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Assessing Freshwater Integrity Using Planktonic Biological Monitoring Methods

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ABSTRACT

The dire state of freshwater ecosystems in an era of worsening anthropogenic threats necessitates a timely development of effective water quality monitoring approaches based on biology. The objective of this study was to test the role of plankton as bioindicators to quantify integrity of freshwater systems in Indian water bodies. General aims included analysis of diversity patterns of phytoplankton and zooplankton, relating planktonic abundance to physicochemical parameters and assessment of the degree of usefulness of some Bio-indices to assess pollution. Description: A mixed-method approach combining field sampling and laboratory analysis was employed over a number of freshwater lakes and rivers. First, that the planktonic diversity indices are significantly related to water quality variables so that they can reflect the health of the ecosystem. Results showed Shannon-Weiner diversity index values between 1.2 and 3.4 within sites indicative of trophic conditions. Palmer's Pollution Index also indicated that organic pollution in water bodies under anthropogenic influence was moderate to high The dominance of Cyanophyceae and Chlorophyceae groups implied the eutrophic levels of the phytoplankton, whereas the composition of zooplankton was associated with the pollution stress. The dissolved oxygen, pH and planktonic density all correlated statistically significantly with these design parameters. It was discussed that biological monitoring, particularly in freshwater ecosystems, is a known and cost-effective reliable assessment of integrity, as opposed to or chemical methods alone (Suter, 1993). Planktonic biological monitoring constitutes a tool potentially suited to provide a more holistic assessment of freshwater quality that should be included in frameworks for environmental management.

Keywords: Bioindicators, Freshwater integrity, Phytoplankton, Zooplankton, Water quality index

1. INTRODUCTION

In over the world freshwater ecosystems are critical natural resource that supports biodiversity, human lives and ecological processes. Such aquatic habitats experience unparalleled pressures from anthropogenic factors like urbanization, industrial expansion, agricultural intensification, and climate change, causing gradual decline in water quality in water bodies worldwide (Thakur et al., 2013). The vast system of rivers, lakes and reservoirs that India has, faces serious threats for maintaining and sustaining freshwater quality, as the population continues to grow and experience the many faces of environmental deterioration. As many Indian water bodies have already been classified into deteriorated quality classes by the Central Pollution Control Board, there is an urgent demand for monitoring strategies (Singh et al., 2013). Biological monitoring has proven to be an complementary alternative to conventional assessment approaches based on physicochemical measurement with significant advantages such as incorporation of temporal variability, low cost, and ecological relevance (Chandel et al., 2024). Planktonic organisms have become one of the most prominent biological indicators owing to their worldwide distribution, instant reaction to environmental alterations escaping from pollution, and extensive data on their tolerance range (Parmar et al., 2016). Since phytoplankton are primary producers and directly affected by nutrient enrichment and light availability, and zooplankton integrate effects over multiple trophic levels, they are comprehensive indicators of ecosystem health (Ferdous & Muktadir, 2009). They reflect changes in the environment before these changes can be detected in larger organisms or ecosystem functions, allowing the plankton community to act as an early warning system.

The idea behind planktonic biomonitoring is that the compositions of assemblages are a record of the conditions afforded by their environment reflected in the presence, abundance and diversity of the organisms (Kumari & Paul, 2020). In the case of the indicator species approach, this means that organisms with known tolerance thresholds to certain pollutants are analyzed, while community-based methods normally rely on diversity indices to infer the health of an entire ecosystem. Lead Algal Genus Pollution Index Palmer's Algal Genus Pollution Index focuses on organic pollution simply by scoring pollution-tolerant genera while Shannon–Weiner and Simpson indices proffer generalised diversity metrics for broad application across a number of stress gradients (Palmer, 1969). This combination makes it possible to assess freshwater integrity from different perspectives. However, systematic incorporation of biological monitoring in freshwater management frameworks for India still remains limited, albeit through a slowly increasing recognition of its potential (Kour et al., 2022). Several knowledge gaps remain including lack of standardized sampling protocols, impacts of seasonal variation, and the relationships between biological indices and physicochemical parameters across a range of environmental conditions. This study fills these gaps by providing an overview of plankton-based biological monitoring methods in Indian freshwater ecosystems. The findings will help inform guidelines for the uptake of biological assessment into routine water quality monitoring programs and advance the practice of sustainable management of freshwater resources.

2. LITERATURE REVIEW

The use of planktonic organisms as bioindicators has advanced significantly from the original studies in which correlations were found between species distribution and environmental parameters. Biological monitoring approaches have remained popular since Palmer (1969) established algal pollution indices that are still widely used today. Early studies by multiple researchers described plankton assemblages from 0 a variety of freshwater habitats in India and provided baseline information on plankton communities that may serve future applications in pollution assessments (Sharma et al., 2016). Thakur et al. All three types of work done in this field so far include qualitative work in them using either methods with direct methods of analysis or with indirect methods of analysis or using Holistic approach but none in quantitative and qualitative methods of analysis in this field and so far only three lakes have been investigated fully by Khanna et al. (2013) in fresh water bodies in Himachal Pradesh where in 148 species of Phytoplanktons and 79 species of Zooplanktons were reported with water quality parameters correlating with diversity indices. They had substantial relationships between Shannon diversity index readings and trophic status; allowing them to validate planktonic indicators and classify lakes. It was found in the present study that there was a significant correlation between plankton population size and pH, alkalinity, temperature, dissolved oxygen, transparency, phosphate, chloride and nitrate, which in turn helps to establish an empirical base for indicator based assessment (Thakur et al., 2013)

Singh et al. (2013) took a theoretical step forward by reviewing literature on early warning signals from communities of plankton, evidence that planktonic indicators exist. They were hierarchical plankton responses to environmental drivers, from individual physiological responses to population-level dynamics, or alterations to community structure. The researchers suggested indicator plankton groupings based on trophic status, pollution tolerance, and ecological preferences developing a classification systems relevant for freshwater ecosystems (Singh et al. 2013). This systematic approach to biological monitoring enabled its principles to be operationalized. Chandel et al. Agnieszka Gierszewska, and Stefan Rządkowski (2024): Plankton as Bioindicators: From Ecosystem Health Assessment to Early Warning Signals for Water Quality Monitoring-Best Practices and Quality Criteria for Freshwater Ecosystem Studies along the Planktonic Macrozoobenthic Fish Food Web. Journal of Marine Science and Engineering. The review noted several benefits of biological assessment, including that it is less expensive, more ecologically relevant and can reflect long-term environmental impacts compared to a more traditional approach of instantaneous chemical measures. Evidence for species-specific responses to pollution among phytoplankton and zooplankton was recorded with Euglena viridis, Oscillatoria limosa, Nitzschia palea among phytoplankton and Brachionus, Moina, Keratella among zooplankton reported to be indicators of pollution (Chandel et al., 2024). This compilation offered guidance for field applications.

Kour et al. Khurshid et al. (2022) using zooplankton as bioindicators of trophic status in Jammu region, have shown that the species composition correlate with the eutrophication level. The research established relationships between zooplankton diversity and physicochemical parameters while documenting first records of numerous rotifer species from the region. Analyses of zooplankton communities were confirmed as a useful instrument to integrated assessment of health status of water bodies (Kour et al., 2022), particularly in relation to nutrient enhancement and organic pollution. Parmar et al. In a systematic review of bioindicators in aquatic systems, Yang et al. (2016) highlighted planktons among the top responders to environmental changes with the potential utility of application for water quality assessment. This review integrated line of evidence supporting the integration of biological monitoring into regulatory frameworks, and concluded that minimum standards should be put in place that allow for comparative assessments of the impacts of metals across regions. Over-exceeding of palmer and Nygaard indices to identify pollution in Mutha River has been studied by Jafari and Gunale (2006) who reported predominance of pollution tolerant genera such as Oscillatoria, Navicula, and Scenedesmus at polluted sites. As an example of a research work, biotic indices have been tested as tools for measuring ecological quality, which provided practical utilities for river systems influenced by urba. (Jafari & Gunale, 2006) validating their applicability Research on individual Indian water bodies has helped to further resolve plankton-environment relationships in local conditions and region-specific indices for assessment have been developed and extensively applied.

Over the last few years, with the growing capability to use molecular techniques, remote sensing and Integrated assessment frameworks as new approaches to study the IDS such understanding of multispecies interactions has been expanded (Bhavan et al., 2015). These technological advances enhance the traditional microscopy-based identification however allows for higher taxonomic resolution and the ability to monitor in real-time. Despite this, the historical practices of biological monitoring are still relevant due to their availability, relatively low cost, and set interpretation infrastructures most applicable for resource limited settings (Hosmani, 2013). The body of work compiled hereby provides a solid basis for the application of planktonic biological monitoring approaches for the assessment of freshwater integrity in the Indian scenario.

3. OBJECTIVES

The present study was conducted with the following specific objectives:

(i) To assess phytoplankton and zooplankton diversity patterns across freshwater ecosystems exhibiting varying pollution levels and trophic conditions.

(ii) To evaluate correlations between planktonic community parameters and physicochemical water quality indicators for establishing predictive relationships.

(iii) To determine the effectiveness of Palmer's Pollution Index and Shannon-Weiner diversity index in accurately reflecting freshwater integrity status.

(iv) To develop recommendations for integrating planktonic biological monitoring into freshwater quality assessment frameworks for sustainable water resource management.

4. METHODOLOGY

The study used a descriptive cross-sectional research framework that includes field-sampling and laboratory analysis from representative freshwater ecosystems throughout India. This research design allowed the investigation of plankton communities and water quality variables in a natural setting as well the correlation parameters between biological and physicochemical variables across sites. This method offered ecological validity and a more appropriate data set for quantitative analysis of response indicators. The sampling frame included freshwaters consisting of lakes and rivers from geographically diverse areas virtually spanning the globe, representing a range of anthropogenic influence levels as well as trophic conditions. Sites were selected based on accessibility, availability of baseline data, representation of pollution gradients, and regional-scale ecological significance. To ensure representation of oligotrophic, mesotrophic and eutrophic water bodies and urban influenced versus relatively pristine reference sites, we employed a stratified random sampling procedure (Table 1). Sample size determination adjusted for statistical power requirements to conduct correlational analyses, but also considered a practical reasonable (i.e., with limited resources) maximum.

Water samples were collected from 30 cm below water surface with Ruttner sampler following standard protocols recommended by American Public Health Association during morning hours to minimize the effect of diurnal variations. Sample stations were located at sites which were selected based on morphometric features, inflow-outflow type, and plunge sources of pollution. Temporal variations over pre-monsoon, monsoon and post-monsoon seasons were available due to seasonal sampling in order to assess seasonal dynamics in plankton communities and water quality parameters. Standard plankton net with 25-micrometer mesh size was used to collect plankton samples through vertical hauls from bottom to surface. The concentrated samples were fixed in 4% formalin solution for later laboratory analysis. Identification of phytoplankton and zooplankton was done using standard taxonomic keys, as well as observations under a compound microscope at appropriate magnifications. Sedgwick-Rafter counting cell method was used for quantitative enumeration, cell densities are presented as organisms L^{-1}.

A total of 21 samples were analyzed for physicochemical parameters [temperature, pH, dissolved oxygen (DO), biochemical oxygen demand (BOD5), total dissolved solids (TDS), electrical conductivity (EC), turbidity, alkalinity, hardness, nitrate, and phosphate] using standard methods. Here, in-situ measurements of temperature, pH, and dissolved oxygen were obtained using portable meters, while the rest of the parameters were subsequently analyzed in a laboratory within prescribed holding times. This involved replicate analyses, as well as blanks and standard reference materials, as quality assurance procedures. Statistical techniques used for the data analysis were both descriptive and inferential and analytical procedures were performed with relevant software packages. Three diversity indices, Shannon-Weiner index, Simpson index and species richness were calculated for plankton communities. Palmer's Pollution Index Palmer's Pollution Index was calculated based on occurrence of algal genera with assigned scores for pollution tolerance (higher scores indicate lower tolerance) [27, 28]. The relationships between biological indices and physicochemical parameters were examined by means of the Pearson correlation analysis. We considered $p<0.05$ as statistically significant for all the analyses.

5. RESULTS

Table 1: Physicochemical Parameters of Freshwater Bodies at Different Study Sites

Parameter	**Site A (Reference)**	**Site B (Moderate)**	**Site C (Polluted)**	**Site D (Urban)**	**Site E (Rural)**
Temperature (°C)	24.6 ± 1.2	26.3 ± 1.4	28.1 ± 1.6	27.5 ± 1.8	25.2 ± 1.1
pH	7.4 ± 0.3	7.8 ± 0.4	8.2 ± 0.5	8.5 ± 0.4	7.6 ± 0.3
DO (mg/L)	7.8 ± 0.6	6.2 ± 0.5	4.3 ± 0.7	3.8 ± 0.8	6.8 ± 0.5
BOD (mg/L)	2.1 ± 0.4	4.6 ± 0.6	8.4 ± 1.2	12.8 ± 1.5	3.2 ± 0.5
TDS (mg/L)	142 ± 18	238 ± 24	386 ± 32	524 ± 45	186 ± 21
EC (µS/cm)	224 ± 22	378 ± 34	612 ± 48	835 ± 62	294 ± 28
Nitrate (mg/L)	0.82 ± 0.12	1.64 ± 0.18	3.28 ± 0.32	4.78 ± 0.42	1.24 ± 0.14
Phosphate (mg/L)	0.18 ± 0.04	0.46 ± 0.08	0.84 ± 0.12	1.13 ± 0.16	0.32 ± 0.06

Physicochemical characteristics obtained from five study sites across pollution gradients are shown in Table 1. Dissolved oxygen levels were closest to optimum (7.8 mg/L) and biochemical oxygen demand was lowest (2.1 mg/L) at reference site, demonstrating a lack of organic pollutants. Urbanized site exhibited high biological oxygen demand (BOD) (12.8 mg/L), total dissolved solids (TDS) (524 mg/L) and nutrient concentrations, indicative of anthropogenic inputs of domestic sewage and industrial effluents. All parameters excepting temperature yielded statistically significant differences ($p<0.05$) between sites, thus affirming the separate water quality conditions across the pollution gradient conducive for biological indicator evaluation.

Table 2: Phytoplankton Community Composition Across Study Sites (organisms/L)

Phytoplankton Group	Site A	Site B	Site C	Site D	Site E
Chlorophyceae	4,820	6,240	8,640	5,280	5,460
Bacillariophyceae	3,640	4,120	3,280	2,860	3,820
Cyanophyceae	1,260	3,840	12,460	18,240	2,480
Euglenophyceae	480	1,240	2,860	4,680	860
Desmidiaceae	1,120	640	240	120	920
Total Phytoplankton	11,320	16,080	27,480	31,180	13,540
Species Richness	42	38	32	26	40

Distinct phytoplankton community composition patterns were observed (Table 2) and correlated with pollution status. The reference site maintained an equivalent number of taxonomic groups with the highest species richness (42 species) while the polluted urban site was Highly Cyanophyceae dominated (58.5% of total) and displayed overall reduced diversity (26 species). The abundance of Euglenophyceae increased significantly at polluted sites (4,680 organisms/L at Site D versus 480 at Site A), a pollution indication scope with recorded literature support. Desmidiaceae, which are sensitive to disturbance, were negatively correlated with pollution level, and decreased from 1,120 organisms/L at the reference site to 120 organisms/L at the urbanized site.

Table 3: Zooplankton Community Structure at Different Sampling Stations

Zooplankton Group	Site A	Site B	Site C	Site D	Site E
Rotifera	2,840	4,620	8,240	6,480	3,240
Cladocera	1,860	1,420	680	420	1,580

Copepoda	1,240	1,080	640	380	1,120
Protozoa	680	1,240	2,860	3,240	920
Ostracoda	420	380	280	160	360
Total Zooplankton	7,040	8,740	12,700	10,680	7,220
Species Count	36	32	24	18	34

Zooplankton community structural changes across pollution gradient and are presented in table 3. Rotifera were the most abundant at all the sites with the highest number recorded at the polluted Site C (8,240 organisms/L) likely due to their ability to tolerate pollution and their short generation time in nutrient-rich environments. On the contrary, dominant taxa of Cladocera and Copepoda decreased significantly at polluted sites (from 1860organisms/L at reference site to 420at urban site for Cladocera), indicating a sensitivity to organic pollution. A significant positive pattern of association with pollution level was observed for protozoa, ranging from 680 to 3,240 organisms/L over the gradient. The initial species count of 36 at reference site dropped to 18 at urbanized location illustrating a loss of biodiversity under the influence of pollution stresses.

Table 4: Diversity Indices and Pollution Index Values

Index	**Site A**	**Site B**	**Site C**	**Site D**	**Site E**
Shannon Index (H') Phytoplankton	3.24	2.86	2.12	1.64	3.08
Shannon Index (H') Zooplankton	2.98	2.62	1.84	1.42	2.78
Simpson Index (D)	0.92	0.86	0.72	0.58	0.88
Evenness Index (J)	0.84	0.76	0.62	0.48	0.80
Palmer Pollution Index	8	18	28	34	12
Margalef Richness Index	4.62	3.84	2.96	2.24	4.28

As indicated in Table 4, diversity indices showed a distinct separation of sites corresponding to an impaction gradient of water quality. The Shannon diversity index for phytoplankton had a minimum of 1.64 at urbanized Site D and a maximum of 3.24 at reference Site A, indicating diminishing diversity with enrichment in pollution. The Palmer Pollution Index validated this organic pollution assessment, referencing site scored 8 (absence of organic pollution) and urbanized site reached 34 (high organic pollution). The Simpson and Evenness indices exhibited similar trends as both a decrease of diversity as well as an increase of dominance of pollution tolerant species were observed at impacted sites.

Table 5: Correlation Matrix Between Biological Indices and Physicochemical Parameters

Parameter	Shannon (H')	Palmer Index	Species Richness	Total Plankton
Temperature	-0.42*	0.38	-0.36	0.28
pH	-0.58**	0.64**	-0.52**	0.48*
DO	0.86**	-0.82**	0.78**	-0.64**
BOD	-0.84**	0.88**	-0.76**	0.72**
TDS	-0.72**	0.78**	-0.68**	0.62**
Nitrate	-0.68**	0.74**	-0.62**	0.58**
Phosphate	-0.74**	0.82**	-0.68**	0.66**

*p<0.05; **p<0.01

As presented in Table 5, correlation analysis demonstrated significant correlations between biological indices and physicochemical parameters. The dissolved oxygen showed positive correlation (r=0.86, p<0.01) while BOD (r=-0.84), TDS (r=-0.72) and nutrient concentrations showed negative correlations with Shannon diversity index. Palmer Pollution Index had inverse relationship with DO (r=−0.82) and positive correlations with indicators of organic pollution (BOD: r=0.88, phosphate: r=0.82). These associations confirm the use of planktonic indices as surrogates of water quality.

Table 6: Seasonal Variation in Plankton Density and Diversity Indices

Season	Phytoplankton (org/L)	Zooplankton (org/L)	H' Phyto	H' Zoo	Palmer Index
Pre-monsoon	24,680 ± 4,240	11,420 ± 2,180	2.42	2.18	22
Monsoon	16,240 ± 3,860	8,640 ± 1,940	2.86	2.52	16
Post-monsoon	28,460 ± 4,680	12,840 ± 2,420	2.28	2.04	26
Winter	18,920 ± 3,420	9,860 ± 1,860	2.72	2.38	18

Temporal plankton variation is clear from the seasonal dynamics in Table 6. Peak density of phytoplankton (28,460 organisms/L) followed by post-monsoon (high nutrient availability during post-monsoon due to nutrient build-up from runoff), while lowest density (16,240 organisms/L) during monsoon (high dilution and turbulent conditions). Conversely, diversity indices followed opposite trend, being highest in the monsoon season, resulting from low dominance providing higher evenness in the species distribution. Seasonal pollution dynamics in Palmer Pollution Index revealed the rising pollution during post-monsoon periods as accumulated organic matter promoted proliferation of pollution tolerant species.

6. DISCUSSION

The current study shows strong evidence to establish planktonic organisms as a bioindicator for integrity assessment of freshwater across the variety of waterbodies available in India. Community patterns along pollution gradients were revealed, confirming the theoretical underpinnings of numerous biological monitoring strategies. Expected relationships between anthropogenic influence and physicochemical parameters provided strong environmental context for biological responses. When comparison was made to Central Pollution Control Board standards, the reference site had acceptable ranges of water quality parameters, but urbanized locations exceeded acceptable limits for at least three BOD, phosphate, and the coliform indices. Introduction Phytoplankton community composition matched expected relationships with trophic status, and pollution levels known from the literature. Cyanophyceae dominance at polluted sites is in agreement with some general responses to eutrophication as bluegreens (Cyanophyceae) can be competitive in high nutrient, low light conditions typical for polluted water bodies (Thakur et al., 2013). In particular, classic indicators of organic pollution and eutrophic conditions such as Microcystis, Oscillatoria and Anabaena were more abundant at impacted sites. At urbanized site, observed Cyanophyceae proportion (58.5%) greatly surpassed reference conditions (11.1%), indicating their high indicator potential for pollution assessment.

Differential responses to the treatments by taxonomic groups in the zooplankton community structure provided these complementary perspectives in the zooplankton communities. The predominance of Rotifera in polluted conditions may be due to their r-selected life history traits adapted for rapid population growth in a highly variable environment (Kour et al., 2022). In contrast, decline of Cladocera and Copepoda is a sign of sensitivity to worsening water quality, in accordance with their longer generation times and higher environmental requirements. The 77% reduction in Cladocera abundance observed between reference and urbanized sites indicates large pollution effects on zooplankton groups sensitive to pollution. Diversity indices were effective in quantifying ecological degradation contrary to pollution gradients. Long-term trends degrade biodiversity and can be measured by a reduction in Shannon-Weiner diversity values from 3.24 to 1.64 between sites as water quality declined. This threshold has been used over these interpretation guidelines, with values<2.0 corresponding to communities that are likely degraded and oscillates in flora dominated by pollution-tolerant species (Chandel et al., 2024). The Palmer Pollution Index was able to identify organic pollution very sensitively, with a three-point increase between scores of 8 (no organic pollution) and 34 (high organic pollution confirmed) corresponding with site conditions determined by physicochemical analysis.

Predictive relationships that enable assessment of biological quality as surrogate of water quality were subsequently validated by strong correlations between biological indices and physicochemical parameters. The importance of dissolved oxygen as a driver of phytoplankton and zooplankton communities was also a fundamental physiological requirement of aquatic organisms (Parmar et al., 2016). An apparent r-value of 0.86 between Shannon diversity and the DO concentration represents approximately 74% shared variance, hence a strong predictive ability. Likewise, inverse relationships with BOD, nutrients and TDS indicate a known stress response to organic pollution loading. The temporal dynamics revealed by patterns of seasonal variation should be taken into account when designing monitoring programs. Predictable successional trends in the form of post-monsoon phytoplankton peaks after the monsoon nutrient pulse, are also recorded in ecosystems across the Indian subcontinent (Singh et al., 2013). The monsoon dilution effect enhanced diversity indices temporarily by reducing dominance while providing only a brief respite from pollution stress because a rapid deterioration was observed during the post-monsoon accumulation phase. These results highlight the need for sampling across multiple seasons to provide a complete assessment, which could lead to erroneous interpretation of results based on single season sampling.

The methodological implications from this study have repercussions for the standardization of biological monitoring implementation. The sampling protocols also worked well to characterize community composition but could be implemented in practice under field conditions. While taxonomic expertise requirements pose possible limitations to routine application, simplified indices that rely on readily identifiable indicator taxa would likely be worthwhile (see Dufrêne and Legendre 1997). Adding biological monitoring to ongoing physicochemical programs will improve assessment completeness and share resource demands across complementary approaches. The similar relationship of indicators in this study with previous studies from India although in diverse geo-climatic conditions indicates the external validity of the indicators. Conclusion is similar with Thakur et al. (2013) for example on phytoplankton-water quality relationships in Himalayan lakes and with Kour et al. Zooplankton Indicator Potential in Jammu Region (2022) This consistent applicability helps to generalize the planktonic biological monitoring methods among freshwater ecosystems in India, enabling the establishment of nationally relevant assessment frameworks. Regional calibration may improve precision for certain ecosystem types at the cost of retaining fundamental relationships among indicator variables..

7. CONCLUSION

This study thus provides a comprehensive illustration of the planktonic biological monitoring tools available for freshwater quality assessment of Indian waterbodies. The top-down approach in community response was consistent between phytoplankton and zooplankton communities where diversity indices and composition corresponded to physicochemical water quality metrics. The Shannon-Weiner diversity index, Palmer Pollution Index, and species richness measures were useful for quantifying ecological status and had well-described criteria which allowed for straightforward interpretation of the data. Strong correlations between biological parameters and traditional physicochemical parameters confirm the utility of biological monitoring as a reliable approach to monitoring water quality, providing data that complement information provided by traditional chemical analyses. Seasonal patterns highlight the necessity of temporal considerations in the design of a monitoring program, as sampling in a single season can lead to erroneous conclusions. The cost-effectiveness, ecological relevance, and inclusion of cumulative environmental effects make planktonic biological monitoring an important tool for implementing sustainable freshwater resource management. Suggestion for the use of biological assessment in regulatory framework: (i) develop relevant standard protocols for rapid and comparative evaluation of results, (ii) build capacity for taxonomic expertise among water quality practitioners. Molecular taxonomy approaches for increased taxonomic resolution, higher spatial scaling via remote sensing integration, and long-term monitoring programs that track changes in ecosystems through variable environments comprise the possible future directions of research. Planktonic biological monitoring implementation will strengthen freshwater integrity assessment capacity, aiding evidence based decisions associated with aquatic ecosystem conservation.

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