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Plankton Diversity as a Bioindicator of Water Quality in Freshwater Ecosystems: Seasonal Trends and Ecological Significance

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ABSTRACT

Freshwater ecosystems face intensifying pressure from nutrient enrichment, urbanization, and climate variability, creating an urgent need for reliable, low-cost tools to monitor ecological condition. Plankton communities—phytoplankton and zooplankton—respond rapidly to physicochemical change because of their short generation times, direct sensitivity to nutrient and light regimes, and position at the base of aquatic food webs. This paper reviews the current scientific literature on the use of plankton diversity as a bioindicator of freshwater quality, with particular attention to seasonal variation and ecological significance. Evidence from lakes, reservoirs, rivers, and wetlands across multiple continents demonstrates that diversity indices such as the Shannon-Wiener index, along with pollution-tolerance indices such as the Palmer index, correlate consistently with trophic state and anthropogenic disturbance. Seasonal patterns show that plankton diversity typically peaks during pre-monsoon or spring transitional periods and declines during periods of nutrient loading, thermal stratification, or monsoonal dilution. The paper concludes that plankton-based biomonitoring, when combined with conventional physicochemical assessment, offers a cost-effective, ecologically integrative approach for tracking freshwater health, though standardization of sampling and identification protocols remains a challenge for broader adoption.

***Keywords**: Plankton Diversity, Bioindicator, Water Quality, Freshwater Ecosystem, Seasonal Variation, Phytoplankton, Zooplankton, Eutrophication.*

Introduction

Freshwater ecosystems—lakes, rivers, ponds, reservoirs, and wetlands—supply drinking water, support fisheries and agriculture, and sustain a disproportionate share of global biodiversity relative to their limited surface area. Yet these systems are among the most threatened on Earth, with freshwater biodiversity declining faster than that of terrestrial or marine environments as a result of eutrophication, pollution, habitat modification, and climate change (Poyang Lake basin studies, as reviewed in freshwater biomonitoring literature, similarly report substantial declines associated with anthropogenic pressure and altered hydrology). Traditional water quality assessment has relied heavily on physicochemical measurements such as dissolved oxygen, biochemical oxygen demand, nutrient concentrations, and turbidity. While these parameters are precise and standardized, they capture only an instantaneous snapshot of conditions and cannot reflect the cumulative, integrated biological response of an ecosystem to fluctuating or intermittent stressors.

Biological monitoring, in contrast, uses the structure and composition of living communities to infer ecological condition over time. Among candidate bioindicator groups, plankton—the assemblage of phytoplankton (algae and cyanobacteria) and zooplankton (rotifers, cladocerans, copepods, and other microinvertebrates) that drift in the water column—offer particular advantages. Plankton exhibit short life cycles and rapid reproductive turnover, allowing their community composition to shift within days to weeks in response to changing nutrient loads, temperature, or contaminant exposure (Chandel et al., 2024). Because they occupy the base of the aquatic food web, changes in plankton diversity propagate through higher trophic levels, making plankton assemblages informative not only about water chemistry but also about broader ecosystem function.

This paper synthesizes recent peer-reviewed research on plankton diversity as a bioindicator of freshwater quality. It addresses three central questions. First, what theoretical and empirical basis supports the use of plankton diversity metrics as proxies for water quality? Second, how does plankton diversity vary seasonally, and what mechanisms drive these patterns? Third, what is the broader ecological significance of plankton-based biomonitoring for freshwater management and conservation? The review draws on studies of lakes, reservoirs, rivers, and wetlands from temperate, subtropical, and semi-arid regions to identify consistent patterns as well as context-dependent variation.

Plankton as Bioindicators: Theoretical Framework

A bioindicator is an organism or biological response used to assess the quality of an environment, providing information that purely chemical or physical measurements cannot capture, including cumulative and indirect biotic effects of pollutants (Chandel et al., 2024). The theoretical basis for using plankton in this role rests on several ecological principles. First, individual plankton taxa differ markedly in their tolerance to organic pollution, nutrient enrichment, and physical disturbance. Pollution-tolerant genera such as Euglena, Oscillatoria, and Chlorella often dominate nutrient-rich, oxygen-depleted waters, whereas pollution-sensitive diatoms and desmids are associated with cleaner, oligotrophic conditions (Chandel et al., 2024). This differential sensitivity underlies classical biotic indices such as the Palmer organic pollution index, which assigns pollution scores to algal genera based on documented tolerance (Palmer, 1969).

Second, community-level diversity indices provide an integrative measure of ecosystem stress that does not depend on identifying a single indicator species. The Shannon-Wiener diversity index (Shannon & Weaver, 1949), which accounts for both species richness and evenness, is the most widely applied metric in plankton biomonitoring. Numerous studies report an inverse relationship between the Shannon-Wiener index and the degree of organic or nutrient pollution: as pollution increases, sensitive taxa disappear, tolerant taxa proliferate, and the community becomes both less rich and less even, driving diversity values downward. Complementary measures, including the Margalef richness index, Pielou's evenness index, and the Simpson dominance index, are frequently used alongside the Shannon-Wiener index to characterize different dimensions of community structure.

Third, plankton bioindication operates at multiple organizational levels. At the taxonomic level, shifts in dominant genera or species signal changing environmental conditions. At the functional level, traits such as body size, feeding mode, and motility respond systematically to disturbance; for example, urbanized freshwater systems tend to become dominated by small-bodied, generalist microphagous zooplankton, a pattern described as functional homogenization (Goździejewska et al., 2024). At the whole-community level, diversity and evenness indices summarize the aggregate biological response. This multi-level sensitivity is a key reason plankton are considered a more holistic indicator than single physicochemical parameters, though the EU Water Framework Directive and comparable frameworks in other regions do not yet universally recognize zooplankton as a standard regulatory indicator, despite growing scientific support for their inclusion (Goździejewska et al., 2024).

Methodological Approach

This review synthesizes findings from peer-reviewed studies published primarily between 2015 and 2026, drawn from limnological, ecological, and environmental science journals. Search terms included combinations of "plankton," "phytoplankton," "zooplankton," "bioindicator," "water quality," "seasonal variation," and "freshwater ecosystem." Studies were selected for inclusion if they reported empirical plankton diversity data linked to water quality parameters, trophic status indices, or pollution gradients in lakes, reservoirs, rivers, or wetlands. Diversity metrics discussed include the Shannon-Wiener index, Margalef richness index, Pielou evenness index, Simpson dominance index, and taxon-specific pollution-tolerance indices such as the Palmer index. Because plankton communities are studied using varied sampling protocols—net sampling, water-column integrated sampling, DNA metabarcoding, and microscopic enumeration—this review treats reported diversity trends qualitatively and comparatively rather than attempting direct quantitative meta-analysis across methodologically heterogeneous studies.

Phytoplankton Diversity and Water Quality

Phytoplankton are primary producers whose growth is directly regulated by light availability, temperature, and the concentration of dissolved nutrients, particularly nitrogen and phosphorus. Because of this direct physiological coupling to water chemistry, phytoplankton community composition is one of the most extensively used biological indicators of trophic state in freshwater systems. In a study of Xuanwu Lake, China, phytoplankton density and community composition tracked the comprehensive trophic level index derived from water quality indicators across seasons, with nutrient limitation shaping community structure differently in different seasons, indicating a strong correspondence between phytoplankton assemblage structure and standard water-quality-based trophic assessment. Reductions in nitrogen and phosphorus loading were associated with corresponding shifts in phytoplankton community structure and biomass, underscoring the responsiveness of these communities to management interventions targeting nutrient inputs.

A study of phytoplankton diversity indices across a barrier lake system found that the Margalef and Shannon-Wiener indices were significantly, though sometimes counterintuitively, correlated with the comprehensive trophic level index depending on season, reflecting the combined influence of nutrient-driven "bottom-up" control and zooplankton-grazing "top-down" control on phytoplankton assemblages. This finding illustrates an important nuance: diversity indices do not always decline monotonically with eutrophication. In lakes experiencing severe, chronic eutrophication, some evidence indicates that the Shannon-Wiener index can show a positive interannual correlation with the trophic level index, even as Margalef richness and Pielou evenness decline, because a small number of highly productive taxa—often cyanobacteria—can dominate biomass while species counts remain comparatively stable in early stages of enrichment.

Complementary evidence from a mesocosm study manipulating nutrient enrichment in shallow, subtropical lake systems found that eutrophication did not significantly alter phytoplankton species richness but did increase total phytoplankton density and chlorophyll-a concentration while decreasing both the Shannon-Wiener diversity index and Pielou's evenness index over time. Notably, functional diversity metrics responded earlier and more sensitively to nutrient enrichment than taxonomic composition alone, suggesting that trait-based diversity measures may serve as more sensitive early-warning indicators of eutrophication than presence-absence species lists. Similarly, research in wetland systems in northeastern China found that environmental heterogeneity—encompassing water depth, connectivity, and physicochemical variability—strongly shaped phytoplankton diversity, with diatom diversity indices closely tracking water-quality change in comparable wetland systems elsewhere in the region.

Classical pollution-tolerance approaches remain relevant alongside modern diversity indices. Application of the Palmer organic pollution index in a reservoir system found that genera such as Oscillatoria, Euglena, Chlorella, Phormidium, Synedra, and Navicula—many of them well-documented pollution-tolerant taxa—dominated at sites subject to greater anthropogenic pressure, while sites farther from human activity showed comparatively lower organic pollution scores (Chandel et al., 2024; see also Palmer, 1969). Collectively, these findings confirm that phytoplankton community composition, diversity indices, and pollution-tolerance scores together provide a multidimensional and generally reliable proxy for freshwater trophic and pollution status, though the direction and strength of specific index-trophic state relationships can vary with the severity and duration of nutrient enrichment.

Zooplankton Diversity and Water Quality

Zooplankton occupy an intermediate trophic position between phytoplankton and higher consumers such as fish, and their community structure integrates both bottom-up nutrient effects and top-down predation pressure. Zooplankton are widely regarded as among the most useful bioindicators of freshwater quality because of their high diversity, rapid generational turnover, and sensitive responses to trophic, thermal, and seasonal gradients (Li et al., as cited in recent freshwater bioindicator literature). A comprehensive study of the Łyna river-lake system in northern Poland examined zooplankton across a land-use gradient spanning headwater, natural, urban, urban-agricultural, and agricultural catchments, finding that natural river zones supported greater habitat heterogeneity and a wider range of feeding niches, whereas urbanized catchments produced pronounced functional homogenization, with small-bodied, broadly generalist microphagous taxa coming to dominate (Goździejewska et al., 2024). This pattern illustrates that land use and catchment-scale disturbance, not only in-stream water chemistry, shape zooplankton diversity outcomes.

Research on an artificial freshwater lake in a semi-arid region of Jordan documented twenty-six zooplankton species and found that Copepoda numerically dominated the community, accounting for roughly two-thirds of total zooplankton abundance in both winter and summer, while Rotifera and Cladocera alternated as the second most abundant group between seasons (Guermazi et al., 2023). High nutrient concentrations and an elevated trophic level index classified the lake as eutrophic to hypertrophic, and the zooplankton community composition corresponded closely with this classification, reinforcing the value of zooplankton assemblages as indicators of trophic status even in artificial and semi-arid freshwater systems. A parallel study of Lake Burullus in Egypt similarly linked zooplankton community composition and diversity to water quality and eutrophication status, finding that community shifts tracked measured nutrient and chlorophyll conditions across the lake (Alprol et al., 2021).

Beyond conventional crustacean and rotifer indicators, emerging research highlights the potential of protist groups within the zooplankton size fraction, such as testate amoebae, as underused but ecologically informative bioindicators, with fluvial systems supporting distinctive testate amoebae assemblages that vary systematically with flow velocity and stream order. Complementary technical reviews of zooplankton biomonitoring in polluted freshwater systems document that determinants of zooplankton community structure in heavily polluted rivers include not only nutrient concentration but also heavy metal contamination and hydrological alteration (Xiong et al., 2016), and that diversity measures in zooplankton and macroinvertebrate communities can respond to trophic status in ways that are sometimes complementary and sometimes contradictory across reservoir systems, underscoring the importance of interpreting zooplankton diversity data alongside other lines of evidence rather than in isolation (Azevêdo et al., 2015). Reviews of protist bioindicators further argue that flexible, rapid generation times and broad taxonomic diversity make protists—including many zooplankton-associated taxa—particularly promising for early-warning biomonitoring applications (Payne, 2013).

Seasonal Trends in Plankton Diversity

A consistent finding across freshwater systems in temperate, subtropical, and monsoonal climates is that plankton diversity fluctuates predictably across the annual cycle, driven by seasonal changes in temperature, light availability, hydrological regime, and nutrient input. In monsoon-influenced systems, elevated surface runoff during the rainy season delivers substantial nutrient loads to receiving waters, which can initially promote phytoplankton diversity and productivity as nutrients become newly available (Chandel et al., 2024). However, this pattern is not universal: a study of zooplankton diversity across three freshwater lakes in northern India found that zooplankton diversity was highest during the pre-monsoon season and lowest during the monsoon season itself, a pattern attributed to dilution effects from heavy rainfall and surface runoff disrupting established community structure. Physicochemical parameters including total dissolved solids, nitrate, sulfate, turbidity, and biochemical oxygen demand showed substantial seasonal fluctuation, generally peaking in the post-monsoon period, with an inverse relationship observed between biochemical oxygen demand and zooplankton abundance, such that higher organic loading during cooler winter months was associated with increased biological activity and shifts in community structure.

In temperate lake and reservoir systems, seasonal succession follows a somewhat different pattern governed primarily by thermal stratification and light regime rather than monsoonal rainfall. Phytoplankton biomass and species turnover typically increase from spring through summer as water temperatures rise and stratification develops, with increased primary productivity subsequently promoting more rapid zooplankton population growth and greater complexity in zooplankton interspecific interactions during the summer growing season, as documented through combined environmental DNA and morphological monitoring of a large deep-water reservoir in eastern China. This spring-to-summer increase in productivity and interaction complexity illustrates how phytoplankton seasonal dynamics cascade upward to shape zooplankton community assembly.

Seasonal and spatial variability has also been documented using molecular methods. DNA metabarcoding of zooplankton across the Poyang Lake basin, the largest lake system in China, revealed that community structure varied significantly by season and location, correlating with turbidity, water temperature, pH, total phosphorus, and chlorophyll-a concentration, with habitat degradation linked to human activity and seasonal hydrological change identified as primary drivers of these community shifts. Related work on a sub-lake of Lake Poyang similarly emphasized that zooplankton population structure, abundance, and dominant taxa varied across seasons and years in ways that tracked shifting physicochemical conditions, providing a scientific basis for water resource management planning.

Underlying mechanisms for phytoplankton seasonal turnover have also been examined directly. Research on temporal beta diversity in freshwater lake phytoplankton communities indicates that seasonal species turnover is shaped by the interplay of temperature, thermal stratification, nutrient availability, light, zooplankton grazing pressure, and allelopathic interactions among algal taxa, with environmental heterogeneity—both spatial differences among lakes and temporal variation within a single lake across seasons—playing a central role in generating observed diversity patterns. Notably, eutrophication has been found to reduce the magnitude of seasonal variation in some biological assemblages, effectively dampening the natural seasonal diversity cycle, while warming has been associated with increased spatial diversity variation among lakes for several planktonic and benthic groups. Taken together, these findings indicate that seasonal plankton diversity trends, while broadly predictable within a given climatic and hydrological regime, are also modulated by the trophic state and thermal history of individual water bodies, meaning that seasonal baselines established in one system cannot always be directly extrapolated to another without accounting for local nutrient and climate context.

Ecological Significance of Plankton Diversity Monitoring

The ecological significance of plankton diversity extends well beyond its diagnostic value for water quality assessment. Plankton form the trophic foundation of freshwater food webs, transferring energy fixed by phytoplankton photosynthesis to zooplankton grazers and, ultimately, to planktivorous fish and higher trophic levels (Goździejewska et al., 2024). Because of this foundational role, changes in plankton diversity and community composition can propagate through the food web, affecting fish recruitment, fisheries productivity, and overall ecosystem stability. A decline in plankton diversity associated with eutrophication or pollution therefore signals not merely a water chemistry problem but a broader risk to ecosystem function and the services freshwater systems provide, including fisheries, water purification, and recreation.

Plankton-based monitoring also offers practical advantages for environmental management. Compared with the cost of routinely testing for the full range of potentially harmful chemical contaminants, biological community monitoring is comparatively inexpensive and, because it reflects cumulative and historical exposure rather than an instantaneous chemical snapshot, can provide a higher degree of reliability for detecting intermittent or diffuse pollution sources (Chandel et al., 2024). Because certain plankton taxa respond to stressors before those stressors become severe enough to cause acute, visible ecological damage, plankton communities can function as early-warning indicators, providing environmental managers a window for intervention before a water body crosses into a degraded or difficult-to-reverse state, such as persistent cyanobacterial dominance.

The concept of functional diversity adds a further layer of ecological significance. Beyond simple counts of taxa, the distribution of functional traits—body size, feeding mode, motility, and habitat preference—within a plankton community reflects the range of ecological niches and ecosystem processes being performed. The functional homogenization documented in urbanized catchments of the Łyna river system, where small-bodied generalist microphages replaced a more functionally diverse assemblage, suggests a loss not just of species but of the functional redundancy that helps freshwater ecosystems buffer against additional disturbance (Goździejewska et al., 2024). This has direct implications for ecosystem resilience: functionally homogenized communities may be less able to maintain key processes, such as algal grazing control, under future stress, including climate change and continued urban expansion.

Plankton diversity monitoring also supports broader conservation and policy objectives. Indicator species analysis and cluster-based community classification approaches can identify taxa characteristic of specific catchment conditions, informing targeted management responses such as riparian buffer restoration, nutrient load reduction, or hydrological reconnection of floodplain habitats (Goździejewska et al., 2024). At a regional scale, recommended strategies drawing on plankton bioindication include applying plankton and associated benthic organisms for early detection of water quality degradation, strengthening technical training for stakeholders such as fish farmers whose livelihoods depend on water quality, and encouraging multi-stakeholder collaboration among government agencies, academic institutions, and resource users (Chandel et al., 2024). These applications illustrate that plankton diversity is not merely an academic metric but a practical tool with direct relevance to freshwater governance and sustainable resource management.

Challenges and Future Directions

Despite its demonstrated value, plankton-based biomonitoring faces several methodological and practical challenges. Taxonomic identification of plankton, particularly phytoplankton and rotifers, requires specialized expertise and can be time-consuming, creating a bottleneck for routine, large-scale monitoring programs. Emerging molecular approaches, including DNA metabarcoding and environmental DNA analysis, offer a promising solution by enabling faster, more standardized, and potentially more sensitive detection of plankton diversity, as demonstrated in recent studies of Poyang Lake and the Qiandao Lake reservoir system. However, molecular methods introduce their own challenges, including reference database completeness, primer bias, and the need to reconcile molecular diversity estimates with the morphological taxonomy underlying most historical monitoring records and regulatory frameworks.

A second challenge concerns the regulatory status of plankton, and zooplankton in particular, within formal water quality frameworks. Despite strong scientific evidence of zooplankton sensitivity to environmental change, zooplankton are not currently recognized as standard indicators under major regulatory frameworks such as the European Union Water Framework Directive (Goździejewska et al., 2024). Broader adoption of plankton diversity metrics in formal regulatory monitoring would likely require further standardization of sampling protocols, diversity index calculation methods, and reference conditions across different freshwater ecosystem types and climatic regions.

A third challenge relates to the complexity of interpreting diversity index responses under different types and stages of disturbance. As several of the studies reviewed here demonstrate, diversity indices do not always respond in a simple, linear fashion to eutrophication or pollution; species richness may remain stable even as evenness declines, and different diversity indices can show divergent or even opposing correlations with trophic status depending on the severity, duration, and type of disturbance involved. Future research would benefit from long-term, multi-decadal monitoring datasets that can disentangle the effects of chronic eutrophication, acute pollution events, climate-driven warming, and hydrological alteration on plankton diversity trajectories, as well as from greater integration of taxonomic and functional trait-based diversity metrics to improve the sensitivity and interpretability of plankton-based water quality assessment.

Conclusion

This review of recent literature confirms that plankton diversity is a robust and ecologically meaningful bioindicator of freshwater water quality. Phytoplankton and zooplankton communities respond rapidly and measurably to nutrient enrichment, organic pollution, land-use change, and hydrological alteration, and diversity indices such as the Shannon-Wiener index, together with pollution-tolerance frameworks such as the Palmer index, provide consistent, if occasionally nuanced, signals of trophic state and ecosystem stress. Seasonal patterns in plankton diversity are shaped by the interaction of temperature, light, nutrient loading, and hydrological regime, producing predictable but system-specific cycles, such as pre-monsoon diversity peaks in monsoonal systems and spring-to-summer productivity increases in temperate lakes and reservoirs. Beyond their diagnostic value, plankton communities are ecologically significant as the trophic foundation of freshwater food webs, and their diversity and functional composition have direct implications for ecosystem resilience, fisheries productivity, and the broader services that freshwater ecosystems provide. Realizing the full potential of plankton-based biomonitoring will require continued methodological standardization, wider integration of molecular identification tools, and stronger incorporation of plankton diversity metrics into formal water quality regulatory frameworks. Given the accelerating pressures facing freshwater ecosystems worldwide, plankton diversity monitoring represents a scientifically grounded, cost-effective, and ecologically integrative complement to conventional physicochemical water quality assessment.

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