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Application of Algae Biomarkers in Water Quality Monitoring

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Abstract The widespread application of algal bioindicators in water quality monitoring is a current research focus. Its application not only provides a profound understanding of aquatic health but also offers valuable insights for the future development of water quality monitoring systems. The combination of laboratory research and field monitoring provides reliable data support for the practical application of algal bioindicators. Differences in the application of algae in various water types highlight their flexibility and adaptability in water quality monitoring. The future prospects of algal bioindicators in water quality monitoring will be driven by technological innovations, big data, and artificial intelligence. This review comprehensively elucidates the importance of algae as bioindicators in water quality monitoring and their practical significance. By analyzing the response mechanisms of algae to pollutants, their applications in different water types, and future directions, the critical role of algae in water quality monitoring is revealed. This provides a comprehensive perspective for better understanding changes in water quality, enhancing the accuracy and comprehensiveness of monitoring.
Keywords Algae; Water quality monitoring; Bioindicators; Ecological adaptability; Practical application

Global water quality issues have prompted urgent concerns worldwide regarding water quality monitoring. With the continuous degradation of the environment, the health of aquatic ecosystems is facing unprecedented threats, particularly the reduction in benthic biodiversity. The urgency of this issue has become a global consensus, driving continuous innovation and improvement in water quality monitoring methods. As primary producers in aquatic ecosystems, algae play a key role in maintaining aquatic ecological balance. Through photosynthesis, they convert sunlight energy into organic matter, providing an energy source for the entire ecosystem. The species and quantity of algae regulate important processes in water, such as nutrient cycling and oxygen production.

The structure of algal communities in water directly influences the stability of the entire aquatic ecosystem. Different types of algae play distinct roles in the water, including oxygen release and the food source for benthic organisms (Hu, 2023). Therefore, the richness and diversity of algae serve as important indicators of aquatic ecosystem health. Algae are highly sensitive to changes in water quality, exhibiting early responses to environmental changes. Their ecological adaptability and diversity make them ideal biological indicators, offering comprehensive information for water quality monitoring. By monitoring the structure and composition of algal communities, researchers can detect problems in water bodies early on, such as eutrophication and pollutant input.

As one of the dominant organisms in aquatic ecosystems, algae play a crucial role in the overall balance of water ecosystems. Their position in the food chain and regulation of nutrient cycling make them ideal biological indicators (Mohsenpour et al., 2021). Traditional water quality monitoring methods often focus too much on specific indicators, making it challenging to comprehensively and dynamically reflect the condition of water bodies. Faced with new environmental challenges and the need for water management, water industry professionals urgently require more comprehensive and efficient water quality monitoring methods to better guide the sustainable use and protection of water resources. Through monitoring algal communities, researchers can gain a more comprehensive understanding of the health of water bodies while providing insights into other biological communities and the entire aquatic ecosystem.

In order to better address global water quality issues, this review aims to conduct in-depth research on the application of algae as biomarkers in water quality monitoring, providing more effective methods and theoretical support for global water quality monitoring, and promoting the protection and restoration of water ecological balance. By exploring the critical ecological roles of algae in aquatic ecosystems, their potential value as biological indicators, and analyzing the challenges and needs in current water quality monitoring, researchers will further scrutinize the shortcomings of existing monitoring methods and advocate for the application of emerging technologies to meet the demand for more comprehensive water quality data.

1 Classification and Characteristics of Algal Biological Indicators

1.1 Classification of algae

Ecological features are crucial for the classification of algae. Algae with various habitat adaptations thrive in different types of water bodies. Taking diatoms as an example, they construct their outer shells using silicates and are therefore relatively abundant in waters rich in silicates. In freshwater systems, green algae (Chlorophyta) may dominate, while in saline lakes, Dunaliella salina, a type of salt algae, may be more common. Studies on functional groups reveal the specific ecological roles of different algae in ecosystems, such as the key role of diatoms in the silicon cycle.

Morphology and genetics are the two main pillars of algal classification. Morphologically, algae can be classified based on cell shape, size, and structure. For instance, dinoflagellates, with their flagellated cell structure (Figure 1), exhibit significant differences from diatoms. With the advancement of molecular biology techniques, particularly the application of DNA sequencing, researchers can more accurately reveal the phylogenetic relationships among algae. For example, by comparing the sequences of specific genes, researchers can determine the phylogenetic relationships of some microalgae, providing a foundation for their more precise classification.

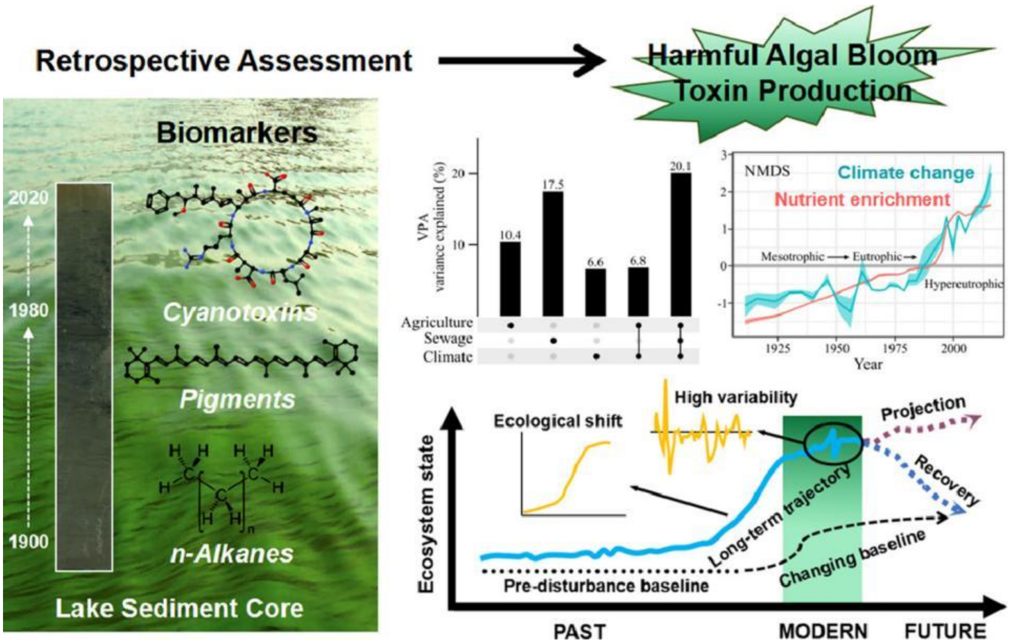

Figure 1 The hazards of algal blooms (Lin et al., 2023)

The spatiotemporal dynamics of algal communities are crucial for their classification and ecological studies. Regarding seasonal variations, some algae, such as diatoms, may proliferate significantly in spring and gradually decrease in summer. The spatiotemporal distribution characteristics of algae in different water bodies also show considerable variability. For example, certain euglenoids may be more abundant in rivers rich in organic matter, while they may be rare in clear lakes. The response mechanisms of algal communities to external pressures are also part of the classification, as some algae may exhibit different adaptations to pollutants or temperature changes.

1.2 Characteristics of algal bioindicators

The ecological adaptability of algae to environmental changes largely determines their value in water quality monitoring. Taking diatoms as an example, this group of algae exhibits robust adaptability and can thrive in various water bodies. For instance, the diatom Nitzschia palea is more adapted to environments rich in silicate, making it more common in lakes and rivers with high silicate concentrations. Its abundance and distribution changes serve as environmental indicator organisms, reflecting fluctuations in water silicate content and indicating the degree of eutrophication in the water. The sensitivity of different algal groups to water health indicators also provides detailed information for water quality monitoring. For example, Chlorophyta is sensitive to nutrients such as nitrogen and phosphorus in water quality, and its abundance changes can be related to the degree of eutrophication in the water body.

The biological characteristics of algae directly relate to their applications in water quality monitoring. The growth rate of algae is a crucial indicator directly related to nutrient content in the water. Taking Cyanobacteria as an example, their growth rate is significantly influenced by nutrients such as nitrogen and phosphorus. Therefore, by monitoring the growth of Cyanobacteria, researchers can promptly detect issues related to nutrient excess in the water.

Additionally, the indicator role of algal community structure in indicating water eutrophication is also a subject of considerable attention. In freshwater lakes, the decrease in diatoms may be associated with phosphorus-rich conditions in the water. Some algae, such as phytoplankton, which are sensitive to organic loads, can serve as indicator organisms in water quality monitoring, reflecting changes in organic content in the water.

However, the application of algal bioindicators in complex water bodies faces challenges. The diversity of complex habitat conditions, physical and chemical parameters, and the interactive effects of different algal groups make accurate classification and interpretation of algal communities complex. Therefore, in practical applications, personnel need to consider multiple indicators to comprehensively assess the ecological condition of the water.

1.3 Relationship between algal communities and aquatic ecosystem health

The structure and composition of algal communities have profound effects on the health of aquatic ecosystems, constituting a complex and subtle relationship within freshwater ecosystems. In-depth research into how different algal communities reflect the health of water bodies and their roles in maintaining ecological balance and functionality is crucial for effective water quality monitoring and the protection of aquatic ecosystems. This enhanced understanding of the relationship between algal communities and aquatic health provides a foundation and support for scientific water quality monitoring and water management.

The composition and structure of algal communities are directly linked to the transparency of water bodies. Transparency refers to the degree to which light passes through the water, which is vital for the growth and development of aquatic plants. Some diatoms, such as the genus Tabellaria, are often associated with better water quality conditions. They possess strong sedimentation capabilities for suspended particles in the water, helping to maintain water transparency and providing a more suitable growth environment for benthic plants. Additionally, changes in algal communities serve as a significant indicator of water eutrophication. In nutrient-rich waters, cyanobacteria often proliferate excessively, forming cyanobacterial blooms (Li et al., 2023). Algae in these blooms may produce toxins, posing a threat to the ecological balance of water bodies and aquatic organisms (Figure 1). Nutrient enrichment issues in water bodies are often associated with factors such as agricultural runoff and urban sewage discharge. Therefore, by monitoring the structure of algal communities, potential eutrophication problems in water bodies can be detected and addressed in advance.

In addition, algal communities have a direct impact on ecosystem services such as oxygen production and organic matter decomposition in water bodies. Some algae generate oxygen through photosynthesis, serving as a source of oxygen for the aquatic environment. Simultaneously, other algae contribute to the cycling of organic matter by decomposing organic substances in water bodies. The changes in the structure of different algal communities also exhibit a synergistic relationship with water body health. For instance, during the ecosystem restoration phase, the gradual increase in diatoms may indicate improved water transparency and an increase in the abundance of benthic plants. This positive interaction contributes to the recovery and stability of aquatic ecosystems.

2 Ecological Adaptability of Algal Biomarkers

2.1 Response mechanism of algae to pollutants

Algae exhibit diverse response mechanisms when affected by pollutants, providing key clues for the assessment of water pollution levels (Li et al., 2022). For example, Diatoms are a type of siliceous shell algae whose cell wall structure plays a unique role in the bioaccumulation of pollutants. The cell wall of diatoms has a high affinity for pollutants such as heavy metals, so in water contaminated with heavy metals, diatoms may accumulate a large amount of these harmful substances (Figure 2). Its bioaccumulation characteristics provide a potential biomarker for monitoring heavy metals in water bodies (Zheng et al., 2023).

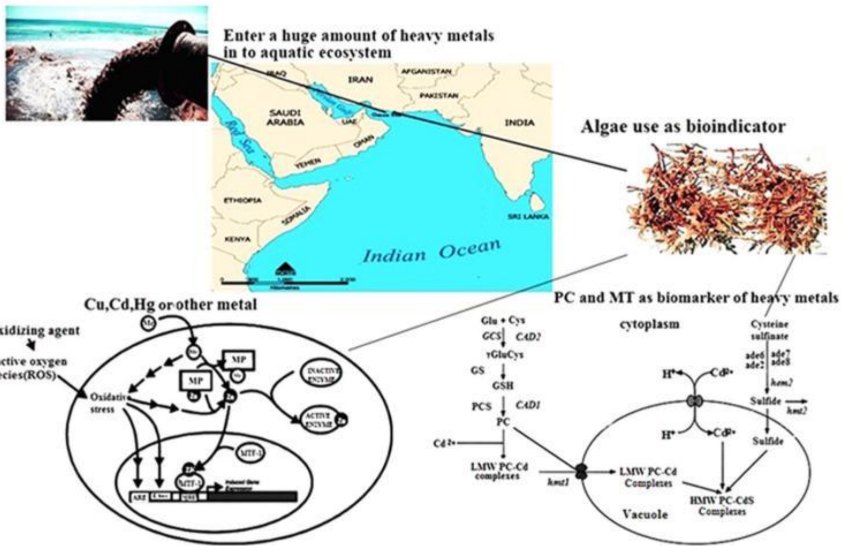

Figure 2 Accumulation of heavy metals inside algae (Sinaei et al., 2018)

Additionally, some algae exhibit resistance to pollutants. Cyanobacteria, a common type of algae, may demonstrate relatively higher growth rates in water bodies rich in organic pollutants. This resistance may be related to the physiological characteristics of Cyanobacteria, such as their ability to adapt to high-temperature environments. The enhanced photosynthetic capacity of Cyanobacteria also contributes to resisting organic pollution in the environment. Therefore, the differential response mechanisms displayed by various algae in the face of pollutants provide more comprehensive information for water quality monitoring.

2.2 Interpretation of temporal and spatial distribution characteristics

The temporal and spatial distribution characteristics of algal communities are directly related to the health of water bodies. Seasonal changes have a significant impact on algal distribution (Chen et al., 2023). In spring, warm temperatures and ample sunlight provide an ideal environment for algal reproduction. Therefore, water bodies in spring often exhibit higher algal abundance. As temperatures decrease, algal abundance in autumn may decrease, and the conditions suitable for algal growth gradually diminish.

In addition to seasonal changes, water depth and geographical location are also important factors influencing the distribution of algal communities. Depth affects the distribution of light and nutrients, so algal communities in water bodies of different depths may exhibit vertical stratification. Geographical location involves factors such as climate and water body type, leading to regional characteristics in algal communities in different locations. For instance, in eutrophic regions, diatoms may dominate, while in waters with a more balanced nutrient content, other types of algae may be more abundant.

2.3 Cooperative interactions in diverse algal communities

Diverse algal communities in aquatic environments may exhibit complex cooperative interactions. Algal species from different functional groups may influence each other through mechanisms such as competition, symbiosis, and resource conversion, thereby forming a relatively balanced ecosystem in the water. Interaction mechanisms within algal communities include symbiotic relationships, competitive interactions, and resource transformation. For instance, in some freshwater lakes, a symbiotic relationship exists between diatoms and green algae. Diatoms, through photosynthesis, produce oxygen, increasing the oxygen content in the water and providing a more suitable environment for the survival of green algae. Conversely, green algae, by absorbing carbon dioxide, promote eutrophication in the water, creating a more suitable living environment for diatoms.

The cooperative interactions within these diverse algal communities are crucial for the stability and ecological balance of water bodies. By delving into the relationships between different algal species, researchers can better understand the operational mechanisms of ecosystems in aquatic environments, providing a scientific basis for water management and ecological conservation. Understanding these cooperative interactions also aids in predicting and mitigating threats faced by aquatic ecosystems, contributing to the better preservation of water body health and sustainability.

3 Application of Algal Biomarkers in Water Quality Monitoring

3.1 Integration of laboratory research and field monitoring

In the field of water quality monitoring, the integration of laboratory research and field monitoring is a crucial element driving the application of algal biomarkers. Algal studies under laboratory conditions provide researchers with opportunities to gain in-depth insights into algal physiological characteristics, ecological adaptability, and more. Through laboratory cultivation, researchers can observe the growth of algae under the influence of different pollutants, thereby inferring the degree of pollution in water bodies. The practical application of this laboratory research plays a significant role in developing water quality monitoring schemes, assessing the degree of water pollution, and more.

Simultaneously, field monitoring, involving the observation and sampling of algal communities in natural environments, provides data under real water conditions. Through field monitoring, researchers can better understand the distribution of algae, community structure, and their relationship with environmental changes in natural water bodies (Figure 3). The combination of field monitoring and laboratory research allows researchers to validate the reliability of laboratory results in actual water environments, ensuring the accuracy and comparability of monitoring data.

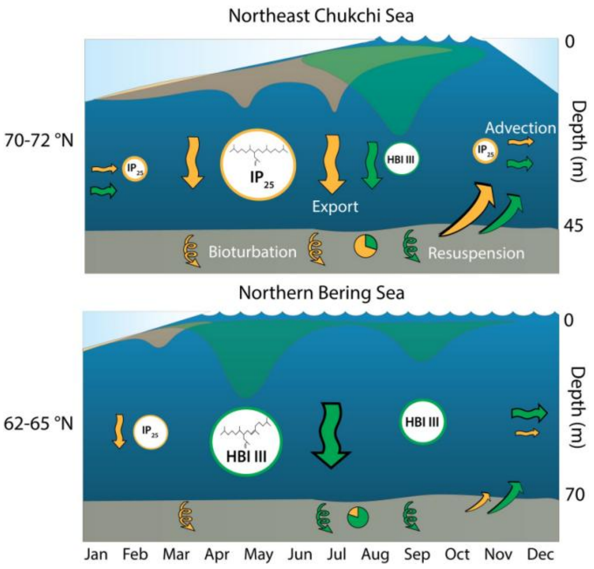

Figure 3 The production, flux and fate of HBIs in the Pacific Arctic at different latitudes (Koch et al., 2020)

The role of modern technology in algal monitoring is becoming increasingly prominent. Advances in molecular biology techniques, such as DNA sequencing, have made rapid identification and classification of algae possible. Simultaneously, the application of remote sensing technology has turned large-scale, high-frequency water monitoring into a reality, providing convenience for the field monitoring of algal biomarkers. The utilization of these modern technologies offers a more comprehensive and efficient means for water quality monitoring, enhancing the effectiveness of algal biomarkers in practical monitoring efforts.

3.2 Application of algal biomarkers in different types of water bodies

The application of algal biomarkers in water quality monitoring is not limited to specific types of water bodies but demonstrates strong versatility. In different water bodies such as rivers, lakes, coastal areas, etc., the application of algal biomarkers shows both similarities and differences.

In rivers, the distribution of algae may exhibit spatial heterogeneity due to the fast flow of water, impacting the indication effectiveness of certain algae species sensitive to flow velocity (Yin and Li, 2023). As lakes are relatively enclosed water bodies, algae biomarkers are more susceptible to the accumulation of pollutants here (Huang et al., 2023), so the application of algae in lake water quality monitoring is particularly important. In coastal areas influenced by tides and currents, the dynamic changes in algal communities are more complex. The composition of algal communities may vary significantly with different seasons and tidal states, requiring monitoring that considers both spatial and temporal characteristics. The influence of different water body characteristics on algal biomarkers needs to be thoroughly investigated in specific environments to optimize monitoring strategies.

The widespread adoption of algal biomarkers in large-scale water quality monitoring is crucial for improving monitoring efficiency. Validating and comparing the applicability of algal biomarkers in different water bodies allows researchers to establish universal monitoring indicators and methods. This approach facilitates rapid monitoring of a broader range of water bodies. This promotion not only enhances monitoring coverage but also provides general technical support for water quality management in different regions and types of water bodies.

3.3 Future development directions of algal biomarkers

There are still many directions for expanding and optimizing the application of algal biomarkers in water quality monitoring. Technological innovation is expected to play a crucial role in driving advancements in algal monitoring in the future. With continuous developments in molecular biology, remote sensing technology, and other fields, laboratories will have access to more efficient and precise technical tools for the identification and monitoring of algae, thereby enhancing monitoring accuracy and reliability. The application of big data and artificial intelligence (AI) is also anticipated to bring new breakthroughs to algal monitoring. Through deep learning and pattern recognition applied to extensive monitoring data, researchers can better understand the spatiotemporal distribution patterns of algae, promptly identify anomalies, and provide more intelligent support for water quality management.

The prospects of algal biomarkers in the global water quality monitoring system are promising. As awareness of the importance of water environmental protection increases, algal monitoring is poised to become a vital component of water quality monitoring. Strengthening international cooperation, establishing a global water quality monitoring network, and facilitating the sharing and comparison of algal biomarkers can better address water quality challenges on a global scale, safeguarding humanity's shared water resources.

4 Summary and Outlook

The diversity of algal biomarkers plays an irreplaceable role in water quality monitoring. The rich diversity of algae not only reflects the ecological complexity of water bodies but also provides more comprehensive information for monitoring. From Chlorophyta, Bacillariophyta to Phaeophyta, various algae exhibit significant differences in their response mechanisms and adaptability to the environment. As biological indicators, the ecological adaptability and potential applications of algae are crucial focal points of research. The response mechanisms of algae to environmental factors, including pollution, temperature, and light, involve multiple aspects of their growth and reproduction. These ecological features endow algae with unique potential for application in water quality monitoring (Si et al., 2023). In-depth understanding of how algae respond to pollutants, temperature changes, and other factors allows researchers to interpret these characteristics more accurately in aquatic environments, providing a finer basis for the biological indication role of algae. The potential value of algae in water health monitoring lies not only in their sensitivity to pollutants but also in their key role in the aquatic food web, offering a sensitive and comprehensive indication of the overall health of aquatic ecosystems.

The continuous development of modern technology presents unprecedented opportunities for algae monitoring. Advances in molecular biology techniques enable more precise classification and identification of algae, offering more efficient means for water monitoring (Bhatt et al., 2022). Simultaneously, the application of remote sensing technology makes it possible to monitor large water bodies, providing a broader coverage for monitoring efforts. Under the impetus of this technology, algae monitoring is evolving from traditional field surveys to a multi-level monitoring system that combines laboratory research with modern technological approaches. The application of big data and artificial intelligence facilitates the processing of massive data, allowing algae monitoring to better integrate into the global water quality monitoring network. Despite significant achievements in targeted research, there are still limitations in the current studies. For instance, methods for accurate identification of algae in mixed communities are not mature enough and require further improvement and optimization. Additionally, the challenges in data collection, especially in complex water bodies and harsh environmental conditions, need to be addressed.

Future research should focus on the dynamic study of algal communities, the application of algal biomarkers in climate change, and the forward-looking role of algal monitoring in ecosystem management. The dynamic study of algal communities can better reveal the evolution of algae under different seasons and water conditions, providing a basis for more accurate monitoring. The application of algal biomarkers in climate change is an emerging field, where research can explore how algae respond to climate change and the potential impact of this response on water body health. Furthermore, incorporating algal monitoring into forward-looking studies on ecosystem management will contribute to better maintaining the ecological balance of water bodies, providing more effective means for the protection and management of aquatic ecosystems.

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