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Management and Mitigation Strategies for Harmful Algal Blooms: Current Approaches and Future Prospects

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Abstract This study explores the management and mitigation strategies for harmful algal blooms (HABs), with a focus on analyzing their formation mechanisms, monitoring and early warning technologies, the effectiveness and limitations of various control methods, and the practical application of integrated management measures. It also discusses the current challenges in governance and future development directions. The occurrence of harmful algal blooms is the result of multiple interacting factors, including excessive nutrient inputs, climate change, altered hydrological conditions, and ecosystem imbalance, posing serious threats to aquatic ecosystems, human health, and socioeconomic development. Current response measures primarily fall into three categories: proactive source prevention, direct in-water intervention, and impact mitigation based on monitoring and early warning, encompassing various physical, chemical, and biological methods. Advanced technologies such as satellite remote sensing, unmanned aerial vehicles, and artificial intelligence models have become important tools for monitoring and early warning. In terms of integrated management, watershed-scale nutrient control, ecological restoration measures such as constructed wetlands and ecological floating islands, combined with best management practices (BMPs), have shown promising results. Typical regional cases further validate the importance of cross-sectoral collaboration and comprehensive policies. However, current governance still faces challenges such as high costs, limited technology application, unstable long-term control effects, and increased difficulty due to climate change. Research indicates that a single governance method is insufficient to achieve long-term effective control of harmful algal blooms, highlighting the need for more integrated, adaptive, and ecosystem-based management strategies in the future.
Keywords Harmful algal blooms; Management strategies; Formation mechanism; Monitoring and early warning Comprehensive Management

1 Introduction

Harmful algal blooms (HABs) refer to the phenomenon where tiny algae and cyanobacteria rapidly and massively multiply within a short period of time. These types of algae produce toxins, consume oxygen in the water, and form large amounts of algae bodies, thereby damaging the water environment. Such phenomena not only occur in freshwater areas such as lakes and rivers, but are also common in estuaries and oceans. It has now become a key issue in global water quality and ecological environment (Anabtawi et al., 2024; Brenckman et al., 2025;). Originally, this phenomenon was very rare, but in recent years, with the increase in nutrients such as nitrogen and phosphorus in the water, combined with the effects of climate warming, hydrological changes, and human activities, harmful algal blooms have become more frequent, longer-lasting, and have a wider impact (Chang, 2025). Global studies have shown that since the end of the last century, the frequency and impact of harmful algal blooms have significantly increased, especially in coastal and inland lakes in Asia, Africa, Europe, and North America (Feng et al., 2024).

The greater the quantity of harmful algal blooms, the greater the impact on the ecology, resources, and human health. From an ecological perspective, a large number of algae will block sunlight, affecting the growth of aquatic plants and altering the entire food chain. When the algae die and decompose, they consume a large amount of oxygen, causing water to become oxygen-deficient and leading to the mass death of fish and shrimp, making the living environment in the water worse and worse (Anabtawi et al., 2024; Liu et al., 2025). Many harmful algal