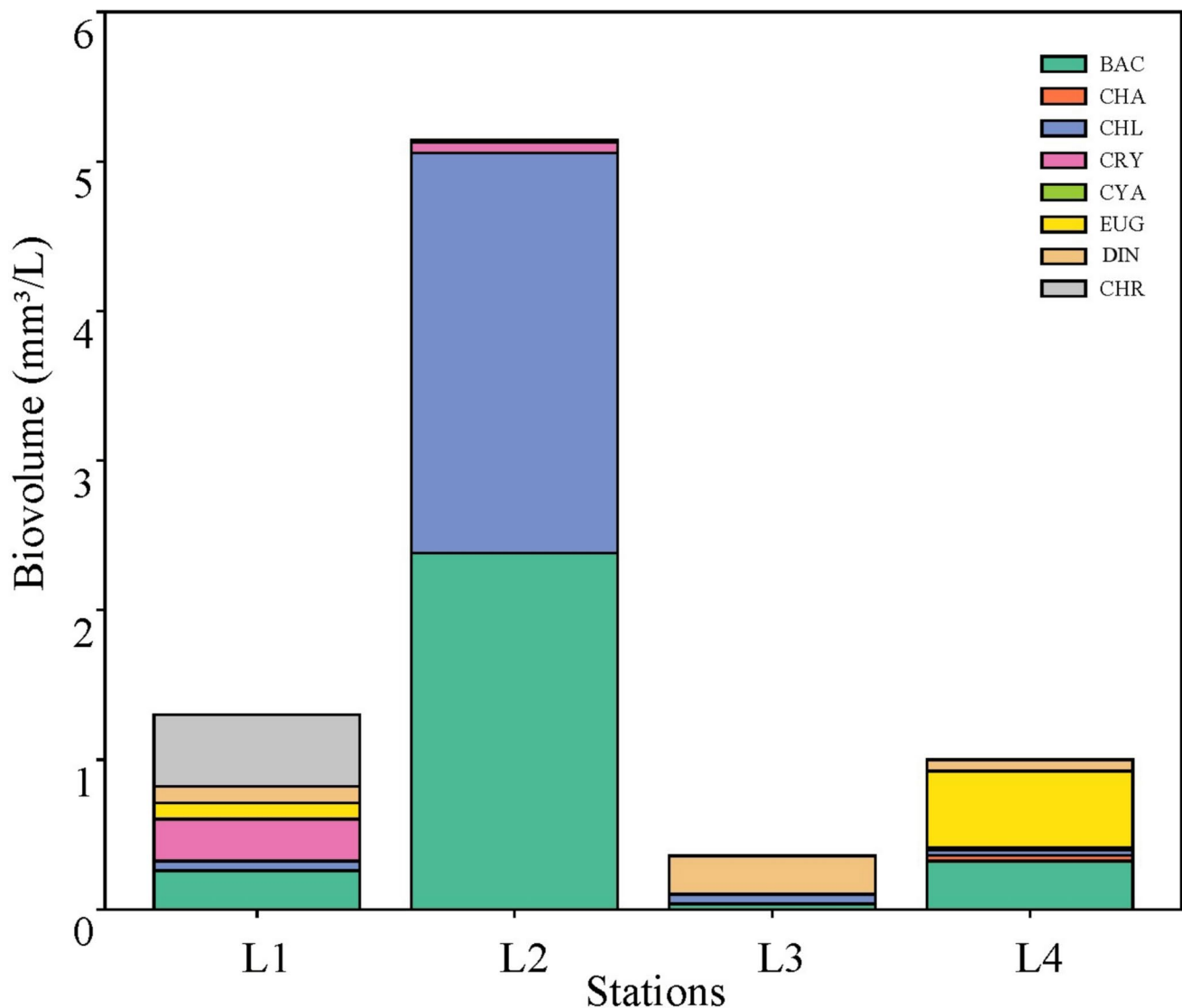


Fig. 3 Total phytoplankton mean biovolume in the four lakes from different ecoregions. Codes of lakes (L1–L4) with their full names are given in Table 1. Phytoplankton classes: BAC Bacillariophyceae,

CHA Charophyceae, CHL Chlorophyceae, CHR Chrysophyceae, CRY Cryptophyceae, CYA Cyanobacteria, DIN Dinophyceae, EUG Euglenophyceae,

presence of *T. cordiformis*, *P. limnophilus* var. 'swirenkoi', *G. attenuatum*, *N. cryptocephala*, and *N. cari* contributed to the dissimilarity between group II and group III. The within-group similarity in sampling stations of Lake Gölbaşı in Asi Basin as group I was 17.4% based on the contributions of *P. nanoplantica*, *C. ovata*, *Parvodinium cunningtonii*, *C. placentula*, and *Anomoeoneis sphaerophora*. The within-group similarity in lakes of the Burdur Basin as group II was 14.9% due to the presence of *T. cordiformis*, *G. attenuatum*, *F. capucina*, and *N. cari*. The phytoplankton species contributing most to within-group similarity (24.0%) in the

Meriç-Ergene basin as group III included *P. limnophilus* var. 'swirenkoi', *Gyrosigma kuetzingii*, *Gymnodinium discoidale*, and *G. attenuatum*.

The distribution of phytoplankton taxa across Lakes Gölbaşı (L1), Burdur (L2), Salda (L3), and Dalyan (L4) was strongly influenced by key environmental factors, including EC, TOC, TP, TSS, pH, NO_3^- , and temperature ($p=0.002$; see Fig. 4). CCA demonstrated a robust relationship between phytoplankton assemblages and environmental gradients, explaining 99.8% of the variation along the first two axes (Table 2). Lake Gölbaşı (L1), located in the Asi Basin, was

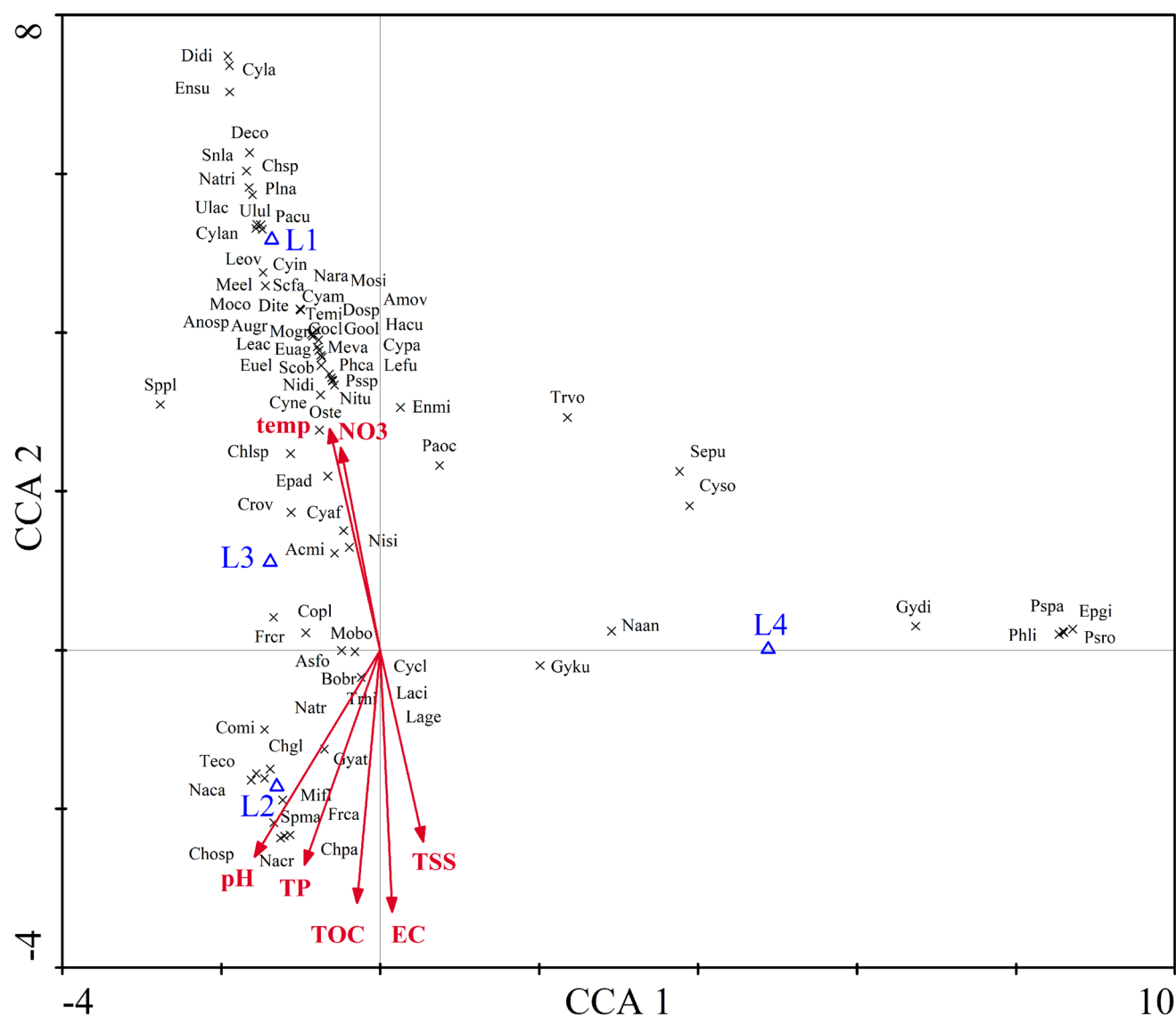


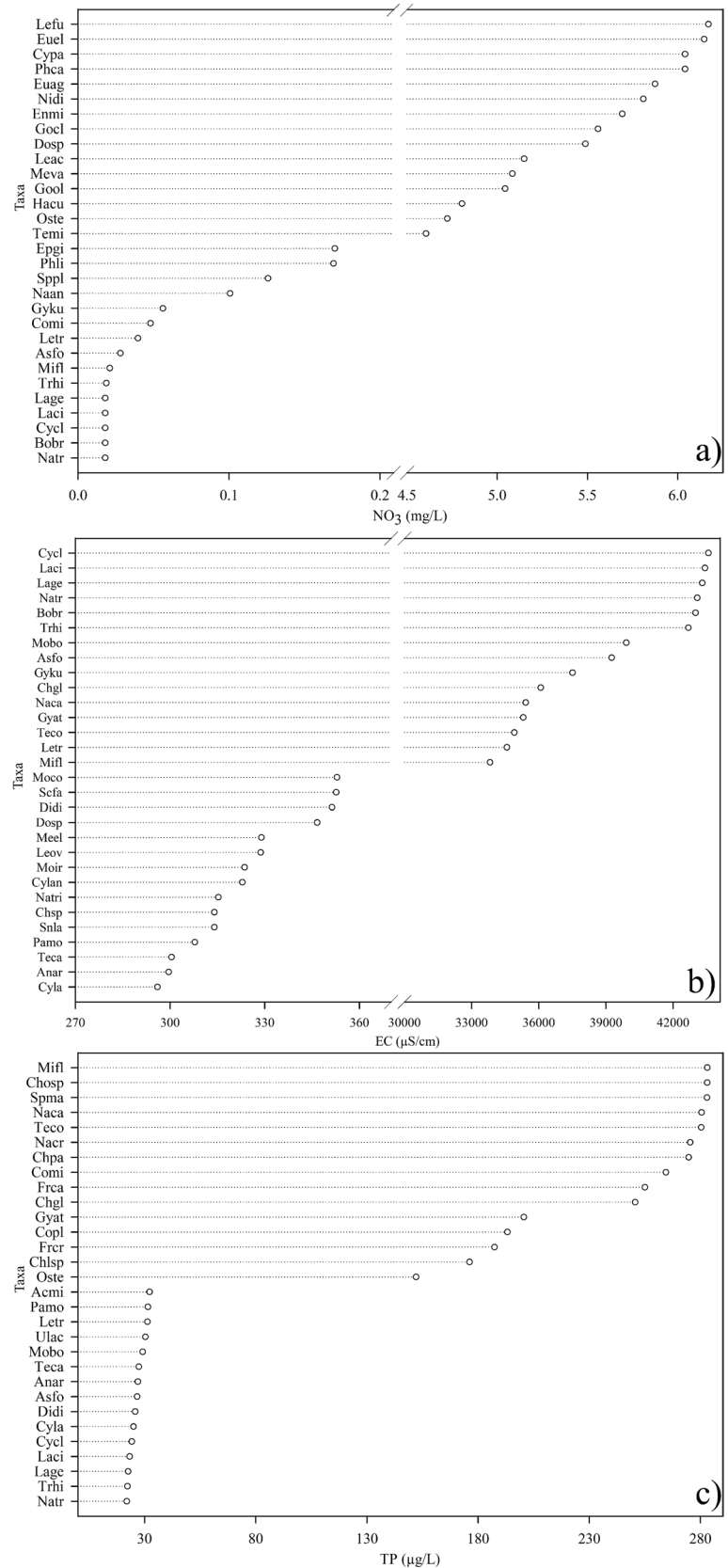
Fig. 4 Phytoplankton species (x symbol)–environmental variables (arrows) relationships in sampling stations (upright triangles) in the studied lakes. Codes of lakes (L1–L4) with their full names are given in Table 1 and species with their full names are given ESM S3.

CCA Canonical correspondence analysis, EC Electrical conductivity, NO_3^- nitrate, temp temperature, TOC total organic carbon, TP total phosphorus, TSS total suspended solids

Table 2 Main results of canonical correspondence analysis using the Monte Carlo permutation test for assessing the relationship biovolume phytoplankton species–environment variable relationship

Axes	λ_1	λ_2	λ_3	λ_4	Total inertia
Eigenvalues	0.906	0.882	0.750	0.717	5.635
Species–environment correlations	0.997	0.998	0.996	0.987	
Cumulative percentage variance					
- of species data	16.1	31.7	45.1	57.8	
- of species–environment relation	21.4	42.3	60.1	77.0	
Sum of all eigenvalues					5.635
Sum of all canonical eigenvalues					4.227
Summary of Monte Carlo test					
Test of significance of first canonical axis: eigenvalue = 0.906					
$F = 0.958$				$p = 0.002$	

Fig. 5 Optimum values of phytoplankton taxa for nitrate (NO_3) (a), electrical conductivity (EC) (b), and total phosphorus (TP) (c). Figures show the top 15 species and the bottom 15 species with highest and lowest optimum levels, respectively. Codes for full names of taxa are given in ESM S3



distinct from the other lakes due to its elevated water temperature and NO_3^- levels, both factors favoring species such as *Lepocinclis fusiformis*, *Lepocinclis acus*, *Eudorina elegans*, *Euglena agilis*, *Phacus caudatus*, *Dolichospermum* sp., and *Nitzschia dissipata*, which prefer NO_3^- optima exceeding 75% of the observed gradient (Fig. 5a). Lake Burdur (L2) was associated with high EC, TP, TOC, TSS, and pH, supporting taxa including *Cylindrotheca closterium*, *Lagerheimia ciliata*, *Lagerheimia genevensis*, *Navicula tripunctata*, *Chlamydomonas globosa*, *Microcystis flos-aquae*, *Navicula cari*, *Navicula cryptocephala*, and *Spirulina major*. WA regression revealed that *Cylindrotheca closterium* and *Lagerheimia* species thrived at EC levels in the upper quartile of

the gradient (Fig. 5b), while other species showed a similar preference for high TP levels (Fig. 5c). A few species, including *Fragilaria capucina*, *Cocconeis placentula*, *Pantocsekiella ocellata*, and *G. discoidale*, which were associated with Lake Salda (L3), were positioned near the origin of the CCA axes. Lake Dalyan (L4), a brackish lagoon ecosystem, was separated along the positive x -axis in the ordination, with species such as *P. limnophilus* var. 'swirenkoi', *G. discoidale*, *Gyrosigma kuetzingii*, *Pseudanabaena* sp., *N. antonii*, and *Epithemia gibba* preferring high EC levels ranging from 20,300 to 37,507 $\mu\text{S}/\text{cm}$. These findings highlight distinct phytoplankton–environment interactions across

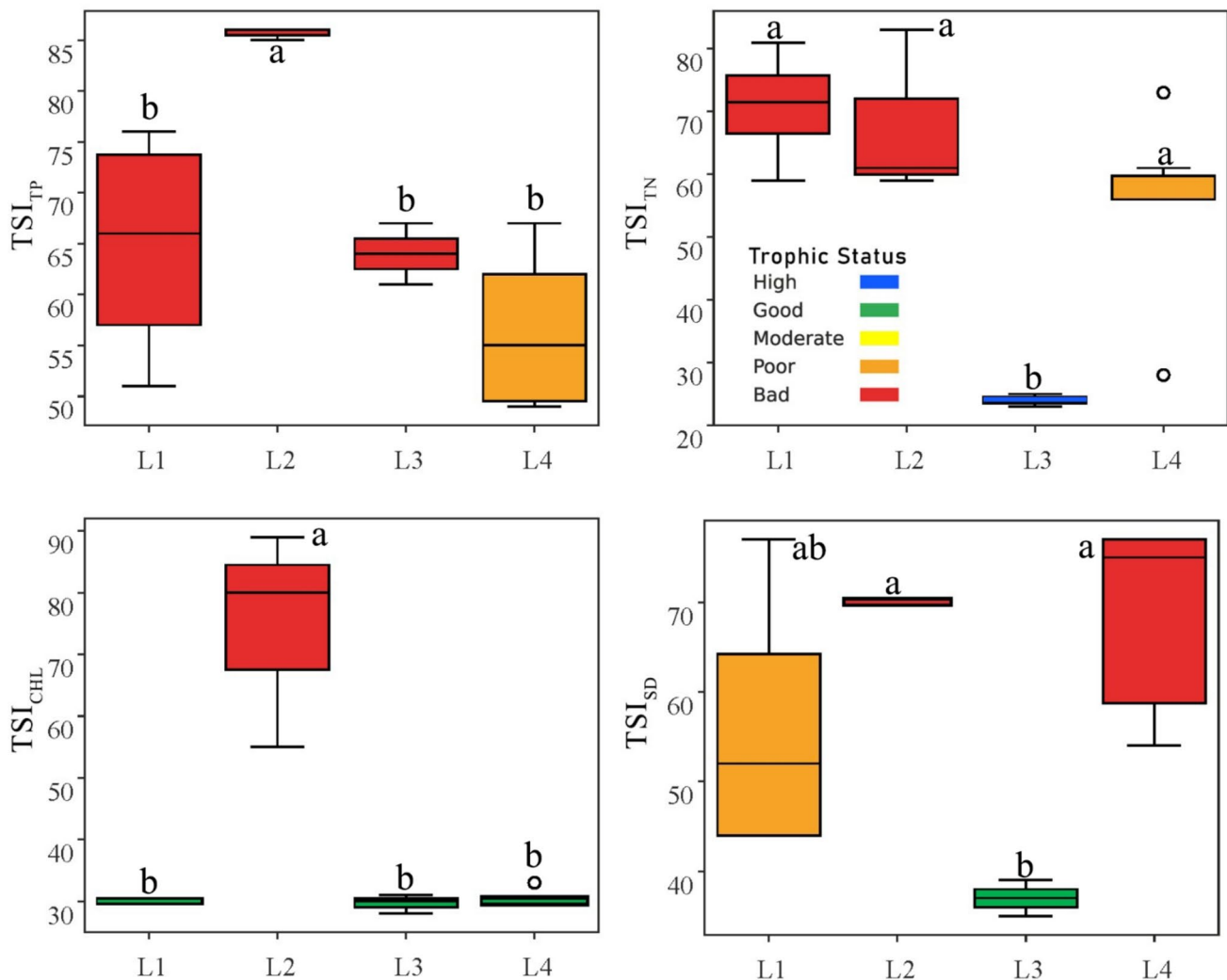


Fig. 6 Boxplots of trophic states of the lakes in the different basins. Colors indicate trophic state, where blue indicates ultra-oligotrophic state (High ES); green, oligotrophic state (Good ES); yellow, mesotrophic state (moderate ES); orange, eutrophic state (poor ES); red, hypertrophic state (bad ES). Codes of lakes (L1–L4) with their full names are given in Table 1. Trophic State Index (TSI) results in relation to total phosphate (TSI_{TP}), total nitrogen (TSI_{TN}), Secchi depth

(TSI_{SD}), and chlorophyll-*a* (TSI_{CHL}) are shown (Carlson 2007). Eutrophication criteria are given in ESM S1, and in the TSWQR 2016 [see text]). For each parameter, different letters above the boxes indicate statistically significant differences among lakes at the $\alpha=0.05$ level. Identical letters denote no significant difference according to Duncan's multiple range test (95% confidence interval). ES Ecological status

lakes in different ecoregions with varying physicochemical conditions.

Trophic state and ecological status of sampling stations

Trophic states of the studied lakes assessed using the TSI for TP (TSI_{TP}), TN (TSI_{TN}), SD (TSI_{SD}), and chlorophyll-*a* (TSI_{CHL}) varied significantly among the stations ($p < 0.05$; Fig. 6). The TSI_{TP} resulted in the identification of a hypertrophic state in Lakes Gölbaşı (*L1*), Burdur (*L2*), and Salda (*L3*), whereas Lake Dalyan (*L4*) was categorized as eutrophic. This classification was further supported by TSI_{TN} , except for Lake Salda (*L3*), which was ultra-oligotrophic. The TSI_{SD} indicated that Lakes Burdur (*L2*) and Dalyan (*L4*) were hypertrophic, while Lake Gölbaşı (*L1*) was eutrophic, and Lake Salda (*L3*) remained oligotrophic.

Phytoplankton-based indices (MPTI and Phyto-Tr) and multimetric approaches, including ABOZ and BCG,

provided insight into the ES of the lakes (Fig. 7). Regression analyses between logTP and these indices revealed strong relationships for MPTI ($R^2 = 0.84$), BCG ($R^2 = 0.96$), and ABOZ ($R^2 = 0.63$), while Phyto-Tr exhibited the weakest correlation ($R^2 = 0.45$) (Fig. 8). In addition, Spearman's correlation analysis indicated that the TP gradient was strongly and positively correlated with MPTI ($r = 0.90$, $p < 0.01$), while it exhibited a strong negative correlation with the BCG ($r = -0.97$, $p < 0.01$) and ABOZ ($r = -0.54$, $p < 0.05$). No significant correlation was observed between TP and Phyto-Tr. According to the MPTI classification, Lakes Gölbaşı (*L1*) and Dalyan (*L4*) were categorized with a Good ES, whereas Lake Salda (*L3*) was classified as moderate ES, and Lake Burdur (*L2*) as poor ES. The ABOZ Index, which incorporates multiple chemical parameters, classified Lakes Salda (*L3*) and Dalyan (*L4*) as Good ES, while Lake Gölbaşı (*L1*) was assessed as moderate ES, and Lake Burdur (*L2*) as poor ES. The BCG, which combines biological and chemical assessments, classified Lakes Gölbaşı (*L1*), Salda (*L3*), and

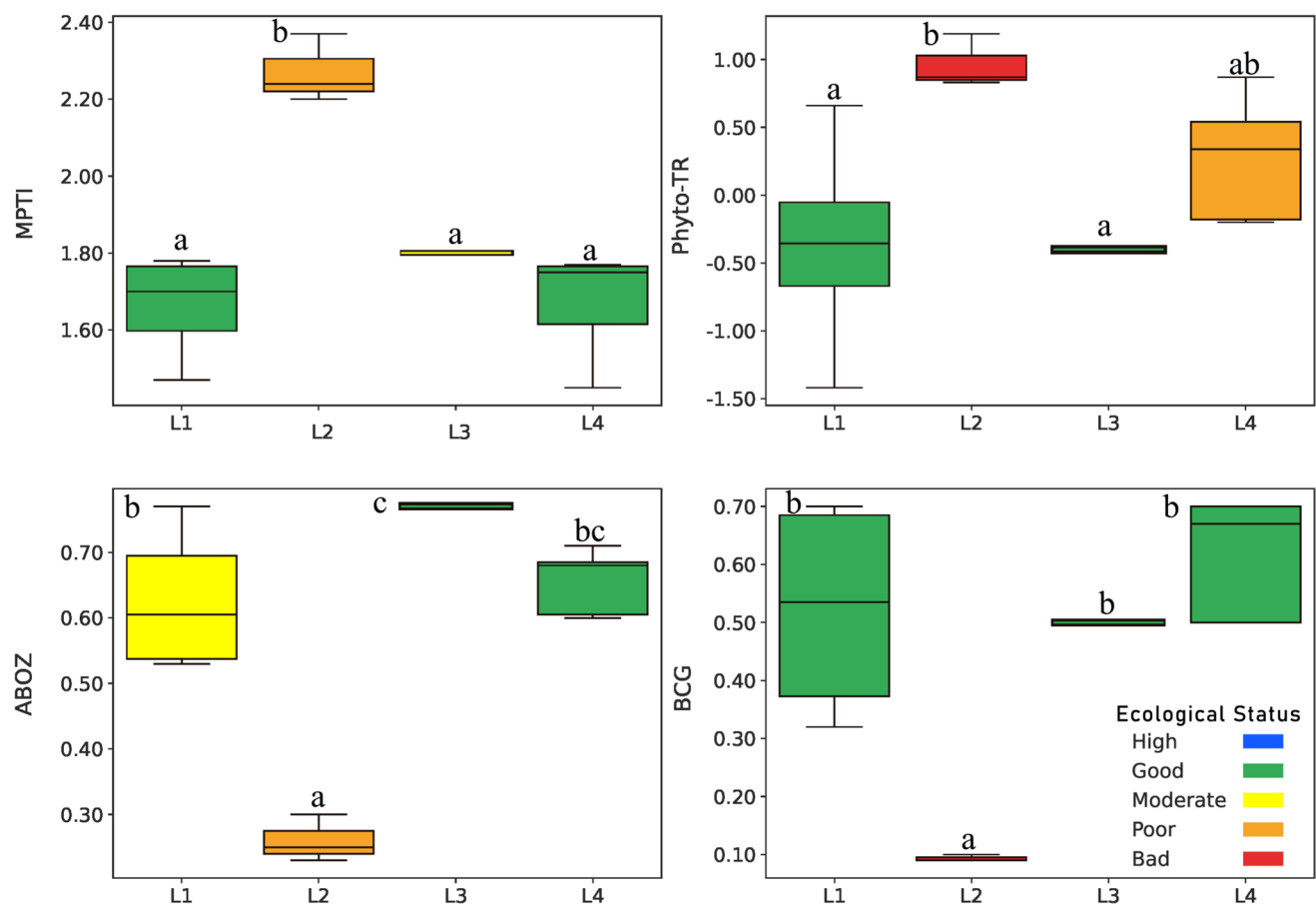


Fig. 7 Box plots of ecological status of the lakes in the different basins. Colors indicate ecological status (ES), where blue indicates high ES; green, good ES; yellow, moderate ES; orange, poor ES; red, bad ES. Codes of lakes (*L1*–*L4*) with their full names are given in Table 1. For each parameter, different letters above the boxes indicate

statistically significant differences among lakes at the $\alpha = 0.05$ level. Identical letters denote no significant difference according to Duncan's multiple range test (95% confidence interval). ABOZ Aquatic Biotic Omnimeric Zenith, BCG Biological Condition Gradient, MPTI modified Phytoplankton Trophic Index

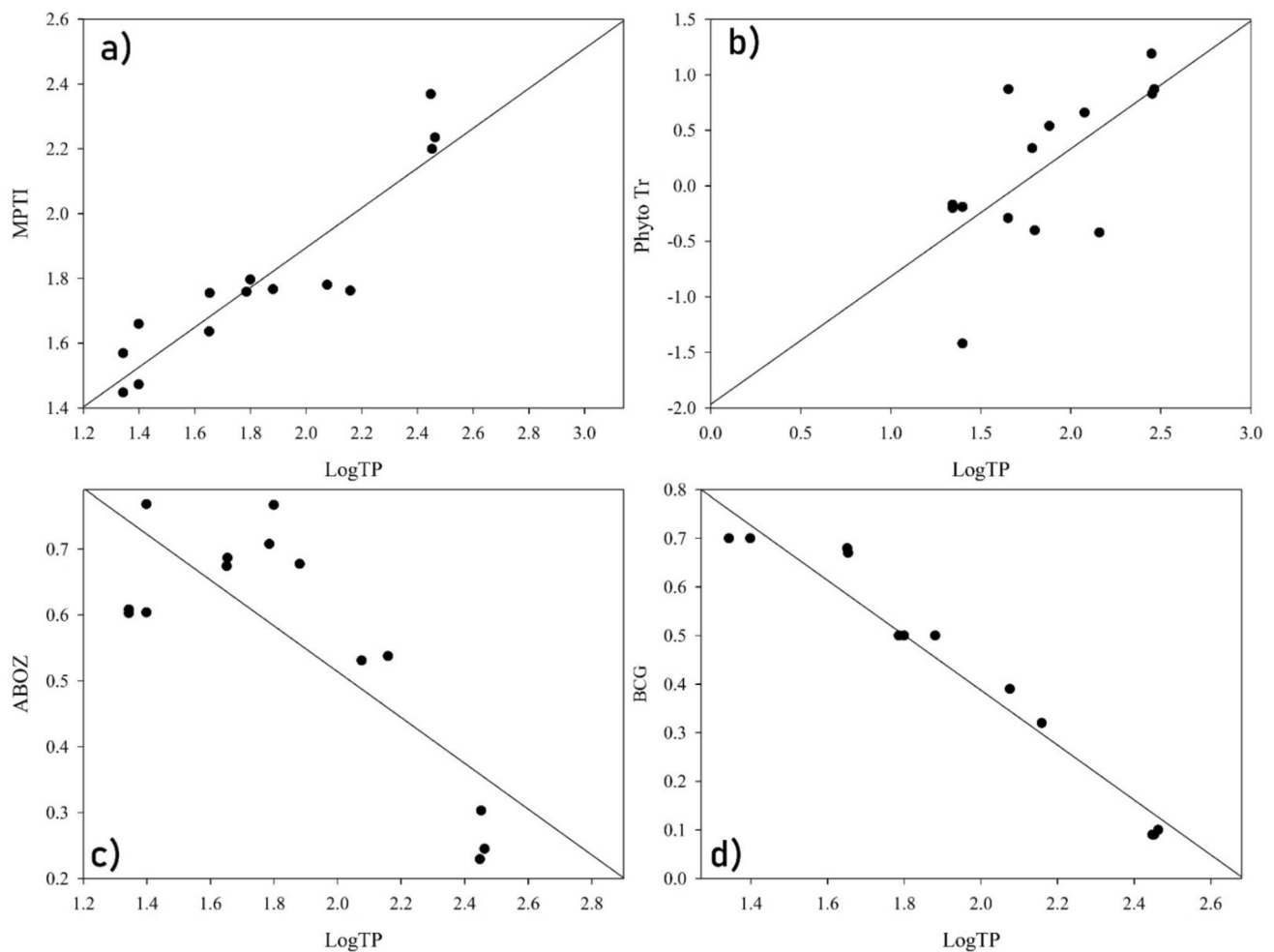


Fig. 8 Logarithmic total phosphorous (logTP) versus MPTI (a), Phyto-Tr (b), ABOZ (c), and BCG (d). ABOZ Aquatic Biotic Omnimetric Zenith, BCG Biological Condition Gradient, MPTI modified Phytoplankton Trophic Index

Dalyan (L4) as good ES, while Lake Burdur (L2) was categorized with bad ES (Fig. 7).

Discussion

This study provides a comprehensive analysis of the physicochemical and biological variability of four lakes situated across distinct ecoregions, and the findings emphasize how regional environmental gradients drive interactions with lake-specific characteristics to shape differences in lake ecology.

While ecoregional factors such as climate, geology, and catchment land use establish a broad environmental context, intrinsic lake properties—including lake morphometry (e.g., surface area, depth), basin type, salinity, and hydrological residence time—play a critical role in regulating local physicochemical conditions and biological communities. The

findings therefore contribute to a more integrated understanding of how both large-scale (ecoregional) and local-scale (lake-specific) drivers jointly influence aquatic ecosystem structure and functioning across diverse environmental settings.

Ecoregional influence on physicochemical characteristics

Significant differences in the physicochemical profiles of the lakes reflect the influence of their respective ecoregions, driven by geological factors, climate regimes, and human impacts. The relatively high water temperature recorded in Lake Gölbaşı (L1) suggests a strong thermal influence, likely due to regional climatic conditions. Lakes located in carbonate-rich ecoregions, such as Lakes Salda (L3) and Burdur (L2), exhibit alkaline conditions with elevated pH values, consistent with the presence of carbonate and ultramafic minerals. The high pH of these lakes suggests an

alkaline environment, which may influence the availability of nutrients (Davraz et al. 2019). This geochemical signature fosters unique biogeochemical cycles, such as the formation of hydromagnesite stromatolites in Lake Salda (a terrestrial analog of the paleolake in Jezero Crater on Mars), which may serve as analogs for ancient aquatic environments (Balci et al. 2020; Çelekli and Zariç 2024; Güneş et al. 2024). Conversely, lakes in other ecoregions, such as Lakes Gölbaşı (L1) and Dalyan (L4), show relatively low pH values and greater variability in ionic content, reflecting distinct climatic and hydrological inputs.

Ecoregional differences among the lakes can be largely attributed to variations in geology, hydrology, climate, and catchment land use, all of which are known to shape key physicochemical conditions such as ionic composition, EC, and nutrient availability. Geological setting determines baseline ion concentrations and influences EC, while hydromorphological factors—particularly depth and water-residence time—moderate stratification, mixing intensity, and sediment–water interactions (Kalff 2002). Climatic gradients further contribute by altering evaporation–precipitation balances, thereby affecting salinity and nutrient concentration. In addition, land-use patterns within lake catchments strongly regulate external nutrient inputs, with agricultural landscapes typically associated with higher nitrogen and phosphorus loading, and more natural or forested catchments contributing substantially less (Carpenter et al. 1998; Allan 2004). Collectively, these ecoregional drivers provide a coherent explanation for the physicochemical and biological variability observed among the studied lakes.

Eutrophication patterns also differ among ecoregions, with Lake Burdur (L2 having the highest TP and EC and low SD), displaying hypertrophic characteristics driven by intense nutrient inputs and limited hydrological flushing, which are common in tectonically enclosed basins with high human activity (Tuygun et al. 2023; Çelekli et al. 2025). Excessive nutrient loadings, particularly nitrogen and phosphorus from human activities, are major contributors to eutrophication in lakes globally, including Lake Burdur (Suresh et al. 2023). Increased water abstraction for irrigation and other uses has significantly reduced water levels in Lake Burdur, exacerbating eutrophication by concentrating nutrients and reducing water exchange (Davraz et al. 2019). In contrast, oligotrophic conditions prevail in Lake Salda (L3; relatively low TP and TN with high SD), highlighting the protective effect of its geochemical and climatic setting that limits nutrient enrichment. This contrast in ecoregion in terms of nutrient dynamics and trophic states underscores the necessity of tailored management approaches that consider local environmental contexts. The lowest EC was found to be in Lake Gölbaşı (L1), suggesting lower ionic content, potentially due to freshwater inflows or dilution effects. Different ecoregional factors could affect the EC level in this lake, influenced by ionic content, temperature, and mixing

with other water sources, such as freshwater or brackish water (Çelekli and Lekesiz 2021). The significant spatial variations in physicochemical parameters across the studied lakes underscore the influence of geographic and environmental factors (e.g., nutrient inputs, climate, land use, lake morphology, and hydrology) on water quality (Çelekli et al. 2020).

Ecoregional variation on phytoplankton assemblages and environmental drivers

The results of the present study reveal significant spatial variations in the physicochemical properties and phytoplankton communities across the studied lakes, underscoring the influence of environmental factors on aquatic ecosystems. Phytoplankton assemblages exhibit distinct compositions that are aligned with the physicochemical gradients which are in turn shaped by ecoregion-specific factors. The differences in phytoplankton assemblages among the studied lakes provide valuable insights into ecological processes and environmental conditions. The CCA confirmed that phytoplankton communities exhibited distinct compositions across the studied lakes and that these were largely influenced by key environmental drivers such as EC, TP, TSS, TOC, temperature, and NO_3 . These findings highlight distinct phytoplankton compositions and biovolume distributions across the lakes, reflecting their unique environmental conditions (Reynolds 2006; Padisák et al. 2009; Çelekli et al. 2024).

Lake Burdur (L2), classified in a hypertrophic state, exhibited elevated levels of high TP, EC, TOC, TSS, and pH. These conditions favor pollution-tolerant species such as *C. closterium*, *L. ciliata*, *L. genevensis*, *N. tripunctata*, *C. globosa*, *M. flos-aquae*, and *S. major*. Notably, *M. flos-aquae* and *S. major* are known to proliferate in nutrient-rich and turbid waters (Chorus and Welker 2021), further highlighting the eutrophic nature of the lake. *Microcystis flos-aquae* is a well-established indicator of eutrophic–hypertrophic conditions, being strongly associated with elevated nutrient concentrations, particularly TP and TN levels (Reynolds et al. 2002; Padisák et al. 2009). Çelekli et al. (2023) reported that its frequent dominance in eutrophic and hypereutrophic lakes, where it often forms dense blooms under conditions of increased nutrient loading. Paerl et al. (2020) similarly emphasized that *Microcystis* blooms are closely linked to anthropogenic nutrient inputs, including agricultural runoff and wastewater discharge, providing Cyanobacteria with a competitive advantage over other phytoplankton taxa. Notably, the observation that the highest biovolume of cyanobacteria was in Lake Burdur (L2) underscores the potential risk of harmful algal blooms, which could further deteriorate water quality through oxygen depletion and toxin production (Huisman et al. 2018).

The prevalence of *L. ciliata* and *L. genevensis* in association with high TP, EC, TOC, and TSS suggests their adaptation to eutrophic and turbid environments. TP is a primary driver of phytoplankton biomass, with high TP levels often favoring taxa capable of exploiting elevated nutrient conditions (Reynolds et al. 2002). Additionally, increased TOC and TSS levels can reduce light penetration, creating favorable conditions for mixotrophic or light-tolerant species (Dokulil and Teubner 2010). The dominance of *Lagerheimia* species in these environments aligns with previous findings indicating their capacity to thrive under high nutrient and organic matter loads (Huisman et al. 2018). Moreover, *L. genevensis* has been identified as an indicator species in moderately nutrient-rich and brackish environments across Europe, with its occurrence positively correlated with elevated EC (Çelekli and Lekesiz 2021). These findings suggest that *Lagerheimia* species have a physiological tolerance to higher ionic concentrations. The co-occurrence of *C. globosa* and *Lagerheimia* taxa under high EC conditions indicates their potential utility as bioindicators of ionic enrichment and organic loading in inland waters.

Lake Salda (L3) exhibited characteristics typical of oligotrophic systems, with relatively low TP concentrations and the highest water transparency of all four studied lakes, as indicated by SD. This nutrient-poor, high-clarity environment supported a low total phytoplankton biovolume dominated by Dinophyceae (71%), which thrived under high pH and alkaline conditions. The prevalence of Dinophyceae in this lake corroborates previous findings linking this dinoflagellate species to alkaline waters with low TP (Çelekli et al. 2018). High pH environments, as observed in Lake Salda (L3), appear to favor dinoflagellate abundance, likely through such mechanisms as efficient intracellular pH regulation and enhanced utilization of dissolved inorganic carbon (Hinga 1992). Additional adaptive traits, including mixotrophy and vertical migration, enable certain species of Dinophyceae to optimize resource acquisition in stratified, alkaline waters where nutrients are limited (Wang et al. 2021). Also, elevated alkalinity may suppress competing phytoplankton groups, facilitating dinoflagellate dominance (Cao et al. 2023). Collectively, these factors highlight how Lake Salda's ecoregion—characterized by oligotrophy, high pH, and clear waters—shapes a specialized phytoplankton assemblage adapted to such ecological constraints.

Lake Gölbaşı (L1), situated at a low altitude in a Mediterranean ecoregion, is characterized by elevated temperature and NO_3^- levels. These conditions supported the proliferation of euglenophyte taxa such as *L. fusiformis*, *L. acus*, *E. elegans*, and *E. agilis*, which are typically associated with nitrogen-enriched environments (Salmaso et al. 2012). Warmer temperatures likely enhance phytoplankton metabolic activity and growth, while increased NO_3^- availability favors taxa that rely on external nitrogen sources. Species

like *L. fusiformis*, *L. acus*, *E. agilis*, and *P. caudatus* are associated with diverse environmental conditions, including varying organic matter levels and climatic zones, and are useful biomarkers for studying environmental changes due to their adaptability and phylogenetic diversity. *Lepocinclis fusiformis* and *L. acus* are tolerant to moderate to high levels of nutrient loading, indicative of mesotrophic to eutrophic lakes (Dhanya and Joseph 2019). *Euglena agilis* demonstrates a broad ecological amplitude, flourishing in habitats with fluctuating nutrients and light availability (Salmaso et al. 2012). *Phacus caudatus*, like other *Phacus* species, thrives in nutrient-rich, organic matter-laden environments, often under eutrophic conditions where organic input is high (Li et al. 2021).

Lake Dalyan (L4), located within a coastal brackish ecoregion, was primarily influenced by high EC levels, ranging between 20,200 and 43,700 $\mu\text{S}/\text{cm}$. This abiotic filter significantly influences phytoplankton composition by favoring halotolerant taxa such as *P. limnophilus* var. 'swirenkoi', *G. discoidale*, *G. kuetzingii*, *Pseudanabaena* sp., *N. antonii*, and *E. gibba* that prefer elevated EC levels. The presence of *Pseudanabaena* sp., a filamentous cyanobacterium, further supports the influence of high EC, as members of this genus have been reported in saline and eutrophic environments (Huisman et al. 2018). Dinoflagellates such as *G. discoidale* exhibit physiological adaptations to osmotic stress that facilitate their persistence under fluctuating salinity regimes (Çelekli 2025). These findings underscore the strong ecological filtering exerted by EC on the Lake Dalyan (L4) phytoplankton community structure and highlight the taxa adaptive strategies of these taxa in response to elevated ionic concentrations. The dominance of Euglenophyceae (51%) further reflects eutrophic and organic matter-rich conditions typical of brackish environments (Lemke et al. 2017). Given the sensitivity of such ecosystems to climate variability and human activities, monitoring salinity fluctuations is essential for understanding and managing phytoplankton dynamics in Lake Dalyan (He and Silliman 2019).

Lakes Gölbaşı (L1) and Dalyan (L4) represent transitional systems that require targeted management approaches. The high NO_3^- levels in Lake Gölbaşı (L1) indicate potential agricultural or urban runoff sources, warranting further investigation into nutrient pathways and mitigation strategies. These distinct stressor profiles underscore the necessity of site-specific management strategies tailored to each lake's ecoregional context.

In addition to ecoregional influences, lake morphometry—particularly depth—plays a fundamental role in regulating limnological processes and phytoplankton dynamics. Differences in depth shape key mechanisms such as stratification stability, light penetration, sediment–water interactions, and internal nutrient cycling, which collectively determine phytoplankton growth conditions. Shallow, polymictic

lakes typically undergo frequent mixing and sediment resuspension, a process which enhances nutrient availability and favors fast-growing, eutrophic taxa. In contrast, deep, stratified lakes maintain more stable vertical gradients and often support phytoplankton groups adapted to low nutrient levels (Kalff 2002; Reynolds 2006). These depth-driven differences therefore represent an important confounding factor that interacts with—and in some cases may overshadow—ecoregional gradients when interpreting ecological patterns among lakes.

Catchment land use adds another critical layer of regional variation, as agricultural, urban, and natural landscapes strongly modulate external nutrient inputs and, consequently, ES. Sentinel-2 land-cover data (ESRI 2024) indicate that the studied lake catchments range from agriculture-dominated systems to predominantly natural or forested landscapes. This gradient corresponds well with observed differences in conductivity, nutrient concentrations, and phytoplankton composition. These patterns are consistent with widely reported effects of land use on nutrient loading and trophic state, where agricultural catchments typically contribute higher nitrogen and phosphorus inputs, while forested or rangeland-dominated basins tend to sustain lower external nutrient pressures (Carpenter et al. 1998; Allan 2004). Altogether, the combined influence of morphometry and catchment land use provides a more robust explanation for the ecological variability among the lakes than ecoregional factors alone.

Trophic state and ecological status implications

The TSI evaluations revealed distinct nutrient statuses among the studied lakes, reflecting the influence of both natural ecoregional characteristics and anthropogenic pressures. Lake Burdur (L2), located in a semi-arid, agriculturally impacted basin, was classified as hypertrophic, consistent with its TP and chlorophyll-*a* concentrations. In contrast, Lake Salda (L3), situated in a more geologically isolated and carbonate-rich region, was classified as oligotrophic, characterized by low TN, high water clarity, and low chlorophyll-*a* levels; however, increasing tourism and potential anthropogenic pressures could threaten the current trophic state. This lake serves as a critical ecological reference for minimally impacted systems, although increasing tourism poses a growing threat to its trophic integrity. Studies have shown that even slight nutrient inputs can disrupt the ecological balance of oligotrophic lakes, leading to shifts in community structure and water quality deterioration (Bocaniov et al. 2013). Conservation measures, including strict regulations on nutrient inputs and habitat protection, are recommended to preserve its unique ecosystem. Lakes Gölbaşı

(L1) and Dalyan (L4), both classified as eutrophic, exhibited intermediate trophic conditions. In Lake Gölbaşı, elevated TN and NO₃⁻ levels likely stem from agricultural and urban runoff, in alignment with the presence of nitrogen-tolerant phytoplankton (Reynolds et al. 2002; Salmaso and Padisák 2007). The eutrophic status of Lake Dalyan (L4), however, reflects a different set of ecoregional pressures: its brackish character and high EC create a niche environment favoring salinity-tolerant phytoplankton taxa (Kruk et al. 2011). These findings underscore the role of both nutrient loading and salinity gradients as dominant ecological filters within distinct ecoregions.

The phytoplankton-based ES assessments—using indices such as MPTI, Phyto-Tr, and BCG with ABOZ (multiple chemical evaluation)—further clarified these trends. Strong correlations between logTP and MPTI, ABOZ, and BCG highlight the sensitivity of these indices to phosphorus-driven changes in phytoplankton communities. These findings reinforce the notion that excessive nutrient inputs could be a primary driver of ecosystem degradation, potentially accelerating eutrophication trajectories and altering lake trophic dynamics over time. Conversely, the Phyto-Tr Index displayed a weaker relationship with TP, suggesting that it may respond to broader environmental gradients or specific taxonomic compositions. The ES assessments revealed notable variability among the studied lakes: Lake Burdur (L2) consistently exhibited poor to bad ES across all indices, reflecting elevated TP, TOC, and TSS concentrations together with low SD. These conditions support the proliferation of bloom-forming taxa such as *M. flos-aquae*, confirming severe eutrophication and strong anthropogenic pressure. This degradation highlights the need for urgent interventions such as nutrient load reduction, improved wastewater treatment, and agricultural best management practices (Carpenter et al. 1998).

Lake Salda (L3), despite minor classification differences (moderate ES by MPTI, good ES by ABOZ and BCG), maintained relatively stable ecological conditions. Its high transparency (SD = 5 m) and low productivity align with its geochemical context—particularly high carbonate content and alkaline buffering capacity, which restrict nutrient availability (Çelekli et al. 2024). However, its sensitivity to tourism underscores the need for continued protection and regulation. Lake Salda (L3), despite its oligotrophic state, may be vulnerable to future anthropogenic pressures, particularly tourism-related activities. Preservation efforts should focus on maintaining its pristine conditions through stringent environmental regulations and sustainable visitor management strategies. However, the lake's vulnerability to potential anthropogenic disturbances necessitates continued monitoring and conservation efforts.

Deterioration in Lake Gölbaşı (L1) may be attributed to its higher TN and NO_3^- concentrations, which can influence phytoplankton composition by favoring nutrient-tolerant species (Reynolds et al. 2002; Salmaso and Padisák 2007). While this lake currently maintains moderate ecological function, ongoing monitoring is necessary to prevent further decline.

Lake Dalyan (L4) showed good ES across all indices, suggesting a relatively balanced ecosystem, although its high EC indicates a strong influence of salinity on phytoplankton assemblages, favoring brackish water taxa such as *G. discoidale* and *Pseudanabaena* sp. (Kruk et al. 2011). Ongoing surveillance to detect early signs of ecological stress are warranted. Lakes Gölbaşı (L1) and Dalyan (L4), exhibiting intermediate trophic states, require continued monitoring to ensure the maintenance of nutrient levels. Restoration strategies, such as sediment dredging or biomanipulation, may be considered if signs of further eutrophication emerge (Søndergaard et al. 2016).

These results demonstrate that ecoregional factors—such as hydrological connectivity, climate, salinity, and land use—play critical roles in shaping trophic dynamics and ecological quality. While nutrient loading remains a central driver of eutrophication across all lakes, the specific ecological trajectories and dominant pressures vary based on regional context. The study reinforces the utility of phytoplankton-based indices in water quality assessments and their capacity to capture regional differences in ecological integrity (Phillips et al. 2013; Zhang et al. 2020). Long-term, integrative monitoring that combines biological indices with physicochemical parameters will be vital for managing these ecosystems. Future research should also consider climate change impacts on nutrient cycling, salinity regimes, and phytoplankton dynamics to anticipate ecosystem shifts in different ecoregions (Poikane et al. 2021; Mihaljević et al. 2024).

Conclusion

The results of this study demonstrate that both ecoregional and lake morphometric characteristics (e.g., surface area, depth, basin shape, among others) jointly shape the substantial spatial variability in physicochemical properties, phytoplankton assemblages, and trophic states of Turkish lakes.

While climate, geology, and catchment land use provide an overarching environmental framework, lake-specific characteristics—including depth, basin morphology, salinity, and hydrological conditions—act as key regulators of local ecological processes. In several cases, these intrinsic factors appear to exert a stronger control on nutrient dynamics, EC,

and phytoplankton composition than ecoregional context alone. The results of the CCA demonstrated that nutrient concentrations (particularly TP, TN, and NO_3^-) and EC are the primary environmental drivers shaping phytoplankton community composition. These findings underscore the necessity for ecoregion- and morphometric-specific management strategies to address eutrophication and maintain ecological integrity. Among the studied systems, Lake Burdur (L2), a designated Ramsar site, exhibited hypertrophic conditions, characterized by the highest EC, nutrient levels, and chlorophyll-*a* concentrations, coupled with the lowest SD. Lake Gölbaşı (L1) showed signs of trophic deterioration, likely driven by elevated TN and NO_3^- levels, which promote nutrient-tolerant species and may signal early eutrophication processes. In contrast, Lake Salda (L3) maintained oligotrophic conditions, supported by its unique geochemical properties, including high carbonate content and alkaline pH, which limit nutrient bioavailability and buffer eutrophication. Lake Dalyan (L4) exhibited good ES across all assessment indices, despite its high EC, which favors brackish-adapted phytoplankton; this suggests a relatively stable ecosystem influenced primarily by natural salinity gradients rather than nutrient over-enrichment. That the MPTI, BCG, and ABOZ strongly correlated with the TP gradient affirms the reliability of these indices as tools for ES assessment in diverse aquatic environments. The integration of multimetric phytoplankton indices with physicochemical assessments provides a robust framework for evaluating ES across diverse lake types. However, the pronounced differences in lake depth and morphometry highlight the need to account for intrinsic variability when interpreting ecoregional influences.

Overall, the results demonstrate that ecological variability among lakes arises from the interaction of multiple environmental drivers operating across spatial scales, rather than from a single dominant factor. This observation highlights the importance of adopting integrated, multiscale assessment approaches that incorporate both regional and lake-specific characteristics. Future monitoring and management strategies should therefore apply depth-adjusted and regionally calibrated frameworks to more accurately capture ecological gradients and support effective lake conservation and restoration efforts.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s00027-026-01318-y>.

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Author contribution Abuzer Çelekli: conceptualization; administration, data curation; data validation, methodology; software analysis;

initial final draft writing, review, and editing. Özgür Eren Zariç: conceptualization; data curation; methodology; software analysis; review and editing.

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Data availability The data can be available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval Not applicable.

Informed consent Not applicable.

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