they are only widely used in regions with sufficient funds. In areas with high algae risks but scarce resources, the monitoring capabilities are weak, and they are often not detected until the algae outbreak occurs (Feng et al., 2024).

6.2 Instability of long-term control effects

Even if governance measures are implemented, long-term control effects are often unstable. A comprehensive analysis of global on-site governance measures shows that most physical, microbial, and plant-based control methods, when used alone, do not significantly improve water quality; the observed governance benefits mainly come from a few chemical control methods, and their effects usually only last for a short period. The summary of governance strategies for operating reservoirs also indicates that water flow regulation and internal nutrient control can temporarily suppress algal blooms, but as climate and nutrient load conditions change, or residual nutrients in sediments and algae propagules are not treated, the control effects will fail.

The most fundamental way to control the rampant growth of algae is to reduce the nutrients in the water. However, for severely eutrophic water bodies, it takes a long time to restore and the process is unstable, prone to recurrence. Currently, there is no universal method that can completely solve the problem of large-scale and long-term algal blooms. Therefore, the monitoring plan needs to be continuously optimized, and various comprehensive control measures need to be repeatedly evaluated for their effectiveness. For most water body management, the goal is generally to reduce the frequency of algal blooms and mitigate the damage, rather than completely eradicating algae (Anabtawi et al., 2024; Liu et al., 2025).

6.3 Management challenges exacerbated by climate change

Climate change makes the management of algal blooms increasingly challenging, as it turns the management goal into a "moving target", making the already difficult task of reducing emissions even more complicated. The rise in temperature makes water more prone to stratification, and the duration of stratification becomes longer; coupled with changes in hydrological conditions, as well as the increasing occurrence of extreme weather such as ocean heat waves, heavy rains, and droughts, all these create a more favorable environment for harmful algae to grow, prolonging the season and expanding the range of algal blooms. Long-term data shows that although some lakes in North America and Europe have been managed for several decades and have been controlling the input of nutrients, toxic algal blooms have reappeared (Feng et al., 2024), which is the result of the combined effect of climate warming and residual pollution.

Extreme weather events such as ocean heat waves and El Niño have triggered rare large-scale algal blooms, with toxic algae proliferating in the Pacific Ocean and waters in the Southern Hemisphere. This has also sounded the alarm for subsequent algal bloom control efforts. Climate change has significantly reduced the effectiveness of the original emission reduction targets and control methods. Pet et al. pointed out that whether it is nutrient control or water diversion and dilution, all types of control strategies must be re-planned in light of the new water temperature and volume. Emission reduction targets need to be adjusted promptly, and the algal bloom warning line should also take climate factors into account. The combination of climate change and human activities has made the timing and location of algal blooms more difficult to predict, which not only increases the difficulty of prediction but also makes the governance work more cumbersome (Feng et al., 2024; Hwang et al., 2024). If the monitoring network and engineering measures cannot keep up with the pace of climate change, the existing governance methods will soon become ineffective.

7 Future Directions

7.1 Integrated management combining multiple technologies

Future HAB mitigation is expected to rely on integrated, multi-technology portfolios rather than single interventions. Recent reviews stress that physical, chemical, and biological methods each have characteristic limitations, and that combining them can compensate for weaknesses in efficacy, cost, and environmental side-effects (Anabtawi et al., 2024; Lan et al., 2024). Integrated strategies include pairing watershed nutrient controls with in-reservoir hydrodynamic manipulation, selective chemical treatments, and biological controls to deliver