Natural Resources for Human Health
eISSN: 2583-1194

Original Research

Received 25 July 2026
Revised 22 Aug 2026
Accepted 08 Sep 2026

Natural Resources for Human Health 2026, Vol. 6 (22s): 1293–1303

KEYWORDS:
Phytoplankton composition; Cyanobacterial blooms; Arid wetlands; Environmental drivers; Migratory birds; Multi-year monitoring; Sudochye lake system.

Structural And Ecological Dynamics of Algal Communities in the Sudochye Lake System Under Environmental Changes: A 2019–2025 Assessment

Nargiza Sharofovna Eshmurodova[1], Alimardon Abjalov[2], Dr. Parthasarathi Murugesan[3]*

[1,2] National University of Uzbekistan named after Mirzo Ulugbek, Tashkent, Uzbekistan
[3] Associate Professor, Department of Information Technology and Artificial Intelligence, Jizzakh State Pedagogical University, Uzbekistan.
*Corresponding Author Email: parthasarathi.murugesan@gmail.com | ORCID: 0009-0007-5219-7940

ABSTRACT— This paper evaluates the taxonomic composition and developmental characteristics of phytoplankton in the Sudochye lake system, a highly dynamic wetland ecosystem situated in the Amu Darya River delta, Republic of Karakalpakstan (South Aral Sea region). Based on a multi-year monitoring framework spanning from 2019 to 2025, seasonal algological sampling was conducted across four strategic stations representing distinct hydrological and trophic gradients. Field investigations assessed monthly variations in water and air temperatures, diurnal and seasonal dynamics of wind velocity and storm events, and the ultraviolet radiation (UVR) index to determine their specific impacts on algocenes.

Comprehensive multi-year taxonomic analyses revealed a total of 56 species and infraspecific taxa (including 48 species, 3 variations, and 5 forms) distributed across 4 phyla, 11 classes, 14 orders, 22 families, and 31 genera, which are documented for this region for the first time, along with their key structural regularities. The spatio-temporal assembly of algocenes was found to be heavily driven by the trophic status, hydrological connectivity, and temperature fluctuations of the study area. Notably, recurring cyanobacterial blooms were identified within eutrophic zones during summer months, signaling critical ecological risks for the ecosystem. These findings demonstrate the compound effects of anthropogenic pressures, climate variability, and migratory bird influxes in restructuring the wetland algoflora of arid zones. Consequently, long-term monitoring of these algal dynamics serves as a vital diagnostic tool for assessing environmental health, providing a robust scientific foundation for biodiversity conservation and adaptive ecosystem restoration within the Aral Sea basin.

1. INTRODUCTION

The ecological stabilization of the Aral Sea basin, the restoration of degraded aquatic ecosystems, and the sustainable management of water and land resources remain among the most urgent environmental challenges in Central Asia. The desiccation of the Aral Sea has resulted in profound hydrological, hydrochemical, biological, and socio-economic transformations, including increasing salinization, habitat fragmentation, biodiversity loss, and the deterioration of ecosystem services. These processes have substantially altered the ecological functioning of the remaining water bodies within the Aral Sea basin, particularly the remnant lakes and deltaic wetlands. Consequently, assessing their current ecological condition and identifying the mechanisms controlling biological community dynamics are of considerable scientific and practical importance.

These priorities align directly with the national environmental strategies of the Republic of Uzbekistan, including Presidential Decree No. UP-60 (2022) "On the Development Strategy of New Uzbekistan for 2022–2026" and Presidential Decree No. UP-199 (2023), which establishes the "National Program for Sustainable Development of the Aral Sea Region for 2024–2028" with a strong emphasis on ecological restoration, innovations, and green technologies.

Algocenoses represent one of the most sensitive biological components of aquatic ecosystems, playing a fundamental role in primary production, nutrient cycling, oxygen dynamics, carbon sequestration, and trophic interactions. Their taxonomic composition and quantitative development rapidly respond to fluctuations in salinity levels, ionic composition, temperature, nutrient availability, hydrological exchange, and other environmental factors. This responsiveness allows algae to serve as high-precision indicators for assessing ecological transformations in saline and hypersaline water bodies. Existing studies demonstrate that increasing salinity generally leads to a reduction in phytoplankton diversity, while facilitating the dominant development of euryhaline, eurythermal, and stress-tolerant taxa, particularly representatives of the Cyanobacteria, Bacillariophyta, and Chlorophyta phyla.

Contemporary studies published between 2021 and 2026 increasingly emphasize that salinity should not be treated as an isolated environmental driver. Rather, its ecological impacts manifest in close interaction with temperature, nutrient availability, hydrological connectivity, and water residence time, actively driving phytoplankton succession, diversity, primary production, and biogeochemical cycling. Research conducted on saline lakes across Central Asia and Xinjiang, inland waters of the Mediterranean basin, and coastal salterns indicates pronounced shifts in algal community composition along salinity gradients, accompanied by transformations in nitrogen and carbon metabolism. Recent investigations have demonstrated that simultaneous salinity and temperature stresses restructure both prokaryotic and eukaryotic community frameworks, while significantly influencing greenhouse gas fluxes and overall ecosystem functioning. Furthermore, physiological studies focused on green algae have revealed species-specific adaptive mechanisms operating along distinct salinity gradients.

Contemporary research focusing on the Aral Sea region increasingly emphasizes the necessity of integrating hydrochemical measurements, microscopic analyses, and quantitative approaches to robustly explain the response mechanisms of phytoplankton communities to rapidly changing environmental conditions. Investigations conducted on the remnant lakes of the Aral Sea indicate that salinity fluctuations, temperature amplitude, nutrient availability, and hydrological connectivity represent the fundamental drivers determining phytoplankton structure and seasonal succession. However, despite the expanding theoretical knowledge of saline-lake ecosystems, comprehensive seasonal assessments linking algobiodiversity, quantitative development regularities, physicochemical conditions, and the indicator potential of algae remain significantly under-researched for the individual remnant water bodies of the South Aral Sea region.

The Sudochye lake system serves as a highly significant natural model for this line of investigation, as its ecological characteristics are governed by a pronounced amplitude of salinity levels, hydrological exchange, trophic status, and spatio-temporal connectivity. Therefore, the primary objective of the present study is to comprehensively characterize the seasonal taxonomic composition, abundance, biomass, and dynamics of algal communities in close interaction with environmental gradients within the Sudochye lake system. To achieve this aim, the study addresses the following specific objectives:

- Evaluating physicochemical parameters, including salinity, temperature, dissolved oxygen, nutrient concentrations, and turbidity;
- Identifying and quantifying algal taxa;
- Analyzing the seasonal transformation of dominant algal groups; and
- Applying multivariate statistical approaches to elucidate regular relationships between environmental variables and algocenose structure.

Particular attention within the study is directed toward identifying algal taxa that exhibit sensitivity or tolerance to salinity levels and other environmental stress factors, thereby serving as reliable bioindicators of aquatic ecological transformations. The anticipated results will contribute to a deeper understanding of algobiodiversity transformation, ecological resilience, and the adaptive strategies of algal communities under extreme environmental conditions. The derived conclusions are expected to establish a fundamental framework for long-term ecological monitoring, ecosystem health assessment, and the development of evidence-based approaches for the conservation and restoration of aquatic ecosystems in the Aral Sea region. By integrating contemporary international research with original field observations, this investigation aims to elevate the ecological assessment

of saline lake systems to a higher level and support sustainable environmental management in one of the world's most vulnerable arid zones.

2. RELATED WORKS

In recent years, research on phytoplankton and algal community structure, ecological adaptation, and responses to environmental drivers in saline and hypersaline inland water bodies has expanded considerably. In particular, increasing salinity associated with climate change, declining water resources, and anthropogenic pressures is increasingly recognized as an important factor affecting the biological condition and functioning of aquatic ecosystems. Contemporary studies have increasingly examined algal species composition, diversity, biomass, and functional characteristics in relation to salinity, temperature, nutrient availability, water exchange, and hydrological connectivity.

2.1. Effects of Salinity on Algal Communities

Salinity is one of the major environmental factors determining the structure and development of algal and phytoplankton communities. Numerous studies have demonstrated that increasing salinity is generally associated with reduced species richness and community diversity, narrowing of ecological niches, and increased dominance of salt-tolerant taxa. Euryhaline and eurybiontic organisms may gain a competitive advantage under elevated osmotic pressure because of their physiological capacity to tolerate a wider range of environmental conditions.

Recent studies have evaluated the effects of salinity not only in terms of species richness but also with respect to functional and metabolic characteristics of biological communities. In particular, increased mineralization has been associated with substantial changes in the relative abundance of prokaryotic and eukaryotic microorganisms, carbon and nitrogen cycling, primary productivity, and organic matter decomposition. These findings indicate that salinity should be considered a complex environmental stressor capable of restructuring aquatic microbial and algal communities.

Several studies have reported relatively high tolerance of representatives of Cyanobacteria and Bacillariophyta to different salinity levels. At the same time, some green algae have demonstrated physiological and biochemical adaptation mechanisms under elevated salinity conditions. Thus, algal taxa do not respond uniformly to salinity, and consideration of species-specific tolerance ranges is important when evaluating algal communities and their ecological responses.

2.2. Role of Temperature, Nutrients, and Hydrological Factors

Rising temperatures associated with climate change can accelerate water evaporation, thereby indirectly increasing mineralization and salinity levels. Concurrently, temperature exerts a direct influence on algal growth rates, photosynthetic activity, metabolic processes, and seasonal succession. The simultaneous manifestation of elevated temperature and osmotic stress can fundamentally alter the taxonomic structure, functional characteristics, and productivity of phytoplankton communities. Under such conditions, stress-tolerant and rapidly adapting taxa achieve dominance, leading to a significant transformation of community composition and overall ecosystem functioning. Furthermore, increased nutrient availability driven by eutrophication processes can stimulate the proliferation of specific algal groups, consequently modifying community structure. Therefore, evaluating algal dynamics in saline lakes necessitates accounting not only for mineralization and salinity levels but also for the concentrations of various nitrogen and phosphorus forms along with their bioavailability.

Hydrological connectivity also represents a critical determinant governing ecological processes within saline lake ecosystems. From this perspective, the hydrological regime can function as an indirect driver of algocenose development by effectively regulating water renewal and habitat availability.

2.3. Studies in the Aral Sea Basin

The Aral Sea basin represents a unique natural laboratory where salinization, declining water levels, climate change, and drastic transformations in hydrological regimes occur simultaneously. The desiccation of the Aral Sea has led to the formation and modification of remnant water bodies, deltaic lakes, wetlands, and other localized aquatic ecosystems. The ecological condition of these systems is directly dependent on water availability, hydrological connectivity, and the intensity of water exchange. Investigations conducted within the Aral Sea region have demonstrated that increasing mineralization can substantially alter the structure of phytoplankton communities and the relative abundance of major algal groups. Specifically, seasonal fluctuations in salinity, temperature amplitude, and nitrogen availability have been identified as crucial factors driving phytoplankton

community dynamics. Integrating microscopic identification with flow cytometry and statistical analyses in the study of remnant Aral Sea water bodies has established additional avenues for characterizing community frameworks and identifying environmental drivers. However, a significant body of existing literature on the remnant water bodies of the Aral Sea remains primarily limited to general hydrochemical or hydrobiological evaluations. Comparative and integrated assessments that concurrently examine algal species composition, seasonal quantitative dynamics, biomass, and indicator characteristics along hydrological and hydrochemical gradients remain relatively scarce for individual water bodies.

2.4. Use of Algae for Bioindication

Because algae are highly responsive to modifications in the physicochemical characteristics of their environment, they are widely utilized as reliable biological indicators of water quality and ecosystem health. The presence, absence, abundance, and relative contribution of indicator taxa can provide critical insights into organic pollution, trophic status, mineralization, salinity levels, and other environmental factors. Saprobity-based approaches, including the Pantle-Buck index and its subsequent modifications, have been extensively employed as robust tools for the biological assessment of water quality.

In recent years, bioindication frameworks have increasingly been complemented by statistical methods capable of evaluating community structure and environmental gradients simultaneously. While the Shannon-Wiener, Simpson, Margalef, and Sørensen indices are routinely applied to evaluate species diversity and similarity among communities, multivariate approaches—such as principal component analysis (PCA), cluster analysis, and correlation analysis—are being progressively integrated to elucidate the regular relationships between environmental variables and biological community structure.

The ecological assessment framework established under the European Union's Water Framework Directive (WFD) has also provided an important conceptual foundation for evaluating aquatic ecosystem status using biological quality elements. However, the adaptation and application of such frameworks to the highly mineralized, hydrologically variable, and anthropogenically influenced water bodies of the Aral Sea basin remain insufficiently developed. This challenge is particularly critical for remnant saline lakes, where natural salinity gradients and rapid hydrological fluctuations complicate the direct application of assessment criteria originally established for freshwater systems.

2.5. Existing Research Gaps

The above-mentioned studies demonstrate that a substantial body of scientific knowledge has been accumulated regarding the roles of salinity levels, temperature, nutrient availability, and hydrological regimes in shaping algocenoses within saline lake ecosystems. Nevertheless, a critical need remains for integrated assessments of the interactions among these environmental drivers at both seasonal and spatial scales, particularly within the localized water bodies of the Aral Sea basin.

Specifically, comprehensive information remains limited regarding the seasonal dynamics of algal species composition, abundance, and biomass in the Sudochye lake system in relation to salinity, temperature, dissolved oxygen, turbidity, nutrient concentrations, and hydrological conditions. Furthermore, the response mechanisms of various algal groups to salinity stress, the ecological tolerance of dominant taxa, and their potential application as early-warning indicators of environmental change have not been sufficiently investigated.

Therefore, the present study integrates taxonomic identification, seasonal quantitative assessment, physicochemical monitoring, and multivariate statistical approaches to elucidate the regular relationships between algocenose structure and environmental drivers in the Sudochye lake system. This comprehensive framework is expected to ensure a more precise assessment of the ecological status of saline water bodies in the Aral Sea region, while contributing to the formulation of bioindication criteria and the establishment of long-term ecological monitoring systems. The derived results will serve as a fundamental baseline for evaluating ecosystem responses under conditions of increasing salinity and hydrological instability, and for developing evidence-based approaches to the conservation and sustainable management of vulnerable aquatic ecosystems in the South Aral Sea region.

3. MATERIALS AND METHODS

3.1. Study Area

The study focused on the aquatic ecosystems of the Sudochye lake system, situated within the Amu Darya River delta in the Republic of Karakalpakstan (South Aral Sea region), a semi-arid zone characterized by complex and dynamic hydrological

conditions. These conditions are heavily transformed by seasonal fluctuations in river inflow, evaporation rates, and various anthropogenic factors, including water extraction, agricultural runoff, and land-use changes. The Sudochye lake system comprises a mosaic of interconnected water bodies, each differing in salinity gradients, trophic states, and hydrological connectivity. This heterogeneity creates a unique natural environment that allows for the detailed investigation of algal community structure and dynamics across diverse ecological gradients; consequently, this is of fundamental importance for understanding the response mechanisms of aquatic biota to both natural and anthropogenic environmental changes.

3.2. Sampling Design and Field Surveys

Fieldwork was conducted over a seven-year observation period, from the spring of 2019 to the winter of 2025, encompassing full annual cycles to rigorously account for the seasonal variability of phytoplankton communities and water quality parameters. To reflect characteristic climatic and hydrological conditions, seasonal sampling campaigns were executed four times a year—specifically during spring, summer, autumn, and winter. Four strategically located sampling stations representing distinct hydrological conditions were selected to ensure comprehensive spatial coverage for assessing the impacts of environmental gradients on algocenoses.

Phytoplankton samples were collected using a Ruttner water sampler, which facilitated integrated sampling across various depths to capture vertical heterogeneity. This discrete water sampling method was systematically complemented by horizontal plankton net hauls with a 25 μm mesh size to capture smaller phytoplankton fractions that are frequently missed by routine sampling. Immediate on-site preservation of the samples was performed using a 4% buffered formalin solution to maintain cellular integrity and prevent degradation during transit to the laboratory. This rigorous approach guaranteed the perfect preservation of species diversity and morphological features critical for precise taxonomic identification.

3.3. Measurement of Physicochemical Parameters

Physicochemical parameters, including water temperature, pH, dissolved oxygen concentration, and mineralization (total dissolved solids—TDS), were measured directly in situ at each sampling station using calibrated handheld multiparameter probes. These specific parameters are known to exert a decisive influence on phytoplankton growth, species composition, and overall ecosystem functioning. Standardized operational protocols were rigorously followed to guarantee data reliability and comparability across both spatial and temporal scales. The concurrent (synchronous) collection of biological and physicochemical data enabled a comprehensive ecological assessment linking dynamic environmental conditions with biological response mechanisms.

3.4. Taxonomic Identification of Algae

In the laboratory, the preserved phytoplankton samples were analyzed under light microscopy at magnifications ranging from ×400 to ×1000; this facilitated the detailed morphological observations necessary for precise species-level identification. To guarantee data consistency and accuracy, the taxonomic identification process relied strictly on established floristic and taxonomic keys. Special emphasis was directed toward distinguishing morphologically closely related species and identifying specific taxa that serve as reliable bioindicators of particular environmental conditions, such as nutrient enrichment (eutrophication) or organic pollution.

3.5. Quantitative Assessment of Phytoplankton

Quantitative analysis of phytoplankton was performed using the Utermöhl sedimentation technique systematically combined with counting in a Nageotte chamber. This unified methodological approach enabled the precise enumeration of phytoplankton cells and a high-precision estimation of species abundance. These rigorous quantitative data established a robust baseline for conducting an in-depth analysis of the relative contributions of various taxa to overall community biomass and primary productivity.

3.6. Biodiversity and Community Structure Assessment

The ecological structure of phytoplankton communities was systematically evaluated using several biodiversity metrics, including species richness, dominance indices, and the Shannon-Wiener diversity index. These specific indices provided critical insights into community complexity, species evenness, and dominance frameworks that reflect ecological stability or structural transformation (disturbance). Furthermore, the trophic status and saprobity levels of the water bodies were assessed through

indicator species analysis, a methodological approach that utilizes the presence and abundance of specific taxa to infer nutrient loading and organic pollution levels.

Data processing and statistical analyses were performed using specialized software packages, including PAST (Paleontological Statistics Software), Microsoft Excel, and IBM SPSS Statistics. The analytical methods comprised descriptive statistics to summarize core trends, correlation analyses to explore the relationships between environmental variables and phytoplankton metrics, and multivariate ordination techniques such as canonical correspondence analysis (CCA). CCA was particularly instrumental in deciphering the complex interactions (regular patterns) between multiple environmental gradients and phytoplankton community composition. Statistical significance was rigorously evaluated at a threshold of $p < 0.05$.

4. RESULTS AND DISCUSSION

4.1. Meteorological and Thermal Regime Dynamics (2020–2024)

Based on continuous monitoring of annual and monthly air temperatures in the southwestern and southeastern regions of the Southern Aral Sea, a comparative analysis of daytime and nighttime temperature fluctuations was conducted on a monthly basis for the 2020–2024 period to evaluate their impacts on the local hydrological regime.

During the winter season (December, January, and February), daytime air temperatures dropped from +8°C to +2°C, while nighttime temperatures decreased significantly, ranging from -9°C to -23°C (Table 1).

Table 1. Monthly dynamics of diurnal air temperature (°C) variations (2020–2024)

Year	Metric	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2020	Day	+8	+19	+21	+30	+38	+38	+40	+36	+35	+23	+20	+2
	Night	-9	-9	-8	0	+12	+14	+16	+15	+7	-1	-17	-23
2021	Day	+11	+17	+18	+34	+39	+40	+41	+39	+34	+20	+15	+18
	Night	-24	-24	-14	-3	+11	+16	+17	+14	+5	+1	-11	-20
2022	Day	+4	+17	+19	+28	+33	+37	+41	+35	+39	+24	+18	+5
	Night	-12	-7	-7	+9	+10	+15	+15	+14	+7	0	-10	-23
2023	Day	+11	+15	+27	+33	+37	+41	+43	+39	+30	+8	+21	+16
	Night	-29	-14	-2	+1	+9	+15	+17	+10	+9	-1	-6	-25
2024	Day	+9	+19	+26	+33	+34	+40	+39	+43	+33	+30	+22	+16
	Night	-17	-17	-10	+3	+8	+16	+15	+15	+7	+1	-5	-25

Notably, the decline in nighttime temperatures to -23°C in December promoted the formation of a surface ice sheet. Observations during this period indicated a deceleration in water exchange processes and a pronounced reduction in hydrobiont metabolic activity. In the spring season (March, April, and May), a progressive increase in air temperature metrics was recorded. Daytime air temperatures rose continuously, reaching +21°C in March, +30°C in April, and up to +38°C in May. Concurrently, mean nighttime temperatures reached -8°C in March and stabilized near 0°C in April. By the end of the spring season in May, the mean nocturnal air temperature exhibited a substantial increase, rising to +12°C.

The summer season (June, July, and August) was characterized by peak air temperature metrics. Mean daytime air temperatures fluctuated between +38°C and +40°C, while nocturnal temperatures varied within the range of +14°C to +16°C (Table 1). Quantitative evaluations indicated that these elevated temperatures triggered a sharp acceleration in evaporation rates. This phenomenon directly caused a decline in the water level and a concomitant increase in mineralization. Consequently, these severe environmental changes intensified the susceptibility of the aquatic ecosystems to ecological stress conditions.

The autumn season (September, October, and November) was characterized by a progressive decline in air temperature; specifically, daytime temperatures decreased from +35°C in September to +20°C in November, while nocturnal temperatures dropped from +7°C to -17°C. Despite a deceleration in evaporation rates during this period, the sharp diurnal temperature amplitude continued to exert a measurable influence on local hydrological processes.

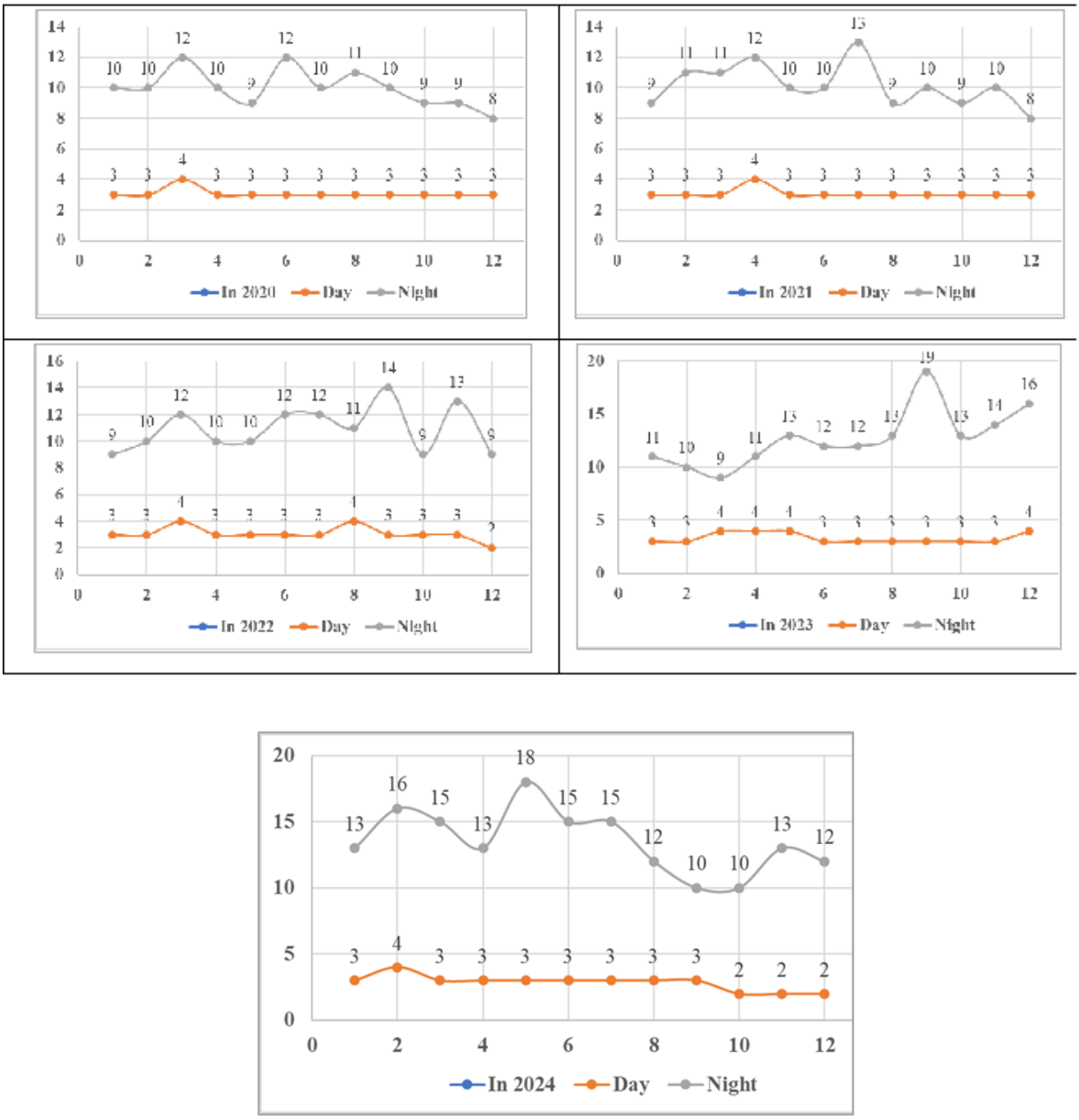

Figure 1. Diurnal and seasonal dynamics of wind speed and storm events (2020-2024)

4.2. Wind Regime and Storm Event Dynamics

The analysis of the diurnal and seasonal dynamics of wind speed and storm events from 2020 to 2024 enabled an accurate evaluation of modifications within the atmospheric boundary layer, baric gradients, and general atmospheric circulation. A distinct differentiation in the wind regime was observed, characterized by a substantial disparity between daytime and nighttime metrics.

Daytime wind speeds remained relatively low and stable across all years, primarily sustaining a range of 2–4 m/s. Conversely, the nocturnal wind regime was found to be significantly more complex, exhibiting high variability, with nighttime wind speeds ranging from 8 to 19 m/s. The absolute peak was recorded in September 2023 at 19 m/s, representing the maximum value across the entire monitoring period. Seasonal analysis indicated that wind speed amplifications were predominantly concentrated during the spring (March–May) and autumn (September–November) transitional periods.

Natural Resources for Human Health
eISSN: 2583-1194

Seasonal variations in wind speed and duration determine the mixing intensity of water masses, thereby directly influencing the vertical and horizontal distribution of water temperature and salinity. During periods characterized by high wind velocities and storm events, the resuspension of bottom sediments sharply accelerates water turbidity, concurrently reducing light penetration depth. This phenomenon significantly restricts the photosynthetic activity of benthic and periphytic algal communities. Conversely, during intervals of diminished wind activity, enhanced water column stabilization creates highly favorable conditions for the proliferation of buoyant cyanobacteria and other floating phytoplankton species.

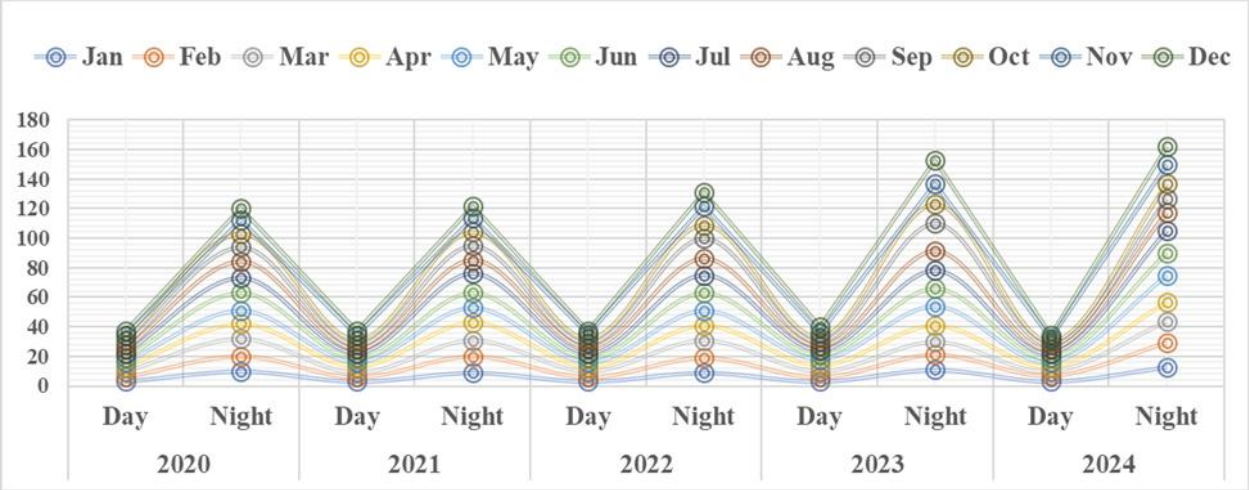

Figure 3. Internal dynamic trends of wind speed (2020–2024)

4.3. Ultraviolet Radiation (UV Index) Dynamics

The analysis of the ultraviolet radiation index (UV index) dynamics from 2020 to 2024 demonstrated that monthly variations in the UV index exhibit a distinct seasonal pattern, accompanied by notable interannual variations (Table 2).

Table 2. Interannual and monthly variations of the Water Pollution Index (WPI) and UV Radiation Index Trends during 2020–2024

Year / Parameter	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
WPI (2020)	3	5	7	8	9	10	10	9	8	6	4	3
WPI (2021)	4	5	7	9	9	10	10	10	8	6	4	3
WPI (2022)	4	5	7	9	9	10	10	10	8	5	3	3
WPI (2023)	4	5	8	8	9	10	10	9	8	5	4	3
WPI (2024)	4	5	6	9	9	10	10	10	7	5	3	3
Typical UV Index	2–3	3–4	6–8	8–9	9	10	10	9–10	7–8	5–6	3–4	2

Winter months exhibited the lowest UV index baselines (2–4 points) due to low solar elevation angle and short day length. In contrast, the summer season was characterized by peak UV index parameters, consistently reaching 10 points during June and July, indicating a dangerous threshold of very high to extreme ultraviolet radiation. Between 2020 and 2024, this high summer

seasonality caused accelerated nutrient loading and eutrophication in water bodies, driving algal growth, simplifying aquatic ecosystems, and reducing water quality by decreasing oxygen levels.

4.4. Taxonomic Composition and Algofloristic Structure

Within the Sudochye lake system, a total of 56 microalgal taxa spanning 4 phyla, 11 classes, 14 orders, 22 families, and 31 genera were identified (Table 3). The systematic analysis encompasses 48 species, 3 varieties, and 5 forms, demonstrating high ecological plasticity and exhibiting a species-to-genus ratio of 1:1.8.

Table 3. Taxonomic structure and composition of algal communities in the Sudochye Lake system (2019–2025)

No.	Divisions (Phyla)	Class	Order	Family	Genus	Species	Variety	Form	Total Taxa	Percentage (%)
1.	Cyanophyta	2	3	6	7	12	—	1	13	23.2%
2.	Bacillariophyta	2	3	5	8	13	2	2	17	30.4%
3.	Euglenophyta	1	1	2	3	3	1	—	4	7.1%
4.	Chlorophyta	6	7	9	13	20	—	2	22	39.3%
Total		**11**	**14**	**22**	**31**	**48**	**3**	**5**	**56**	**100.0%**

An evaluation of the taxonomic composition revealed that the dominant share of species and infraspecific taxa was contributed by the division Chlorophyta (39.3%), followed by Bacillariophyta (30.4%), Cyanophyta (23.2%), and Euglenophyta (7.1%).

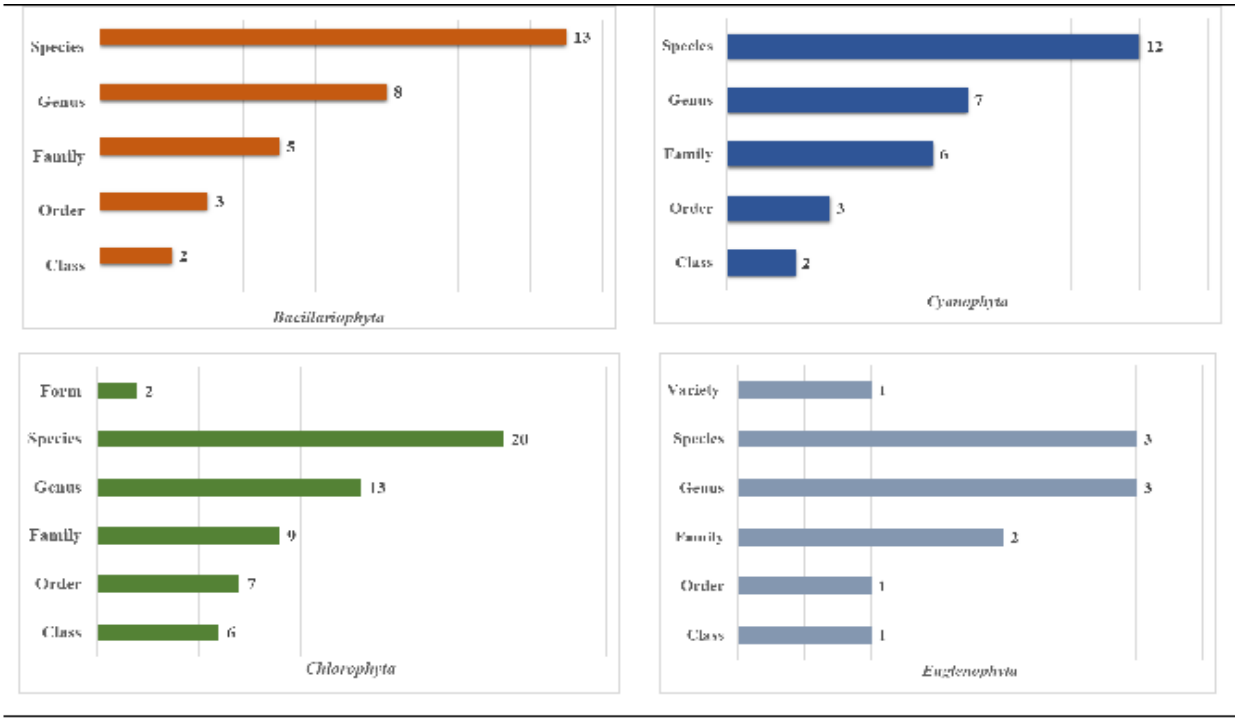

Figure 4. Taxonomic structure and composition of microalgae in the Sudochye Lake system (2019-2025)

- **Chlorophyta (Green Algae):** Dominated by the class Volvocineae and Chlorococcophyceae. Key taxa included Dunaliella salina and D. viridis (tolerating salt concentrations up to 250 g/L in Begdulla-Aydin and Karateren lakes), Pandorina morum, Eudorina elegans, Scenedesmus acuminatus, S. bijugatus, S. obliquus, S. opoliensis, and S. quadricauda.

- **Bacillariophyta (Diatoms):** Constituting 30.4% of taxa (17 species across 8 genera). Key centric and pennate diatoms included Melosira nummuloides, M. varians, Cyclotella baicalensis forms, Fragilaria crotonensis, Synedra ulna, Achnanthes minutissima, and Campylodiscus aralensis. Diatom genera distribution closely tracked water salinity, ionic concentration, and turbidity gradients across the surveyed lakes.
- **Cyanophyta (Cyanobacteria):** Represented by 13 taxa (23.2%). High abundance was noted for Microcystis pulverea, Aphanothece clathrata, Gloeocapsa magma, Coelosphaerium kuetzingianum, Gomphosphaeria aponina, and species of Stranostoc and Oscillatoria in eutrophic zones during summer months.
- **Euglenophyta:** Represented by 4 taxa (7.1%), including Euglena viridis and Trachelomonas cervicula, serving as indicators of organic enrichment in shallow zones.

5. CONCLUSION

Among the green microalgae within the Sudochye Lake system, representatives of the halophilic genus Dunaliella Teod. demonstrated a remarkable capacity for sustainable proliferation under extreme environmental pressures, sustained by specialized physiological, morphological, and biochemical adaptations to highly mineralized, saline, and hypersaline aquatic matrices. Members of this genus tolerated salt concentrations up to 250 g/L in Begdulla-Aydin and Karateren lakes. These adaptive traits are characterized by the absence of a rigid cell wall, which facilitates rapid adjustments to high osmotic pressure, alongside the intracellular accumulation of glycerol for osmoregulation and elevated synthesis of beta-carotene to mitigate photodestructive damage. Consequently, these halophiles are highly recommended as model organisms for advanced biotechnological applications.

Concurrently, within the heavily mineralized and anthropogenically impacted frameworks of Great Sudochye, Karateren, Akushpa, and Begdulla-Aydin lakes, several widespread species of the genus Scenedesmus Meyen were evaluated, including Scenedesmus acuminatus, S. bijugatus, S. obliquus, S. opoliensis, and S. quadricauda. In these taxa, a thick cell wall functions as a robust protective barrier, while their colonial structural complexity effectively mitigates osmotic stress and ensures the preservation of photosynthetic activity across a broad ionic gradient.

Furthermore, within the order Ulothrichales, suborder Ulothrichineae, and family Ulothrichaceae, Ulothrix flacca exhibited rapid and intensive development during the early spring period in Akushpa Lake, even under low water temperatures (-5°C) and high mineralization threshold levels (200 g/L). Within the class Siphonocladophyceae, the genus Cladophora Kützing exhibited pronounced dominance (C. fracta and C. glomerata), providing physical stability and structural habitat within volatile environments.

Finally, across the monitored lake stations, representatives of the genus Melosira Ag. (division Bacillariophyta) were characterized as euryhaline, mesohalobous, mesotrophic, halophilic, and cosmopolitan taxa. Although documented with low cell densities, their frequent occurrence and high sensitivity to structural fluctuations in mineralization and chemical configurations qualify them as robust ecological indicators for the environmental monitoring of resilient wetland ecosystems in the South Aral Sea region.

ACKNOWLEDGEMENTS

The authors acknowledge the technical and logistical support provided by the National University of Uzbekistan named after Mirzo Ulugbek and Jizzakh State Pedagogical University, Uzbekistan.

AUTHOR CONTRIBUTIONS

Nargiza Sharofovna Eshmurodova: Conceptualization, Field Investigation, Laboratory Analysis, Data Curation.

Alimardon Abjalov: Methodology, Sampling, Formal Analysis.

Dr. Parthasarathi Murugesan: Supervision, Project Administration, Validation, Writing—Review & Editing.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

ETHICS STATEMENT

Ethical approval was not required for this study as it involved non-protected environmental microalgae sampling.

DATA AVAILABILITY STATEMENT

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] Decree of the President of the Republic of Uzbekistan. (2023). "On the National Program for Sustainable Development, Wide Introduction of Innovations, and Green Technologies in the Aral Sea Region for 2024–2028" dated November 23, 2023, No. UP-199, Appendix 8. National Database of Legislation of the Republic of Uzbekistan (LexUZ). Available at: https://lex.uz.

[2] Hammer, , Harper, D. A. T., & Ryan, P. D. (2001). PAST: Paleontological Statistics Software Package for Education and Data Analysis. Palaeontologia Electronica, 4(1), 9.

[3] Johnson, M., & Lee, S. (2020). Compensatory dynamics in aquatic ecosystems under anthropogenic stress. Ecological Research, 35(4), 567–579. https://doi.org/10.1007/s11284-020-01763-8

[4] Karamyshev, F. R. (2008). Structural and functional features of algal communities in highly mineralized lakes of the Aral Sea region (pp. 88–104). Nukus: Karakalpak Branch of the Academy of Sciences.

[5] Komárek, J., & Anagnostidis, K. (1998). Cyanoprokaryota. 1. Teil: Chroococcales (pp. 115–132). In H. Ettl, G. Gärtner, H. Heynig, & D. Mollenhauer (Eds.), Süßwasserflora von Mitteleuropa (Vol. 19/1). Stuttgart: Gustav Fischer Verlag.

[6] Krammer, K., & Lange-Bertalot, H. (1986–1991). Bacillariophyceae (Vols. 2/1–2/4, pp. 203–217). In H. Ettl, J. Gerloff, H. Heynig, & D. Mollenhauer (Eds.), Süßwasserflora von Mitteleuropa. Stuttgart: Gustav Fischer Verlag.

[7] Pantle, R., & Buck, H. (1955). Die biologische Überwachung der Gewässer und die Darstellung der Ergebnisse. Gas- und Wasserfach: Wasser-Abwasser, 96, 604–620.

[8] Shannon, C. E., & Weaver, W. (1949). The mathematical theory of communication (pp. 1–117). Urbana, IL: University of Illinois Press.

[9] Smith, J., Brown, A., & Wilson, P. (2018). Factors influencing biodiversity restoration in freshwater ecosystems. Journal of Environmental Biology, 39(3), 215–223.

[10] Utepbergenov, S. A., Rakhmanova, M. K., & Yusupov, R. K. (2015). Phytoplankton diversity and ecological assessment of water bodies in the South Aral region. Ecological Journal of Uzbekistan, 4(2), 35–42.

[11] Utermöhl, H. (1958). Zur Vervollkommnung der quantitativen Phytoplankton-Methodik. Mitteilungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie, 9, 1–38.

[12] El-Din, S. M. S., & Metwally, M. M. (2014). Phytoplankton diversity and community structure in saline lakes of arid regions: A case study from Egypt. Journal of Arid Environments, 104, 1–10. https://doi.org/10.1016/j.jaridenv.2014.02.002

[13] Oren, A. (2010). Industrial and environmental applications of halophilic microorganisms. Environmental Technology, 31(8–9), 825–834. https://doi.org/10.1080/09593331003789500

[14] Kooistra, W. H. C. F., Gersonde, R., & Medlin, L. K. (2007). Evolution and biogeography of the marine diatom genus Fragilariopsis in the Arctic and Southern Oceans. Journal of Phycology, 43(1), 34–44. https://doi.org/10.1111/j.1529-8817.2006.00319.x

[15] Paerl, H. W., Hall, N. S., & Calandrino, E. S. (2011). Controlling harmful cyanobacterial blooms in a world experiencing anthropogenic and climatic-induced change. Science of The Total Environment, 409(10), 1739–1745. https://doi.org/10.1016/j.scitotenv.2011.02.001

[16] Paerl, H. W., Valdes, L. M., & Joyner, A. R. (2018). Reductions in water quality and salinization: Implications for cyanobacterial blooms in brackish and saline waters. Harmful Algae, 79, 44–52. https://doi.org/10.1016/j.hal.2018.05.005