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Ecological Assessment of Lake Alakol's Coastal Waters using Algae-Based Indicators

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Abstract

This study explores the ecological importance of microalgae in aquatic ecosystems, with particular emphasis on their function as indicators in water quality assessment. An analysis of the algal flora of Lake Alakol revealed the dominance of indifferent species alongside a substantial proportion of mesosaprobic taxa, suggesting a moderately polluted condition of the lake. Phytoplankton communities exhibited adaptive responses to fluctuating environmental factors, while functional group analysis provided key insights into the ecological dynamics of the system. In addition, the study highlights the application of fluorescence-based techniques as innovative tools for water quality monitoring and bioassays. The ecological drivers shaping algal community structure underscore the necessity of continuous ecological evaluation. The main findings of the study can be summarized as follows: (i) the algal flora was dominated by indifferent species, with mesosaprobic forms indicating moderate pollution; (ii) phytoplankton displayed clear adaptive responses to changing environmental conditions; (iii) functional group analysis offered valuable information on ecosystem dynamics; (iv) fluorescence-based monitoring methods proved effective as innovative bioassay tools; and (v) continuous ecological assessments are essential to track and understand algal community shifts. Overall, the findings reinforce the pivotal role of microalgae as bioindicators and stress the importance of further research to guide conservation measures and promote the long-term sustainability of aquatic ecosystems.

Keywords: Microalgae; Water quality; Phytoplankton; Fluorescence; Bioindicators.
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1. Introduction

Recently, there has been an increase in information indicating that inland waters, particularly wetlands, represent some of the most vulnerable ecosystems on a global scale. This leads to a reduction in aquatic biodiversity and disruption of ecological functions and natural resources.[1] This is especially evident in saline aquatic ecosystems, such as wetlands, which are under heightened threat. These ecosystems are subject to unpredictable climate changes, hydrological engineering that does not consider ecological aspects, and increasing anthropogenic water use and pollution.[2] One of the unique lakes is the saline, endorheic Lake Alakol, located in the Balkhash-Alakol Depression, at the border of Almaty and East Kazakhstan regions, in the eastern part of the Balkhash-Alakol Basin. Along with Lakes Sasykkol, Uyaly, Zhalanashkol, and other smaller ones, it forms the Alakol Lake System.

Phytoplankton is retained as one of the biological elements for assessing the ecological status of water bodies, in accordance with the requirements of the Water Framework Directive.[3] Phytoplankton is a crucial component of aquatic ecosystems, generating primary biological products and serving as the basis for food chains present in the aquatic environment.[4] The structural features of phytoplankton are actively used in monitoring systems. Methodological strategies for studying phytoplankton as an indicator of eutrophication are based on the analysis of the species composition of the community.[5] Additionally, modern scientific research increasingly employs an ecosystem approach, which involves analyzing the composition and structural characteristics of producers, such as functional groups of phytoplankton.[6] Numerous studies on phytoplankton in inland waters indicate a reduction in species diversity and a simplification of algal flora structure in highly mineralized waters. There is often an intense proliferation of certain species within plankton communities as salinity increases, especially under conditions where this factor becomes

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Table 1: Coordinates (WGS 1984) of sampling sites with physical field measurement data.

S. No.	Lat (N)	Long (E)	Sample Site	pH	Temp. (Cels)	TDS (mg/L)
1	45°59.468’	081°30.570’	Alakol, Akshi, Zhetysu Region	8.7	21	7902,7
2	45°57'41.2"	81°33'30.2"	Alakol, Akshi, Zhetysu Region	8.6	22	7492,3
3	45°51'35.8"	081°40'23.5"	Alakol, Koktuma, Zhetysu Region	8.7	20	7115,3
4	46°26.394’	081°27.138’	Alakol, Akshi (Rybatskoye), Zhetysu Region	8.4	21.5	8375,2
5	46 °09.010’	082°02.453’	Alakol, Kabanbai, Abay Region	9	20	6484,8
6	46°03.243’	082°02.205’	Alakol (inflow), Kabanbai, Abay Region	9.1	23	7301,8

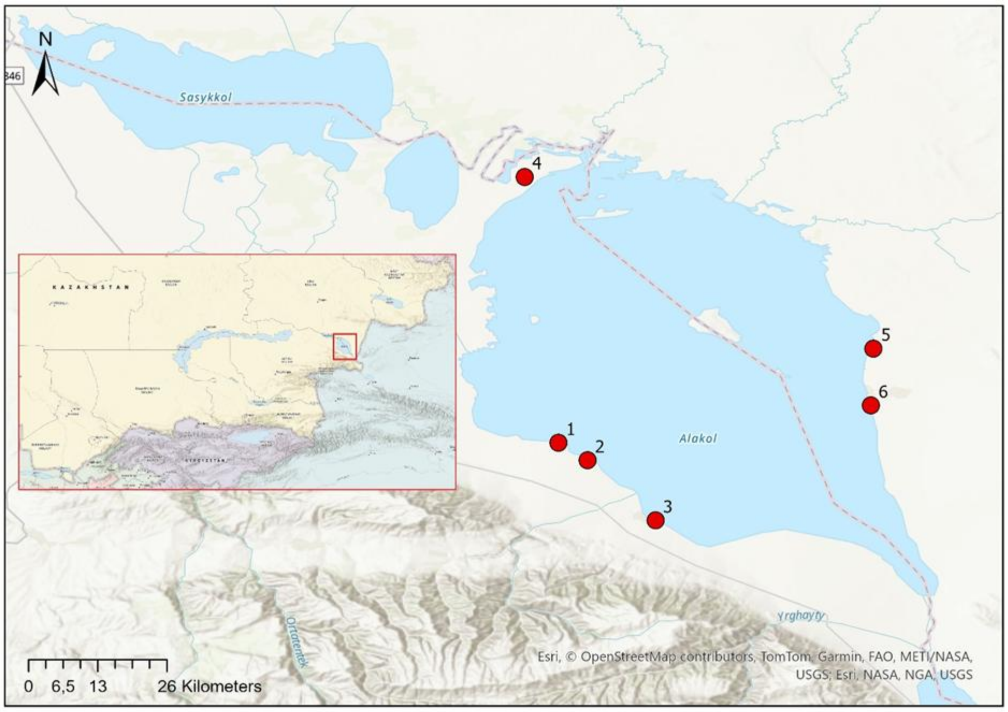

Fig. 1: Map of Sampling Sites (ArcGIS Pro).

extreme.[7] Concurrently, information is presented on the impoverishment of species composition at higher trophic levels (zooplankton, macrozoobenthos) under the influence of extreme salinity levels, and the lack of dependence of phytoplankton species abundance on the degree of mineralization.[7] Under the influence of various ecological factors and anthropogenic pollutants, the photosynthetic activity and cell numbers of algae are the first to change.[8] Changes in phytoplankton photosynthesis lead to alterations in other components of the aquatic ecosystem. Monitoring changes in phytoplankton photosynthetic processes using chlorophyll fluorescence measurement methods is promising.[9] The basis of fluorescent methods is that chlorophyll, located in photosynthetic membranes, acts as a natural sensor of the state of microalgae cells and their photosynthetic apparatus. The primary characteristics of the initial light reactions of photosynthesis are the efficiency of photochemical energy conversion in photosystem II (PSII) (hereafter referred to as photochemical activity of PSII), as well as the coefficients of photochemical and non-photochemical quenching of fluorescence, which are evaluated using the PAM (pulse-amplitude-modulation) method.[10] Recently, methods for rapid measurement of light dependencies (light curves) of various fluorescence parameters, reflecting the development of photochemical and non-photochemical quenching in light, have been actively developed when working with algae cultures. These methods allow for the early detection of changes in the functioning of the photosynthetic apparatus under environmental factors.[11] The advantages of fluorescent methods are their rapidity and high sensitivity, which enable quick diagnosis of the state of microalgae cells directly in their habitat in situ in real time.[12]

The study of the algal community in Lake Alakol is of great interest for assessing biodiversity and monitoring the state of the lake, as well as for predicting and developing recommendations for the conservation and proper functioning

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of natural complexes. The aim of this work is to study the state of the shoreline/littoral waters of Lake Alakol, based on the functional classification and chlorophyll fluorescence of phytoplankton.

2. Materials and methods

2.1 Collection of algological samples and analysis of phytoplankton

Algological samples and taxon studies were conducted in the Almaty region around Lake Alakol. Six sampling stations were strategically selected to capture the spatial heterogeneity of Lake Alakol. The stations included recreational areas Akshi and Koktuma and regions influenced by freshwater inflows near Kabanbai village. This selection was designed to encompass areas with varying degrees of anthropogenic influence and hydrodynamic conditions. Such spatial coverage allowed a more comprehensive assessment of phytoplankton community structure, functional group distribution, and ecological status across different parts of the lake. The coordinates (WGS 1984) of the sampling sites along with physical field measurement data are presented in Table 1 and Fig. 1.

A total of 45 algological plankton samples were collected during a single sampling period. At the time of sample collection, the water temperature ranged from 17 to 23 °C, pH from 8.4 to 9.1, water transparency from 0.5 to 1 m, and depth from 0.5 to 1.5–2 m. At least 50 fields of view were examined across a minimum of 3 preparations. Algal species were identified in both live and fixed states, using a 4% formaldehyde solution as a fixative. Algae were studied using “Premiere” and “Micros Austria” light microscopes at total magnifications ranging from 400× to 1000× Microalgae species were identified using updated keys and AlgaeBase.[13]

The saprobity index (S) was determined using species-specific saprobity indicators and species abundance data. The indicators were taken from published tables of saprobity indicator species.[14-16]

TDS values (6484.8–8375.2 mg/L) indicate that the water can be classified as saline. This high mineralization reflects a considerable content of dissolved salts, characteristic of saline lake environments. Such conditions may impose physiological constraints on aquatic organisms and play a key role in shaping ecosystem structure.

Phytoplankton functional groups were determined following the classifications of Reynolds *et al.* (2002), Padisák *et al.* (2009), and Borics *et al.* (2015).[6,17,18] Functional group assignments were applied to species that accounted for at least 5% of the average phytoplankton biomass, as outlined by Reynolds *et al.* (2002) and Reynolds (2006).[17,19]

2.2 Biophysical research methods

Measurements of fluorescence parameters of phytoplankton samples from various stations in Lake Alakol were conducted using a WaterPAM pulse fluorometer (Walz, Germany). In dark-adapted samples, steady-state fluorescence (F_0) and maximum fluorescence (F) were recorded, as well as the relative yield of variable fluorescence (F_v/F_m), which is a measure of the maximum potential quantum efficiency of PSII (Schreiber *et al.* 2004). In light-adapted conditions, rapid light response measurements of various fluorescence parameters were performed by sequentially increasing the light intensity from 0 to 900 μE/m^2/s. The illumination time was 50 seconds. At the end of each illumination session at a specific intensity, using a saturating pulse (μE/m^2/s), the parameters F_m' and the fluorescence yield in light F(t) were recorded. Based on these parameters, non-photochemical quenching of fluorescence (NPQ) was calculated as $NPQ = (F_m - F_m')/F_m'$, the quantum yield of photochemical conversion of absorbed light energy in PSII as $Y = (F_m' - F_t)/F_m'$, and the relative rate of non-cyclic electron transport at a given light intensity (ETR). The electron transport rate was calculated using the formula $ETR = Y \times Ei \times 0.5$, where Ei is the irradiance (μE/m^2/s).[12]

Based on the obtained light curves (P/E curves), the following photosynthetic parameters were evaluated: the coefficient of maximum light energy utilization (the slope of the P/E curve, α), the maximum relative electron transport rate through the electron transport chain (ETRmax), and the saturating light intensity (E_n). α was calculated as the coefficient of linear regression constructed from points on the light-limited portion of the P/E curve, ETRmax as the average of ETR values on the light-saturated portion (Jassby *et al.* 1976). E_n was calculated using the formula $E_n = ETRmax / \alpha$. The notations and definitions of photosynthetic parameters are provided in accordance with the commonly accepted nomenclature.[12]

The diagram outlines the process of determining parameters from the light curve of the electron transport rate (ETR) in natural phytoplankton using chlorophyll fluorescence parameters. The parameters describing the relationship between non-cyclic electron transport (ETR) and light intensity include the coefficient of maximum light energy utilization (α), the maximum relative electron transport rate (ETRmax), and the saturating light intensity (E_n).

2.3 Statistical analysis

Data analysis and processing were performed using the software packages Origin (OriginLab Corp., USA) and Statistica v.10 (StatSoft, Inc., USA). Statistical analysis was conducted using one-way analysis of variance (ANOVA) with Dunnett's post-hoc test. A p-value of < 0.05 was considered statistically significant. The table presents the mean values (M) and standard deviations (±SD). Each parameter under investigation was analyzed in triplicate.

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3. Results

3.1 Composition of the algal community in lake alakol

The composition of the algal community can vary depending on environmental conditions such as water salinity, nutrient content, and light availability.[20] The composition of the algal community in the coastal waters of Lake Alakol consists of six divisions of microalgae: *Bacillariophyt*a – 24, *Cyanoprocaryota* – 22, *Chlorophyta* – 38, *Euglenophyta* – 7, *Cryptophyta* – 2, *Xanthophyta* – 2 (Fig. 2). The divisions *Bacillariophyta* and ш exhibited the highest biodiversity in terms of species richness. Algae from the divisions *Euglenophyta* and Cryptophyta were rare, indicating their low adaptation to increasing water mineralization conditions. Only representatives of the divisions *Chlorophyta*, *Bacillariophyta*, and *Cyanoprocaryota* were present in all investigated samples, which can be attributed to their wide ecological tolerance, enabling them to survive in saline water.

A visual representation of microalgae observed in water samples from Lake Alakol is shown in Fig. 2. The division *Chlorophyta* (with 38 species) occupies the first place in terms of species diversity, encompassing five classes: *Chlorococcophyceae, Ulothrichophyceae, Volvocophyceae, Siphonocladophyceae,* and *Conjugatophyceae*. From the class *Volvocophyceae*, two representatives of halophilic microalgae were found – *Dunaliella salina* and *Chlamydomonas monadina*. The class *Chlorococcophyceae* comprises 9 families and 20 species, with prominent families including *Scenedesmaceae* and *Chlorococaceae*. Among the *Siphonocladophyceae, Cladophora glomerata (L.) Kütz. and Rhizoclonium hieroglyphicum (Ag.) Kütz*. were identified. Only 5 species of *Ulothrichophyceae,* varieties, and forms were found, with the families *Ulotrichaceae* (genera *Ulothrix* and *Uronema*) being widespread. The genus *Cosmarium* stands out among the *Conjugatophyceae*.

In water samples from area No. 2, species of the genus *Scenedesmus* predominated, while species of the genus *Desmidium* were not observed. In samples from areas No. 2 and No. 4, *Cladophora glomerata (L.) Kütz*. was more developed. Cells of *Cladophora glomerata* (L.) Kütz. constitute the main abundance and biomass of phytoplankton in water sample No. 2 and are commonly found in the water column (Fig. 3).

The majority of diatoms found in Lake Alakol belong to the class *Pennatophyceae.* Prominent genera include *Fragilaria* and *Synedra*. From the order *Raphales*, the most representative families are *Naviculaceae, Nitzschiaceae*, and *Cymbellaceae*. Species such as *Synedra vaucheriae, Cymbella cistula, Achnantes minutissima*, and *Navicula hungarica*, in varying proportions, constitute the dominant complex in terms of abundance in all investigated water samples from Lake Alakol.

Cyanobacteria, in terms of species composition, occupy the third position, comprising 22 species from 10 genera and 12 families. *Chroococcales* include 7 species, with the genus *Gloeocapsa* being the most abundant. The *Hormogoniophyceae* are more diverse, with 15 species. The increased mineralization of water in most parts of Lake Alakol contributes to a higher diversity of *Oscillatoriales* compared to other orders within the *Cyanoprocaryota* division. The dominant family is *Oscillatoriaceae*. Species within the *Cyanoprocaryota* division exhibit significant development in saline lakes, where they play a leading role in planktonic and benthic communities. The dominant cyanobacterial species in all investigated areas were *Oscillatoria tenuis* and *Phormidium tenue*.

Euglenoid algae in Lake Alakol are represented by the class *Euglenophyceae*, the family *Euglenaceae*, and the genera *Eutreptia* and *Euglena*, encompassing a total of 7 species.

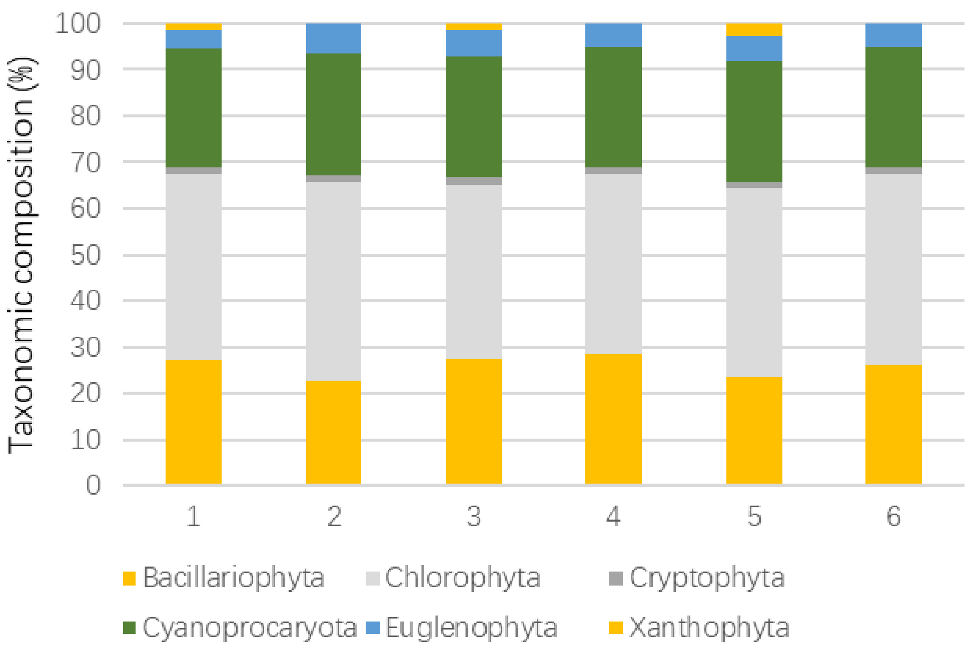

Fig. 2: Taxonomic composition (%) of phytoplankton in the coastal waters of lake Alakol.

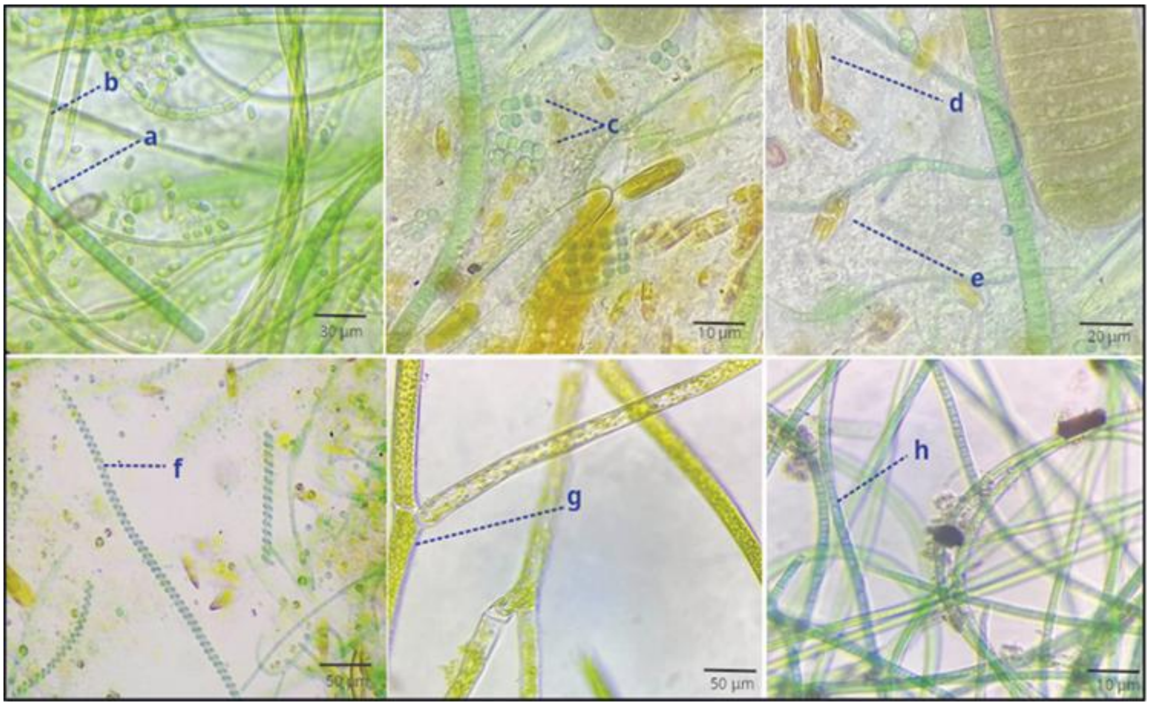

Fig. 3: Microalgae in Water Samples from Lake Alakol (magnification x100), a- *Oscillatoria tenuis,* b- *Phormidium tenue,* c- *Merismopedia punctata,* d - *Pinnularia viridis,* e- *Achnantes minutissima,* f- *Spirulina major,* g - *Cladophora glomerata,* h - *Phormidium ambiguum.*

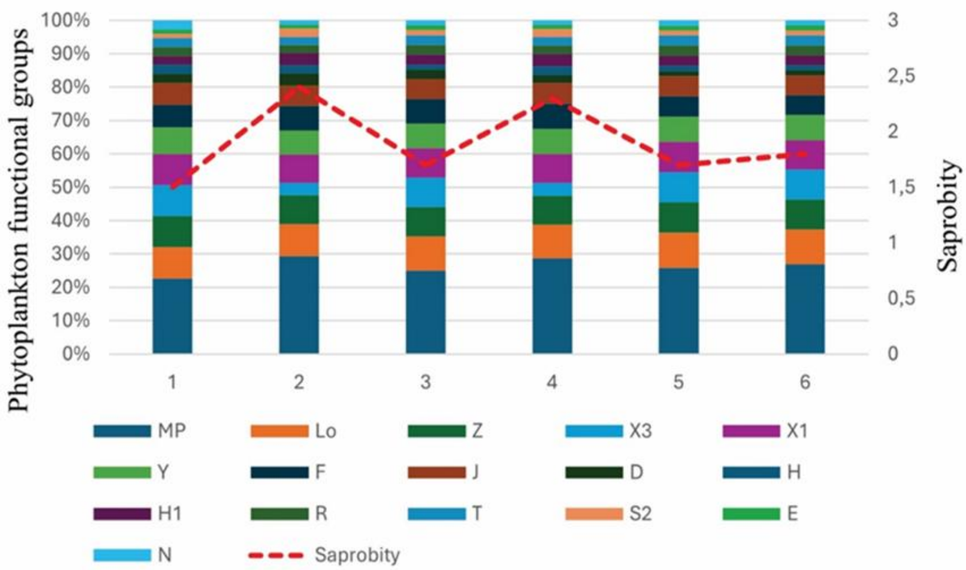

Fig. 4: Functional groups (%) of phytoplankton and saprobity of coastal waters of lake Alakol.

The division *Cryptophyta* contains 2 species – *Cryptomonas salina* and *Cryptomonas ovata*, both characteristic of saline lakes. Representatives of cryptophytic algae were sporadically encountered in all investigated areas of Lake Alakol.

From the division *Xanthophyta*, the species *Tribonema aequale* and *T. affine* were identified in water samples No. 5.

3.2 Functional groups of phytoplankton in lake alakol

Representatives of 16 functional groups are identified among the determined phytoplankton species. Various phytoplankton species are grouped into these functional groups based on similar physiology, morphology, and ecology. These groups have similar requirements and optimal conditions, which often lead to their coexistence in biological communities.[21] The most common codes in all investigated areas were MP (24–17%), Lo – Z (6–8%), X3 – X1 (6–7%), Y (5–6%), F (4–6%), J (4–5%). The remaining functional groups were represented by fewer taxa (Fig. 4).

Most of the species belong to the MP group, representing autochthonous organisms of the pelagic zone that can accidentally enter the phytoplankton from other communities.[6] Representatives of the MP code predominated in all samples, with their abundance being higher in samples 2 and 5. The Lo functional group mainly included cyanobacteria typical of the surface waters of mesotrophic lakes in the summer period. Additionally, single-celled and colonial picocyanobacteria of the Z functional group were found, characteristic of the metalimnion and upper hypolimnion. Functional groups X3 and X1, comprising organisms typical of the mixed layer of eutrophic and hypertrophic shallow lakes, were also recorded. In water samples, except for 2 and 4, algae of functional group X3 predominated, often found in oligotrophic waters with good circulation.[6] Representatives of the Y code, including cryptomonads and dinoflagellates, were also dominant and occurred in almost all investigated samples. These organisms can adapt to diverse environments, especially in conditions of low predation pressure from zooplankton. At stations 2 and 4, algae of code J predominated, including single-celled microalgae from the genera Scenedesmus, Pediastrum, and Coelastrum. These algae prefer shallow, well-mixed, and enriched systems.[20] Representatives of the H1 code, such as Anabaena flos-aquae and Anabaena planctonica, were found in all investigated water samples of Lake Alakol. These organisms have the ability to fix nitrogen and are characterized by high adaptability to low levels of nitrogen and carbon. However, they are sensitive to water column mixing, as well as low phosphorus content and light availability.[15,22]

The analysis of bioindication characteristics of microalgae in the studied areas of Lake Alakol revealed a total of 48 indicator species, for which indices of their relation to organic pollution are known. The majority of indicator species belong to the β-mesosaprobic forms (19 species or 39.8%). Xenosaprobic and oligosaprobic indicator species are few, mainly represented by diatom species such as *Synedra acus Kütz, Synedra ulna,* and *Amphora ovalis*. The highest number of identified indicators belong to green algae (39.5% of the total number of indicators), followed by cyanobacteria (25%), diatoms (22.9%), and euglenoid algae (10.4%), which generally corresponds to the importance of these divisions in the phytoplankton structure of lakes. The frequency of occurrence of saprobic indicators and their level of development did not show noticeable differences in the investigated areas of Lake Alakol. Water quality assessment using indicator organisms according to Pantle-Bucku modified by Sládeček (1973) revealed a β-mesosaprobic character of the water in all studied areas of Lake Alakol, indicating that they can be classified as relatively clean or slightly polluted.[23] The calculated saprobity indices ranged from 1.5 to 2.4 (Fig. 4).

3.3 The fluorescence parameters of phytoplankton in lake alakol

The fluorescent parameters of phytoplankton in Lake Alakol are presented in Table 2, showing fluorescence parameters in dark-adapted samples and under illumination at different intensities, indicating increasing light exposure conditions. The FO parameter, with a high correlation coefficient, corresponds to the total content of pigments in the photosynthetic apparatus of microalgae cells involved in light harvesting. This parameter is considered an indirect indicator of the concentration of light-absorbing pigments in algae.[10,23]

The overall content of photosynthetic pigments varies at the investigated stations, although it is slightly reduced in water samples No. 2 and No. 4. Additionally, on these same stations, the Fv/Fm parameter is decreased, which is determined in a sample adapted to darkness. Fv/Fm represents the potential quantum yield of the photochemical conversion of absorbed light energy into PS2, associated with water decomposition and oxygen release. This parameter determines the efficiency of photosynthesis processes and represents a dimensionless energetic characteristic of photosynthesis, analogous to the coefficient of performance and independent of organism-specific characteristics.[12]

The values of the Fv/Fm parameter in algae samples range from 0.75 (active photosynthesis of microalgae cultures under good conditions) to values close to 0.2 (disruption of photosynthesis under unfavorable conditions leading to growth cessation).[10] This parameter in water samples No. 1, 3, and 5 showed relatively high values (0.62-0.63). However, it slightly decreased in water samples No. 6 and particularly at stations No. 2 and 4. Nonetheless, it's worth noting that the Fv/Fm value of 0.53 is still sufficient for microalgae growth.[11]

Quantum yield of photochemical conversion of absorbed light energy into PS2 (Photosystem II) under light, Y = (Fm'-Ft)/Fm' multiplied by light intensity allows calculating the relative rate of non-cyclic electron transport (ETR). To calculate non-cyclic electron transport in absolute values, it is necessary to determine the number of absorbed quanta, which, considering the low concentrations of natural phytoplankton in the reservoir, is extremely difficult to do on native cells. Table 2 provides parameters describing these dependencies of photosynthetic activity on light intensity (P/E curves): the coefficient of maximum utilization of light energy, the slope angle on the linear segment of the light curve (α), the maximum relative rate of electrons through the electron transport chain (ETR max), and the light saturation intensity (En). The maximum relative rate of electrons through the electron transport chain (ETR max) was highest for phytoplankton at stations No. 1, 3, and 5. A lower value of ETR max was observed for phytoplankton in sample No. 6. Low ETR velocity was noted in samples No. 2 and 4, which is consistent with the reduced values of Fv/Fm. The coefficient of maximum utilization of light energy (α) was highest for phytoplankton in samples No. 1, 3, and 5 and decreased at other stations. The saturating light intensity (EnE_nEn) was highest for phytoplankton in samples 1 and 5, measuring 345 µE/m2^22/s and 355 µE/m2^22/s, respectively. For the other stations, the values showed minimal variation.

Table 2 presents fluorescence parameters for dark-adapted samples: Fv/Fm и F0; NPQ (non-photochemical quenching) values are provided for two light intensities (180 and 900 мкЕ/м2с1). Parameters describing the dependence of non-cyclic electron transport (ETR) on light intensity are included:

Table 2: Parameters of Chlorophyll Fluorescence in Natural Phytoplankton from Different Stations of Lake Alakol.

Fluorescence parameters	Sampling stations of Lake Alakol					
	No. 1	No. 2	No. 3	No. 4	No. 5	No. 6
F_v/F_m	0,62±0,01	0,53±0,01*	0,62±0,01	0,54±0,01*	0,63±0,01	0,58±0,02
F_0, rel. units.	292±22	201±22*	244±22	204±22*	342±22	236±21
ETR_{max}, rel. units	52,9±6,9	35,8±3,6*	48,9±6,9	38,9±6,9*	54,9±6,9	49,1±9,3
α	0,15	0,1*	0,13	0,1*	0,15	0,13
E_n, µE/ m^2 s^1	345±27	321±23	323±27	323±27	355±27	321±49
NPQ_{180} µE/m^2 s^1	0,09±0,01	0,24±0,02*	0,14±0,02	0,24±0,02*	0,09±0,01	0,14±0,02
NPQ_{900} µE/m^2 s^1	0,24±0,01	0,52±0,01*	0,32±0,01	0,53±0,01*	0,22±0,01	0,34±0,01

the coefficient of maximum light energy utilization (α), the maximum relative electron transport rate (ETR max), and the saturating light intensity (En). The data are summarized from three independent experiments. Statistically significant differences ($p<0.05$) are marked with an asterisk (*) and indicate impaired functionality of the photosynthetic apparatus at stations 2 and 4 compared to stations 1, 3, and 6.

The method used in this study also enables the assessment of non-photochemical quenching of fluorescence (NPQ), which is associated with the relative increase in energy dissipation.[12] The NPQ parameter is linked to the xanthophyll cycle, which plays a protective role for the photosynthetic apparatus by dissipating excess energy as heat under high light conditions.[24] This process is reflected in the development of non-photochemical fluorescence quenching under actinic light and is calculated using the formula $NPQ=(Fm/F'm)-1$). The highest NPQ values were observed in phytoplankton from samples 2 and 4, which were characterized by reduced photosynthetic activity.

4. Discussion

Microalgae play a crucial ecological role in many aquatic ecosystems and are of significant importance for biological monitoring.[25] Their rapid reproduction rates and short life cycles make them highly effective indicators of water quality, particularly for assessing short-term impacts. These organisms exhibit high species diversity and a broad distribution range. As primary producers, microalgae are highly sensitive to physical and chemical factors, making them vulnerable to anthropogenic stresses.[26] Changes in the composition and productivity of microalgae can directly impact food web interactions and ecosystem dynamics, necessitating their consideration in predicting the effects of environmental stressors.

The analysis of algal flora composition in Lake Alakol revealed diverse species, including diatoms, green algae, cyanobacteria, euglenoids, cryptophytes, and yellow-green algae. An ecological-geographical analysis indicated that indifferent species predominated, while halophytes adapted to saline conditions were also present. Most indicator species belonged to β-mesosaprobic forms. This classification highlights the β-mesosaprobic nature of the lake, characterizing it as moderately to slightly polluted. Notably, an increase in saprobity levels was observed at stations 2 and 5, likely due to active recreational activities contributing to significant anthropogenic impacts. Similar findings have been reported in studies of other water bodies, such as Lake Balaton, Hungary, where eutrophication and anthropogenic impacts altered the composition of phytoplankton communities and functional groups.[6] Research on β-mesosaprobic microalgae distribution reveals their ecological significance as bioindicators of moderate organic pollution in aquatic systems. Podelleck & Pankow (1986) classified 23 β-mesosaprobic algal taxa in brackish waters, demonstrating their utility for documenting ecological changes at wastewater inlet points. Antoine & Benson-Evans (1986) found β-mesosaprobic conditions in the River Ithon and lower Wye, with pennate diatoms showing consistent distribution patterns and serving as reliable indicators. Barinova *et al.* (2006) identified β- to α-mesosaprobic conditions in the Hadera River using 110 algal indicator species, with saprobity indices ranging from 1.73 to 2.80, corresponding to water quality classes II-IV. The distribution of β-mesosaprobic species correlates with intermediate levels of organic pollution, moderate dissolved oxygen concentrations, and specific conductivity ranges. These studies collectively demonstrate that β-mesosaprobic microalgae serve as effective bioindicators for assessing water quality and ecosystem health in diverse aquatic environments. These studies underscore the importance of microalgae as indicators for evaluating anthropogenic pressures and ecosystem health.

The study highlights the critical role of algal biotopes in bioindication, as they form the base of the trophic pyramid and are among the most susceptible to environmental changes.[26] Phytoplankton, with their diverse physiological and morphological strategies, adapt effectively to changing aquatic conditions. Reynolds (2002) described phytoplankton groups with similar seasonal requirements, explaining their development periodicity. Functional group analysis, based on shared environmental requirements, has proven to be an effective tool for assessing aquatic ecosystem changes. The functional groups identified in Lake Alakol—MP, Lo-Z, X3-X1, Y, F, and J—highlight the prevalence of diatom-dominated MP groups in most samples. These findings align with previous studies indicating that diatoms often dominate in moderately polluted ecosystems.[17] Interestingly, stations with higher total dissolved solids (TDS), such as stations 2 and

4, showed slight shifts in functional group composition, suggesting that elevated salinity may influence the relative abundance of more tolerant or opportunistic taxa.[27] The analysis of rapid light curves of chlorophyll fluorescence in Lake Alakol phytoplankton revealed slight impairments in the photosynthetic apparatus at stations 2 and 4. This was evidenced by a reduction in the relative rate of non-cyclic electron transport activity in PSII and a decrease in the maximum light energy utilization coefficient (α). Additionally, non-photochemical fluorescence quenching (NPQ), associated with the dissipation of excess light energy, was higher at these stations. Studies of eutrophic lakes in Europe have reported similar patterns, where elevated NPQ values were linked to photoprotective mechanisms triggered by excessive light and nutrient loading.[16] Importantly, these photophysiological responses coincide with the saline conditions of Lake Alakol. Total dissolved solids (TDS) at the six sampling stations ranged from 6484.8 to 8375.2 mg/L. Stations 2 and 4, which exhibited lower Fv/Fm values (0.53±0.01 and 0.54±0.01) and reduced ETRmax (35.8±3.6 and 38.9±6.9 rel. units), corresponded to relatively higher TDS levels of 7492.3 mg/L and 8375.2 mg/L. At these stations, the minimal fluorescence (F0) and photosynthetic efficiency (α) were also lower, while NPQ was higher, suggesting photoinhibition and stress in the phytoplankton community. In contrast, stations with moderate TDS (*e.g.* stations 1, 3, 5, and 6) displayed higher Fv/Fm and ETRmax values, indicating better photosynthetic performance. These observations collectively indicate that salinity is a key environmental factor influencing the photosynthetic activity and energy dissipation mechanisms of phytoplankton in Lake Alakol.[27,28]

The natural formation of algal communities in Lake Alakol is strongly influenced by climatic changes, which play a determining role. Establishing a robust monitoring system is essential to assess ecosystem status and predict potential changes in community composition. The high sensitivity of microalgae to environmental stressors further underscores their value as indicators for water quality assessments. By continuing to evaluate the composition and functionality of phytoplankton in aquatic ecosystems, we can enhance our ability to predict and mitigate the impacts of anthropogenic and climatic changes. In this study, the integration of saprobiological assessment, functional group analysis, and chlorophyll fluorescence measurements provided a comprehensive understanding of phytoplankton responses to environmental stressors and overall ecosystem health. The practical significance of this research lies in its contribution to developing recommendations for ensuring the resilience and proper functioning of natural aquatic ecosystems. The observed patterns reinforce the need for ongoing monitoring and the use of advanced bioassay techniques to safeguard water quality in both natural and artificial water bodies.

5. Conclusion

The conducted research highlights the critical ecological role of microalgae as primary producers and sensitive bioindicators of aquatic ecosystem health. The analysis of phytoplankton communities in Lake Alakol revealed diverse algal species and functional groups, reflecting the ecological characteristics and anthropogenic impacts on the lake. Functional group analysis proved effective in assessing changes in the aquatic environment, with notable differences in photosynthetic performance and non-photochemical quenching (NPQ) observed at stations subjected to higher anthropogenic pressures. These findings emphasize the importance of monitoring phytoplankton composition and functional parameters, such as fluorescence and photosynthetic efficiency, as tools for bioindication and environmental management. The increased saprobity levels and stress markers at certain stations suggest the need for targeted conservation strategies to mitigate anthropogenic impacts and preserve the lake's ecological balance. The results also underscore the value of integrating phytoplankton functional group analysis with fluorescence-based methods in developing monitoring systems for aquatic ecosystems. Such approaches provide valuable insights for predicting ecosystem responses to environmental changes and ensuring the sustainable management of water resources. This study contributes to the broader understanding of the dynamics of aquatic ecosystems and offers a basis for formulating strategies to maintain their stability and resilience.

The present study underscores the pivotal ecological role of microalgae as both primary producers and sensitive bioindicators of aquatic ecosystem health. Investigations of phytoplankton communities in Lake Alakol revealed a wide diversity of algal species and functional groups, which reflected both the ecological characteristics of the lake and the extent of anthropogenic influence. Functional group analysis proved to be an effective approach for detecting environmental changes, with pronounced differences in photosynthetic performance and non-photochemical quenching (NPQ) observed at stations exposed to higher human pressures. These results highlight the significance of monitoring phytoplankton composition together with functional parameters—such as chlorophyll fluorescence and photosynthetic efficiency—as key tools for bioindication and environmental management. Elevated saprobity levels and stress-related markers at certain sites further indicate the necessity of targeted conservation strategies to mitigate anthropogenic impacts and maintain the lake's ecological integrity. Moreover, the study demonstrates the value of integrating phytoplankton functional group analysis with fluorescence-based techniques to establish effective monitoring systems for aquatic ecosystems. Such integrated approaches offer critical insights into ecosystem responses to environmental change and support the sustainable management of freshwater resources. Overall, the findings contribute to a deeper understanding of aquatic ecosystem dynamics and provide a foundation for developing strategies to promote ecological stability and resilience.

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Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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Zarina Inelova: Writing – Original draft, Review & editing, Formal analysis, Visualization. **Nurziya Akmukhanova:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – Review & editing, Visualization. **Bolatkhan Zayadan:** Methodology, Formal analysis, Visualization, Writing - Review & editing. **Dmitry Matorin:** Formal analysis, Writing – Review & editing, Visualization. **Emil Boros:** Formal analysis, Writing – Review & editing, Visualization, **Grigorszky István:** Methodology, Formal analysis, Investigation, Writing – Review & editing. **Aktymbayeva Aliya:** Formal analysis, Visualization, Supervision. **Evgeny Sotnikov:** Investigation, Writing – Review & editing. **Gulzhan Yerubayeva:** Methodology, Formal analysis, Visualization. **Gulmira Satybaldiyeva:** Formal analysis, Data curation.

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