

Plankton as Bioindicators in Aquatic Pollution Monitoring

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Abstract

Plankton, the microscopic component of aquatic ecosystems, play a dual role as primary drivers of trophic dynamics and sensitive indicators of environmental change. Their rapid response to physicochemical perturbations, ease of sampling, and ecological relevance render them effective tools for biomonitoring. Shifts in community structure in response to nutrient enrichment, oxygen stress, and thermal or salinity anomalies make plankton excellent bioindicators for environmental changes. Modern tools such as molecular diagnostics, AI-based identification, and remote sensing can be used for enhancing monitoring efficiency.

Introduction

Plankton, comprising both autotrophic phytoplankton and heterotrophic zooplankton, are microscopic organisms that inhabit the water column and form the base of aquatic food webs. While their ecological role in primary production and nutrient cycling is well-established, their importance as bioindicators of aquatic pollution is increasingly being recognized. In the present scenario of aquatic ecosystems being increasingly threatened by various anthropogenic activities, monitoring the health of these systems is critical for maintaining biodiversity, ensuring safe water quality, and guiding sustainable resource management. Among the many approaches used for environmental monitoring, biological assessment using bioindicators has gained prominence due to its ability to reflect cumulative and long-term ecological changes.

Plankton communities respond quickly and predictably to variations in water quality parameters such as nutrient concentration, dissolved oxygen levels, salinity, temperature, and the presence of pollutants, due to their short life cycles, high reproductive rates, and sensitivity to environmental changes. The use of **plankton as bioindicators** is rooted in the principle that specific taxa or community structures can signal the presence and intensity of environmental

stressors. These biological cues are more integrative and reflective of long-term ecosystem dynamics than single-point physicochemical measurements. Plankton-based bioassessment has become an essential tool in **limnology, marine ecology, and water resource management**. Several diversity indices are applied to quantify plankton community responses and assess ecological integrity. In addition, specialized indices have also been developed for rapid and reliable assessments.

With the advent of advanced tools such as **remote sensing, metabarcoding, and machine learning**, the scope of plankton-based monitoring has expanded, allowing for higher-resolution data collection and real-time assessments. These innovations have made it possible to detect subtle ecological shifts and predict harmful algal blooms, offering a proactive approach to ecosystem management. However, challenges remain in the form of taxonomic complexity, variability across spatial and temporal scales, and the need for standardized methodologies. As we strive toward sustainable water governance, plankton offer a cost-effective, sensitive, and ecologically meaningful means to assess and manage the health of aquatic ecosystems.

Plankton

Plankton are broadly classified based on their trophic role, size, and habitat:

- **Phytoplankton:** Autotrophic organisms such as diatoms, blue-green algae, green algae, and dinoflagellates that perform photosynthesis.
- **Zooplankton:** Heterotrophic plankton comprising protozoa, rotifers, copepods, cladocerans, and larval stages of aquatic invertebrates.
- **Bacterioplankton and Mycoplankton:** Involved in the decomposition of organic matter and nutrient cycling.

Phytoplankton form the base of the food chain, while zooplankton transfer energy to higher trophic levels. Their abundance and diversity are regulated by several abiotic factors (light, temperature, nutrients, pH, salinity) and biotic interactions (predation, competition). Plankton, especially phytoplankton, have short generation times, sometimes completing multiple life cycles within a week. This rapid turnover makes them highly responsive to environmental disturbances.

Plankton as bioindicators: mechanisms and relevance

A **bioindicator** is defined as a species or community that provides insight into the environmental condition of an ecosystem through its presence, absence, or measurable biological responses. Plankton should exhibit **sensitivity** by responding detectably to specific environmental changes such as nutrient loading, temperature shifts, or pollution; demonstrate **predictability** by showing consistent and reproducible patterns of change across similar stress gradients; offer **ease of sampling and identification**, allowing for practical and cost-effective monitoring; and possess **ecological significance** in that they play a fundamental role in ecosystem functioning, particularly in energy

transfer and nutrient cycling. Their responsiveness to both natural and anthropogenic influences aids in assessing the health, trophic status, and overall integrity of freshwater and marine ecosystems.

Plankton act as indicators for:

Eutrophication

Eutrophication occurs due to excessive enrichment of water bodies with nutrients, especially nitrogen (N) and phosphorus (P), from agricultural runoff, sewage discharge, or industrial effluents. This leads to rapid phytoplankton growth, especially cyanobacteria such as *Microcystis*, *Oscillatoria*, *Anabaena*, and *Nostoc*. The proliferation of cyanobacteria alters food web dynamics by reducing water transparency, limiting light penetration, and producing toxins. These toxins can harm fish, zooplankton, and even human health when water is used for drinking or recreation. A shift from diverse phytoplankton assemblages to cyanobacterial dominance is a sign of eutrophication and declining water quality.

Pollution detection

Pollution, especially organic and chemical pollution, affects plankton community composition by selectively favoring tolerant species while sensitive species decline. Diatoms such as *Navicula*, *Fragilaria*, and *Asterionella* are highly sensitive to pollutants and heavy metals. Their disappearance indicates increased contamination levels. *Euglena* and other euglenoids thrive in organically polluted waters rich in decomposing organic matter, such as sewage-contaminated ponds or rivers. Certain cyanobacteria and flagellates also proliferate under polluted conditions. A shift from diatom-dominated communities to euglenoids signifies a transition from clean to polluted conditions.

Trophic state assessment

Plankton composition directly reflects the trophic status of aquatic ecosystems. Oligotrophic, or nutrient-poor, waters are characterized by the dominance of diatoms (*Cyclotella*, *Fragilaria*) and other high-oxygen-requiring phytoplankton. Mesotrophic waters (moderate nutrients) would harbor a balanced representation of diatoms, chlorophytes, and moderate cyanobacteria, resulting in good fish productivity without excessive algal blooms. In eutrophic waters (nutrient-rich), cyanobacteria dominate, along with dense blooms of chlorophytes. This will result in high turbidity and oxygen depletion in deeper waters due to decomposition of excessive organic matter. The Phytoplankton Trophic Index (PTI) uses the relative abundance of these groups to determine whether the water body is oligotrophic, mesotrophic, or eutrophic.

Oxygen levels and ecosystem health

The diversity and composition of zooplankton communities are strongly linked to dissolved oxygen levels. In high oxygen conditions, a diverse zooplankton community with large-bodied species such as *Daphnia*, *Cyclops*, and other copepods dominates. This indicates good water mixing and minimal organic pollution. In low oxygen/hypoxic conditions, dominance of small, tolerant species like rotifers (*Brachionus*, *Keratella*) and small copepods occurs because many larger zooplankton species are sensitive to hypoxia and cannot survive in oxygen-depleted environments. Therefore, a simplified

zooplankton community dominated by tolerant species is a reliable indicator of hypoxic stress.

Salinity and temperature stress

Many plankton species are stenohaline or stenothermic, making them indicators of environmental changes such as climate warming or saline intrusion. In estuarine ecosystems, changes in salinity due to upstream freshwater withdrawal or tidal intrusion can be tracked through plankton shifts. Sudden warming events favor the growth of thermophilic cyanobacteria like *Microcystis* while reducing cold-water species such as certain diatoms and cladocerans. Prolonged temperature stress can alter seasonal succession patterns, leading to reduced biodiversity and food web instability. Tracking planktonic species over time provides valuable data on the effects of global warming and anthropogenic salinity changes on aquatic ecosystems.

Plankton diversity indices as ecosystem health metrics

Plankton diversity indices are widely used as reliable indicators of aquatic ecosystem health. The Shannon-Wiener index (H') measures overall diversity, with high values (>3.0) indicating a stable, healthy ecosystem and low values (<1.0) suggesting pollution or degradation. Margalef's richness index (d) reflects species richness, while Pielou's evenness index (J') indicates how evenly individuals are distributed among species, with values near 1.0 showing ecological balance. Simpson's dominance index (D) and the Berger-Parker index highlight dominance by a few species, which often occurs during algal blooms or under hypoxic conditions. For instance, eutrophication typically causes a single species to dominate, resulting in low H' and J' but high D , whereas diverse communities of plankton reflect good water quality. By combining these indices with water quality data such as nutrients, dissolved oxygen, and chlorophyll-a, managers can track ecosystem trends, identify stressors, and develop strategies for sustainable aquatic resource management.

Plankton based indices for biomonitoring

Diatom Index

The Diatom Index is a bioassessment tool that uses the species composition of diatoms (a major group of algae with silica cell walls) to evaluate the ecological quality of freshwater systems, particularly rivers and streams. This index was developed by assigning indicator values to various diatom species based on their sensitivity or tolerance to organic contamination and nutrient enrichment. Common indices are calculated by combining the abundance of each species with its pollution tolerance score. Diatom indices are used to detect changes in water quality over time, as they are highly sensitive to organic pollution, eutrophication, and pH shifts. These are applied in the European Union Water Framework Directive (WFD) monitoring. A high Diatom Index value, the dominance of sensitive diatoms, indicates clean water, and a low value indicates the dominance of tolerant diatoms, suggesting pollution.

Algal Genus Pollution Index (AGPI) Palmer 1969

The Algal Genus Pollution Index is a rapid assessment tool that uses the presence and abundance of algal genera to indicate the level of organic pollution in aquatic habitats. Algal genera are

grouped into classes based on their known pollution tolerance. Each genus is assigned a pollution index value. This index can be used for the quick screening of water bodies for organic pollution or eutrophication. And it requires only genus-level identification; hence, less taxonomic expertise is needed than species-based indices.

Challenges in plankton-based bioassessment

- Accurate identification of plankton requires taxonomic expertise, especially when dealing with cryptic species or juvenile forms that are difficult to distinguish.
- Plankton communities exhibit significant temporal and spatial fluctuations, necessitating regular and systematic sampling for reliable and representative assessments.
- Incorporation of plankton data into legal water quality monitoring and management frameworks remains limited, particularly in many developing countries.
- The absence of centralized, georeferenced databases hampers comparative analyses and the development of large-scale ecological models.

Recommendations and future directions

- Need to standardize protocols for plankton monitoring across regions to ensure consistency and comparability of data.
- Developing region-specific plankton indices can aid in accurate ecological classification and assessment of water bodies.
- Capacity building in taxonomy and microscopy should be promoted to enhance expertise.
- Use of AI and molecular tools can help democratize plankton assessments, making them more accessible and efficient.
- Integrating plankton data with water quality indices, fishery yield information, and remote sensing tools can provide a holistic evaluation of ecosystem health.

Conclusion

Plankton, though microscopic, are indispensable to aquatic ecosystem monitoring. Their high sensitivity, ecological relevance, and ease of study make them ideal bioindicators of water quality, trophic status, and environmental disturbances. As aquatic ecosystems face mounting anthropogenic and climatic stress, it becomes imperative to recognize and institutionalize the role of plankton in environmental monitoring frameworks. In embracing these tiny yet powerful organisms, we gain a dynamic and cost-effective lens to diagnose, predict, and manage ecosystem health, ensuring the resilience and sustainability of our invaluable water resources.

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