



## Using aquatic plants as bioindicators for ecosystem monitoring and water quality assessment

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### Abstract

Aquatic plants are essential indicators of the environmental health of aquatic systems because of their sensitivity and vulnerability. They are also helpful for evaluating water quality in aquatic systems. This research examined the use of macrophytes and phytoplankton as biological indicators of differences in nutrient concentrations, heavy metals, and organic contaminants in freshwater and coastal ecosystems. Evaluating aquatic vegetation provides indications of eutrophication, pollution, and habitat changes through species composition, abundance, and physiological response. This study incorporates biological indicators with laboratory analysis of physicochemical water samples to determine how aquatic plant indicators relate to dissolved oxygen, pH, turbidity, and nutrient concentration. This study emphasizes the need to identify aquatic plant indicators that exhibit variability, as this aspect could have important implications for ecosystem monitoring. Investigation revealed that particular aquatic plant species exhibited morphological and biochemical variation under pollution-stress conditions, including *Eichhornia crassipes* (water hyacinth) and *Lemna minor* (duckweed). The study highlights the potential of aquatic plants and their indicators as inexpensive, sustainable, and ecologically relevant biological indicators, enabling long-term environmental monitoring and resource management. Finally, the use of aquatic plant-based biological indicators provides a means of ecosystem monitoring. Still, it has potential implications for environmental policy development and spatially and temporally based conservation efforts that maintain water quality and biodiversity in aquatic ecosystems.

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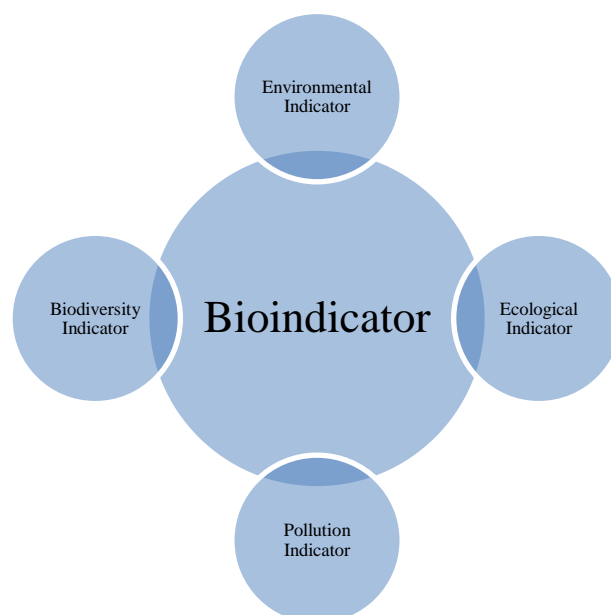
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## Introduction

Bioindicators are living organisms whose presence, distribution, and physiological functions in a living body indicate the health and quality of the ecological environment. They provide an integrative indicator of ecosystem transformation driven by natural changes or human activities. Bioindicators are vital tools in aquatic systems for identifying contaminants, eutrophication, and ecological imbalances before these problems are readily detectable in chemical analyses. The advantage of bioindicators is that they are multi-stressor and accumulate pollutants, and they show long-term trends in an ecosystem that can be missed in traditional physicochemical analysis (Adams and Greeley, 2000). Aquatic bioindicators (such as microorganisms and macroinvertebrates) or plants at the macrolevel of biology are biological sentinels that mediate the relationship between laboratory and actual ecological effects. Their application complements environmental monitoring initiatives by providing continuous, cost-effective, and ecologically significant information in areas where industrial, agricultural, and urban activities have put pressure on water resources (Iliopoulou-Georgudaki *et al.*, 2003; Manjunath *et al.*, 2025).

Submerged, emergent, and floating macrophytes are the most effective

bioindicators because they are stationary, have broad distributions, and can accumulate nutrients and toxic metals from water and sediments. The species *Eichhornia crassipes*, *Lemna minor*, and *Ceratophyllum demersum* exhibit specific physiological and morphological responses to pollutants, including chlorosis, decreased biomass, and alterations in pigment concentration (Ansari *et al.*, 2017). These plants are indicative of local water conditions and provide a good understanding of nutrient dynamics, heavy metal contamination, and organic pollution (Sređić, Knežević and Milunović, 2024). The value of seagrasses and freshwater macrophytes was highlighted by Ferrat, Pergent-Martini and Roméo (2003) as effective bioindicators, particularly for biomarker analysis, including the determination of oxidative stress and changes in enzyme activity induced by xenobiotics. Equally, (Kurilenko and Osmolovskaya, 2007) found that increased aquatic vegetation can assess water quality in small water bodies through patterns of metal accumulation and growth parameters. In addition, aquatic vegetation is a component of biogeochemical cycles. It serves dual purposes in bioindication and bioremediation, providing not only indicator functions but also supporting the removal of pollutants and the restoration of the biosphere (Petrov *et al.*, 2023).



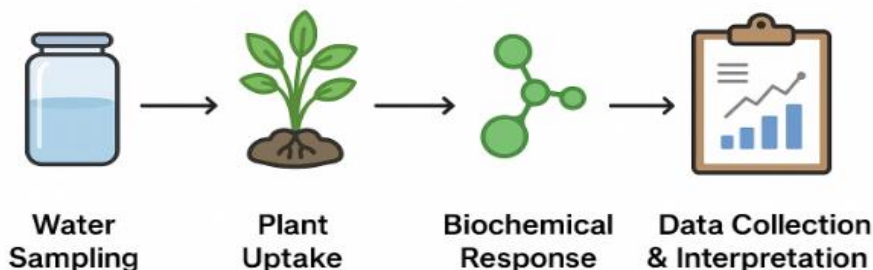
**Figure 1(a): Conceptual classification of bioindicators in ecosystem monitoring.**

The figure (Figure 1(a)) shows the multidimensionality of bioindicators, which are classified into four broad categories: environmental, ecological, pollution, and biodiversity indicators. All the categories are considered to be a particular functional area of ecosystem monitoring: environmental indicators measure the state of habitat and climatic variability, ecological indicators detect the condition of the community structure and species interaction, pollution indicators reveal the existence and the level of contaminants, and biodiversity indicators determine the level of species richness and habitat integrity. The combination of these interrelated areas provides an ecological framework for assessing the health of an ecosystem. In aquatic environments, knowledge of these indicators provides a basis for using aquatic plants as composite bioindicators to detect the dynamics of water quality, nutrient loading, and the effects of pollution in freshwater and coastal ecosystems.

This research paper discusses aquatic plants as bioindicators that can be used to monitor a given ecosystem and water quality, specifically their ability to detect pollution gradients, the accumulation of harmful toxins, and environmental disturbance in aquatic ecosystems. To date, the literature outlines this study's intended comparative experience involving selected aquatic plant species—their potential sensitivity, specificity, and reliability as environmental stress indicators (Manzoor *et al.*, 2021). Moreover, the study aims to incorporate biological and physicochemical methods to provide a comprehensive view of the health of aquatic ecosystems. The paper aims to develop a sustainable method of environmental monitoring by measuring macrophyte diversity, physiological responses, and pollutant absorption. The methodology is consistent with recent trends toward promoting nature-based approaches to water quality worldwide (Zaghloul *et al.*, 2020). Finally, the results are intended to inform policymakers, ecologists, and

environmental managers in adopting plant-based bioindication as a viable,

eco-friendly tool to ensure the integrity of the aquatic ecosystem.



**Figure 1(b): Framework architecture for aquatic plant-based water quality assessment.**

This figure (Figure 1(b)) portrays the fluid process of the proposed framework for aquatic plants-based water quality assessment, which is organized into a series of four stages: 1) water sampling, 2) plant uptake, 3) biochemical response, and 4) tracking of plant responses and interpretation of results. In the first stage, water samples are collected at the location of interest to identify water that may contain chemicals, heavy metals, and nutrients. In the second stage, aquatic plants take up chemicals via roots and/or leaves; therefore, biochemical responses can be measured, including pigments, enzyme activities, and/or heavy metal accumulation. The physiological and biochemical indicators will then be measured and assessed through laboratory analyses and sensors in stage three. Within the stage four timely aspect, either computationally or statistically interpreting data can signal water quality assessment, both of which are dependable plant-based biomonitoring methods that may suggest ecosystem health.

This paper is structured to help readers understand how aquatic plants can serve as bioindicators of water quality and ecosystem health. After the introductory section that establishes background, significance, and intent, section two

discusses the bioindicator role of aquatic plants, establishes a connection to water quality indicators, and outlines the top biological characteristics and species examples used. Section III discusses approaches to collect, analyze, and interpret bioindicator reaction, proposed models for application, and proposes mathematical expressions to improve assessment. Section IV identified examples of the use of aquatic plants for monitoring nutrient conditions, contamination, and biological monitoring, supported by quantitative measures presented in graphical formats. Finally, Section V wraps up the paper with a summary of the significant findings, their relevance to environmental management, and future research ideas that could contribute to the inclusion of aquatic vegetation as a measurement in biomonitoring systems. These sections are grouped to provide a logical progression from theoretical understanding to operational use, maintaining a consistent structure that allows for uninterrupted, aligned conclusions in evaluations.

### **Role of Aquatic Plants as Bioindicators**

Water plants are also very close to and dynamic within the water environment in

which they inhabit; therefore, they are considered good indicators of ecological health. Nutrient levels, pH, dissolved oxygen, and the presence of contaminants such as heavy metals or pesticides affect their growth, distribution, and physiological performance. Since organisms are rooted and continually exposed to sediments and water, macrophytes reflect the outcomes of both short-term and chronic pollution incidents (Oertel and Salánki, 2003). The mass of certain nutrients, such as nitrogen and phosphorus, directly influences the growth of aquatic vegetation, which, in turn, controls oxygen exchange and habitat. When nutrient loading is high, eutrophication increases algal blooms, alters plant community composition, and decreases biodiversity (Desrosiers *et al.*, 2013). Surveillance of such changes in aquatic plant assemblages therefore provides an early warning of water-quality degradation.

Additionally, the bioaccumulation of trace elements in plant tissues can be used for long-term monitoring of contamination trends, reflecting the stability and movement of pollutants in aquatic environments (Polechońska and Klink, 2023). Aquatic plants are among the best bioindicator candidates due to several biological and ecological characteristics. One, they are sedentary and can therefore reflect the local environmental conditions with high precision. Secondly, it allows for the observation of morphological, physiological, and biochemical changes in aquatic plants exposed to pollutants, including chlorophyll degradation, reduced biomass, and altered enzymatic activities (Parmar, Rawtani and Agrawal,

2016). Third, the ecological tolerance ranges of many species are very broad, allowing them to be compared with pollution gradients and habitat types. It was noted that macrophytes exhibit consistent responses to changes in light, temperature, and nutrient levels (Madsen and Wersal, 2017), making them useful for classifying water quality. Also, aquatic flora stores organic and inorganic contaminants in its tissues and serves as passive biomarkers of heavy metals, nutrients, and toxicants, without the need to sample them regularly. They have a high bioaccumulation capacity and species-specific tolerance limits, which allow them to detect sub-lethal concentrations of contamination that may otherwise go undetected by chemical tests (Barinova, 2017). All these qualities together render aquatic plants not only sensitive but also reliable and consistent indicators of environmental change, making them appropriate for both freshwater and coastal monitoring efforts.

Many marine flora species have been identified as useful for water quality assessment. Enrichment and contamination with heavy metals in the nutrient are commonly monitored using submerged macrophytes such as *Ceratophyllum demersum*, *Potamogeton crispus*, and *Myriophyllum spicatum* (Testi *et al.*, 2009). *Lemna minor* (duckweed) and *Eichhornia crassipes* (water hyacinth) are floating plants that serve as useful bioindicators for monitoring organic pollution and metal accumulation, given their rapid growth and surface exposure (Martinez-Haro *et al.*, 2015). Emerging species such as *Typha latifolia* (cattail) and *Phragmites*

australis (common reed) have been studied because they absorb and store pollutants of sediments and water using a large network of roots (Oertel and Salánki, 2003; Desrosiers *et al.*, 2013) noted that even microscopic plant-like organisms, such as benthic diatoms, can serve as effective bioindicators for distinguishing between oligotrophic and eutrophic environments in marine and estuarine ecosystems. The high level of their usage highlights their ecological significance and diagnostic value in summarizing alterations in water chemistry and habitat quality. Integrating macrophyte-based indices and chemical analyses helps researchers obtain an ecologically based assessment of the status of aquatic ecosystems.

### Methods for Using Aquatic Plants as Bioindicators

#### *Sampling Techniques for Collecting Aquatic Plants*

The step in which aquatic plants are used as bioindicators begins with systematic, standardized sampling to ensure credible findings. Sampling is usually carried out at representative locations with varying degrees of pollution, such as upstream, midstream, and downstream locations of

a water body. The spatial distribution of aquatic vegetation is mapped using transect lines or quadrat methods in the littoral zone. Different instruments are used depending on the type of plant: submerged, floating, or emergent. These include grapnels, hand nets, or core samplers. Submerged macrophytes, such as *Ceratophyllum demersum*, are harvested by root lifting to maintain roots and sediments attached.

In contrast, floating plants, such as *Lemna minor*, are harvested with small-mesh nets to avoid tissue damage. Samples are placed in numbered polyethylene bags containing a small amount of native water to maintain their physiological state during transport. Depending on the monitoring goals, the sampling frequency may be as low as monthly or seasonal. Sampling of each species is done at several locations within a site and at similar depths to minimize the effects of variability. Collected plants are then washed with distilled water to remove any attached debris or life, and then analyzed. This standardization will ensure results reflect real pollutant bioaccumulation and physiological responses, rather than artifacts of sampling error or contamination.



**Figure 2: Process flow diagram of aquatic plant bioindicator monitoring and analysis.**

This figure (Figure 2) depicts the series of methodological processes used within this research. The methods can be divided into four central steps: sampling, parameter measurement, data modeling, and performance assessment. The first step is to collect samples. Aquatic plants

are collected from water bodies selected for study. Each imagery bathing event occurs under controlled conditions, ensuring that each water sample conforms to the environmental conditions. The second step is to measurement parameters. At this point

we have measurable parameters that quantify the physicochemical and biological variables e.g., nutrient concentration, chlorophyll concentration and bioaccumulation of contaminants. The third stage is data modeling; you can now take the parameters you measured and statistically and computationally correlate them to plant responses to the water quality parameters. Finally, performance assessment evaluates the reliability and predictive efficiency of bioindicators and their suitability to be used for continuous water quality monitoring or decision making related to aquatic ecosystem health.

#### *Analysis Methods to Measure Bioindicators responses*

Aquatic plants will be subjected to a series of physicochemical and biochemical analyses, which will determine the uptake of pollutants and characterize signs of physiological stress. The first analysis performed will be to assess heavy metals in plant tissue by either atomic absorption spectrophotometry AAS or inductively coupled plasma mass spectrometry, ICP-MS. All samples will be dried in an oven, homogenized with a coffee grinder, and digested with either an HNO<sub>3</sub> + HClO<sub>4</sub> acid combination before the analysis. The concentrations for the metals, e. g., Cd, Pb, Cu, Zn will be determined using the following equations:

$$C_p = \frac{A_s - A_b}{S} \quad (1)$$

Where  $C_p$  = concentration of the pollutant in plant tissue (mg/kg)  $A_s$  = sample absorbance,  $A_b$  = blank absorbance, and  $S$  = slope of the calibration curve. In addition to metals, physiological indicators will also be

determined, such as chlorophyll content, activity of antioxidant enzymes (catalase, peroxidase, and superoxide dismutase), and levels of lipid peroxidation. Chlorophyll will typically be extracted in 80% acetone and quantified at 645 nm and 663 nm via spectrophotometric methods using Arnon's equation:

$$Chl_a + Chl_b = (20.2 \times A_{645}) + (8.02 \times A_{663}) \quad (2)$$

These biochemical indicators will broadly help quantify the magnitude of oxidative stress from exposure to the pollutant, and associated changes to photosynthetic efficiency. Subsequently, we will propose to develop a mathematical model for which to represent the bioindicator efficiency index (BEI) using multiple parameters:

$$BEI = \frac{(W_m + E_r + C_c)}{3} \quad (3)$$

Where  $W_m$  refers to weighted mean metal accumulation,  $E_r$  is the enzymatic response ratio,  $C_c$  represents the change in chlorophyll concentrations compared to control plants. This composite index will allow us to compare pollution intensity across different locations.

#### *Interpretation of Data Collected from Aquatic Plants*

Biological and chemical data are associated with environmental parameters such as elements of pH, conductivity, and nutrient concentrations during the interpretation phase. Also, the relationships can be clarified by applying statistical methods like Principal Component Analysis (PCA) and Analysis of Variance (ANOVA) to combine or analyze these relationships during this phase. The analysis and responses of the listed aquatic plants can

clarify some distribution patterns of pollutants by sensitivity of plant species being investigated. Then, a predictive algorithm can be developed, referred to as Adaptive Bioindicator Response Algorithm (ABRA) for dynamic water quality assessments. Ultimately, the algorithm uses all the parameters measured, normalized, and assigned weightings determined by the toxicity of pollutants. The bioindicator score is calculated as follows:

$$ABRA = \sum_{i=1}^n w_i \left( \frac{R_i - R_{min}}{R_{max} - R_{min}} \right) \quad (4)$$

where  $R_i$  is recorded value of response to a measurable parameter  $i$ ,  $w_i$  is the assigned weight of that parameter, and  $R_{min}$  and  $R_{max}$  are the minimum and maximum values observed. High scores are indicative of greater environmental stress. Using these computational and statistical frameworks, scientists can produce spatial and temporal pollution maps highlighting hotspots of pollution and ecological harm. In this way, "to observe," "to weigh," and "to model" can be viewed as an integration scheme for using aquatic plants as sensitive, integrated bioindicators of freshwater and marine ecosystems.

### Applications of Aquatic Plants as Bioindicators

#### *Monitoring of nutrient levels in water bodies*

Aquatic plants are effective natural sensors of nutrient enrichment, particularly, nitrogen and phosphorus, which are the major motivators of eutrophication. Plant tissues contain the nutrients at the rate they are dissolved in the surrounding waters. Quantitative

determination is done by wet digestion and spectrophotometric or colorimetric determination. The Nutrient Uptake Efficiency (NUE) may be defined as:

$$NUE = \frac{(N_t - N_c)}{N_c} \times 100 \quad (5)$$

$N_t$  is the total amount of nitrogen uptaken by the plant and  $N_c$  is the control concentration of nitrogen. When values of NUE are high, it means that the nutrient loading is too high and can result in algal blossoms and oxygen depletion. Visualization of nutrient trends and regression modeling are done using analytical tools like R, MATLAB and OriginPro that aid in predicting the threat of eutrophication in aquatic environments.

#### *Conflict of Contaminants and Pollutants*

The aquatic macrophytes are highly efficient in accumulating heavy metals, pesticides, and hydrocarbons and hence would be suitable in environment detection of toxic substances. The uptake and internal mobility of the contaminants are measured by the performance metrics, including Bioaccumulation Factor (BAF) and Translocation Factor (TF). These are calculated as:

$$BAF = \frac{C_{plant}}{C_{water}} \quad (6)$$

$$TF = \frac{C_{shoot}}{C_{root}} \quad (7)$$

And  $C_{plant}$ ,  $C_{water}$ ,  $C_{shoot}$  and  $C_{root}$  are concentrations in respective compartments. Any value above one means that it is highly bioaccumulative. Softwares such as ArcGIS and SPSS are used in spatial mapping and statistical correlation of contaminant data at different sites.

### Determination of Ecosystem Health and Biodiversity

In addition to the pollutants, the aquatic plants are used to monitor the stability and bio-diversity of the ecosystem. The Ecological Integrity Index (EII) is

calculated by adding the species richness (S), evenness (E) and pollution tolerance (P):

$$EII = \frac{S \times E}{P} \quad (8)$$

### Performance Evaluation

**Table 1: Performance evaluation metrics for aquatic plant-based bioindication systems.**

Metric	Description	Ideal Range	Tool Used
NUE (%)	Nutrient uptake efficiency	20–60	MATLAB
BAF	Metal accumulation capacity	>1.0	OriginPro
TF	Contaminant mobility index	0.5–1.5	SPSS
EII	Ecosystem health indicator	>0.7	R Studio

Table 1 summarizes the key performance measures applied to assess the effectiveness of aquatic plants in the assessment of water quality and ecosystem monitoring. The table highlights four performance values: nutrient uptake efficiency (NUE), bioaccumulation factor (BAF), translocation factor (TF), and ecological integrity index (EII) including descriptions of the listed performance indicators, optimal value range and other details. Together, these performance parameters provide a quantitative framework by which related aquatic plant efficiency levels in responding to

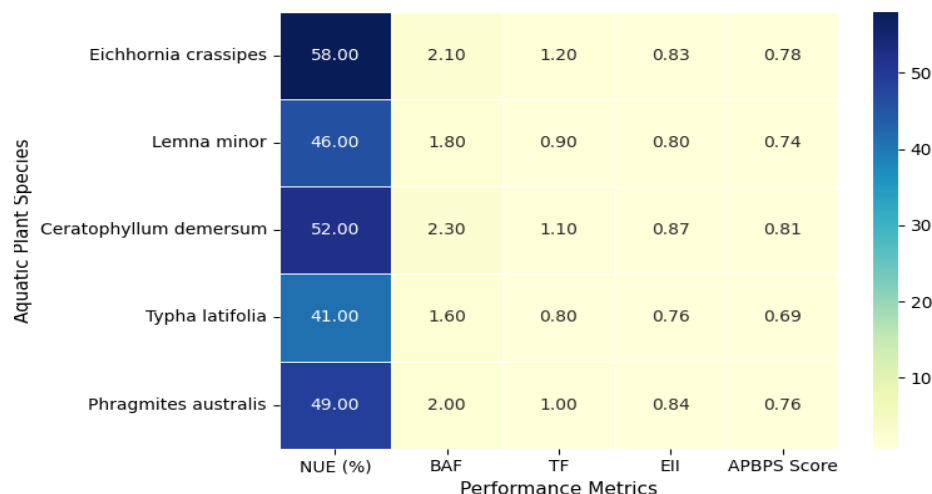
changes in nutrients, retaining pollutants, or reflecting general ecological stability are indicated.

These indices are summed together to form an overall performance evaluation of aquatic plants to produce a composite Aquatic Plant Bioindicator Performance Score (APBPS):

$$APBPS = \frac{(NUE + BAF + TF + EII)}{4} \quad (9)$$

A greater score than 0.75 indicates that there is a very strong bioindication system that can effectively depict the quality of water and the health of the ecosystem.

**Heatmap of Aquatic Plant Bioindicator Performance**



**Figure 3: Heatmap of aquatic plant bioindicator performance.**

The heatmap (Figure 3) shows how five aquatic plant species, namely

Eichhornia crassipes, Lemna minor, Ceratophyllum demersum, Typha

latifolia, and Phragmites australis, performed when subjected to five primary bioindicator parameters, which include Nutrient Uptake Efficiency (NUE) and Bioaccumulation Factor (BAF) and Translocation Factor (TF) and Ecological Index (EII) as well as the Aquatic Plant Bioindicator Performance Score (APBPS). The intensity of the color of each cell is an indicator of the relative strength of the performance of a plant at that metric, with a darker color meaning more efficiency or bioindicator capability. The prescriptive form has identified the species Ceratophyllum demersum and Eichhornia crassipes as the two most effective species, being more capable of removing nutrients through absorption, pollutant accumulation, and translocation. The graphical display, including abundance indices, gives a data-based understanding of the ecological sensitivity of the various aquatic vegetation categories so that researchers can establish and determine which aquatic vegetation species can determine nutrient enrichment, heavy metal contaminations, and health within the ecosystem in freshwater systems.

### Conclusion

The study points out the relevance of using aquatic plants as useful bioindicators to assess aquatic systems and ecosystem viability. Physiological and biochemical responses of aquatic plant species such as Eichhornia crassipes, Ceratophyllum demersum, and Lemna minor demonstrate changes in nutrient levels, pollutant accumulation, and ecological viability. This study suggests the potential of these species to not only indicator contamination indicators, but also nature's remediation

strategy by accumulating and sequestering heavy metals and excessive nutrients with results showing implications for using plants remineralization to improve overall ecological remediation. Performance measurements or indicators such as Nutrient Uptake Efficiency, Bioaccumulation Factor, and Ecological Integrity Index provides a way to contextualize the additional value for calculating the indicator capacity of these aquatic plants. Future investigations could renew biodiversity and biomonitoring modeling using newer molecular examinations and remote sensing technologies to improve landscape fertility sub-models for aquatic systems to provide precise quantification of ecosystem response characteristics across temporally or spatially resolved landscapes. Executing species specificity assessments of tolerance capacity to water quality stressors is especially critical to validate estimates of recovery mechanisms from pollution-induced stress to improve prediction models for future impairment, or pollution threats in aquatic environments. Furthermore, the biodiversity monitoring and evaluation of aquatic plants is necessary, in that most aquatic plants are sentinel species, inhabit, and stabilize ecosystem viability, thus sustaining aquatic structures positively impacted by anthropogenic disturbances and hydrological change.

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