Numerical and process-based models simulate physical-biogeochemical drivers such as stratification, nutrient dynamics, and algal growth to provide mechanistic insight and scenario testing, whereas data-driven models correlate historical environmental variables and remote-sensing products with bloom metrics for short-term prediction (Lan et al., 2024; Campbell and Vinebrooke, 2025). Ensemble frameworks that stack multiple model types (e.g., tree-based methods, neural networks, Bayesian regression) improve skill in predicting exceedance probabilities of algal densities and toxins, offering probabilistic risk forecasts for management programs (Szewczyk et al., 2025).

Machine-learning and deep-learning techniques, including random forests, gradient boosting (XGBoost, LightGBM), artificial neural networks, CNN-LSTM architectures, Transformers, and other hybrid models, now play a central role in HAB prediction (Szewczyk et al., 2025; Wang et al., 2025). These models effectively capture nonlinear relationships among meteorological, hydrodynamic, nutrient, and remote-sensing inputs, achieving high accuracy for short-term HAB detection and multi-day forecasts and demonstrating operational potential for early-warning systems in both coastal and freshwater systems (Park et al., 2024). Integration of explainable AI (e.g., SHAP values) helps identify key drivers and improve interpretability, while coupling ML with real-time monitoring (sensors, satellites, UAVs) is highlighted as critical for sustained performance and generalizability across diverse bloom scenarios (Zahir et al., 2024).

4 Control and Mitigation Methods for Harmful Algal Blooms

4.1 Physical methods: aeration, mixing, and mechanical removal

These physical methods do not add chemical substances to the water body. Instead, they work by altering the water environment or directly removing algae. For instance, by artificially stirring the water or supplementing oxygen at the bottom, the original stratification structure of the water body can be disrupted, reducing the accumulation of algae on the water surface, while increasing the dissolved oxygen in the water and reducing the possibility of nutrient release from the bottom sediment into the water. In this case, the growth conditions of algae will be restricted, and those algae that do not form algal blooms may have more space to grow. If the oxygenation technology is designed reasonably based on the morphological characteristics of the lake or reservoir and the pollution status, it can increase the oxygen content of the water body within a certain period and reduce the release of phosphorus from the bottom sediment, thereby reducing the number of algae to a certain extent (Brenckman et al., 2025). However, this method requires high costs in construction and operation, and the effects vary greatly in different water bodies. If external inputs of large amounts of nutrients continue, the governance effect is often weakened. Therefore, it is still difficult to promote this method in large lakes or sea areas (Lan et al., 2024).

These physical methods include using dredging tools, filtration equipment, or throw in substances that cause algae to sink to the bottom. These are commonly used in small ponds and aquaculture areas and can quickly reduce the excessive algae in the water (Lan et al., 2024). For example, when dealing with marine red tides, clay or modified clay is often used to cause the algae to aggregate and sink to the bottom. However, it is currently uncertain whether this method will harm underwater organisms (Anderson et al., 2025). There is also a method of thoroughly cleaning the bottom sediment, which can remove nutrient-rich sediment and dormant blue-green algae spores. However, this method is costly and environmentally damaging and cannot be frequently used. In general, physical methods are more suitable for emergency handling in areas with high economic value.

4.2 Chemical methods: using algaecides and oxidants

Chemical methods, especially the use of algicides and oxidants, remain common measures for dealing with excessive algal growth. The main reason is that these methods are more effective and can significantly reduce the algal population within a short period of time, as well as lower the toxins produced by the algae. Through a comprehensive analysis of multiple field test results, it was found that among various chemical agents, only a few, such as copper sulfate, hydrogen peroxide, peroxyl acetate, and carbendazim, can improve water quality by reducing the pigment content of the algae, decreasing the cell count, and removing microcystin toxins. Some oxidants, such as hydrogen peroxide and potassium persulfate, have a good inhibitory or killing effect on