increasing amount of nutrients in water, combined with various human activities, have made the phenomenon of large-scale algae outbreaks increasingly common and severe in many places (Wang et al., 2025).

2.3 The flow conditions have changed, and so has the ecological structure

Fluid dynamic conditions, including water flow velocity, turbulence, water stratification and residence time, have a significant impact on the occurrence and development of red tides by influencing the physical environment for the survival of phytoplankton. Long water residence time and weak scouring effect can lead to continuous accumulation of algae, which is very common in nutrient-rich rivers, reservoirs and large lakes; while strong convection and mixing often dilute or destroy red tides. In artificially controlled rivers and reservoirs, sluices, dams and selective water intake can change water depth, water stratification and hydraulic residence time. Under nutrient-rich conditions, a slow water flow and stratified water body usually form, which is conducive to the dominance of cyanobacteria and increases the risk of red tides. On the contrary, management methods such as enhancing water mixing, increasing scouring or reducing water thermal stability can limit the development of red tides, which also indicates that fluid dynamics is crucial in the formation of red tides.

Changes in the ecological structure and food chains are also intertwined with these flow conditions and further affect whether algal blooms will occur. Changes in water body fertility, artificial alteration of water flow, and excessive fishing can all change the number and species of phytoplankton-eating zooplankton, weakening their ability to control algae. In many water bodies that are rich and stratified, these changes will cause algae to gradually shift from being dominated by diatoms to being dominated by cyanobacteria or flagellates. The latter have advantages in terms of taste, toxicity, or ability to adapt to weak water flow and long-term stillness (Brenckman et al., 2025). Once algal blooms occur, they will in turn change the ecological structure, making the water quality worse, the distribution of light and nutrients changing, and biodiversity decreasing. This, in turn, makes algal blooms more likely to occur again, forming a vicious cycle, and keeping harmful algae in the dominant position. Therefore, the formation of harmful algal blooms is the result of changes in the interaction between the physical environment and the ecosystem. Changes in flow conditions, combined with the reorganization of the biological community in the water body, jointly lead to water bodies becoming more prone to frequent and persistent algal blooms.

3 Monitoring and Early Warning of Harmful Algal Blooms

3.1 Traditional water quality and algal monitoring methods

Conventional HAB monitoring relies on in situ sampling combined with physical, chemical, and biological analyses to quantify algal biomass, species composition, and toxin levels. Routine programs typically measure temperature, nutrients, chlorophyll- a, and other water- quality parameters alongside microscopic identification of phytoplankton and cyanobacteria, often supported by spectrophotometry, chromatography, and biochemical or immunological toxin assays. These approaches remain the regulatory backbone because they provide species- level resolution and direct toxin measurements necessary for public- health decisions and seafood or drinking- water safety compliance. Standardized protocols, such as stepwise workflows integrating physical, chemical, and biological sampling with metabarcoding, improve data comparability across stations and over long time series, supporting robust risk assessment and model calibration (Saleem et al., 2023).

However, traditional monitoring is labor- intensive, costly, and limited in spatial and temporal coverage. Ground sampling and laboratory analyses require skilled personnel and specialized facilities, leading to low sampling frequency relative to the rapid dynamics of blooms (Saleem et al., 2023). These constraints can hinder timely detection of bloom onset or rapid intensification, particularly in large or remote water bodies (Byrd et al., 2025). To address these gaps, newer technologies such as biosensors, automated in situ instruments, and molecular tools (PCR/qPCR, metabarcoding) have been developed to shorten assay times, enable near- real- time detection of target taxa or toxins, and complement classical microscopy- based approaches (Zahir et al., 2024). The future of traditional monitoring lies in its integration with automated, molecular, and observational platforms within multi- scale observing systems.