both rapid risk reduction and long-term ecosystem recovery. Studies also highlight the potential to couple treatment with biomass harvesting and valorization, turning blooms into resources (e.g., bio-products, materials) and aligning mitigation with circular and low-carbon development goals (Hwang et al., 2024; Liu et al., 2025).

Scaling such integrated approaches requires frameworks that match tool combinations to bloom type, system characteristics, and management objectives. Inland and coastal reviews propose decision schemes in which preventive nutrient and hydrologic measures form the backbone, while more intensive physical, chemical, and biological tools are deployed tactically during high-risk periods (Feng et al., 2024). Future research priorities include rigorous field-scale testing of multi-method packages, better understanding of cumulative ecological impacts, and design of operational guidelines for "integrated management interventions" that explicitly coordinate watershed, in-water, and downstream coastal actions across the aquatic continuum (Anabtawi et al., 2024).

7.2 Intelligent monitoring and precision management

Rapid advances in observation and computation are driving a transition toward intelligent, precision HAB management. Integrated monitoring concepts emphasize combining satellite and drone remote sensing, automated buoys, in situ biosensors, molecular diagnostics, and toxin assays to provide multi-scale, high- frequency data for early warning (Lan et al., 2024; Brenckman et al., 2025). Numerical models and Earth-system frameworks are increasingly merged with machine-learning methods such as random forests, support vector machines, and LSTM networks to improve detection, short-term forecasts, and scenario analysis for management decisions (Esposito et al., 2025; Rathore et al., 2025).

Next-generation systems seek to directly couple these data streams to real-time decision support. AI-assisted integrated governance frameworks link multi-modal monitoring with treatment modules and microalgal resource recovery, aiming to move from "passive emergency response" to active prevention and control (Lin et al., 2025). Digital-twin lake architectures and automated buoy-ML platforms demonstrate how continuous, high-resolution data can drive dynamic, site-specific interventions and automated alerts that signal bloom thresholds relevant for public health and operations (Zahir et al., 2024; Rathore et al., 2025). At larger scales, efforts to build regional and ultimately global HAB observing systems envision standardized, interoperable networks that feed into precision management at local and national levels.

7.3 Ecologically prioritized and sustainable governance approaches

There is a growing emphasis on ecologically prioritized, sustainable governance that addresses root drivers while minimizing collateral damage. Multiple syntheses stress that long- term control must be grounded in nutrient-enrichment management-especially dual nitrogen and phosphorus reductions, improved wastewater and agricultural practices, and hydrologic restoration-integrated with climate-adaptation strategies to confront the "moving targets" created by warming and altered hydrology (Feng et al., 2024; Brenckman et al., 2025). Ecological and nature-based solutions, including wetland nutrient capture, biomanipulation, restoration of macrophytes and seagrasses, and promotion of algicidal and growth-inhibiting bacterial communities, are highlighted as core elements of sustainable HAB prevention (Liu et al., 2025; Hwang et al., 2024).

Governance frameworks are evolving toward cross-sectoral, multi-level arrangements that link water quality, fisheries, public health, and climate objectives. Reviews call for integrated observing networks, open data, and participatory approaches that incorporate local stakeholders, indigenous concepts such as "Sato-Umi," and community co-management to maintain social license for interventions (Hwang et al., 2024). Future directions emphasize embedding HAB policy within broader ecosystem-based and SDG-aligned agendas, strengthening institutional capacity for adaptive management, and ensuring that technological innovation is consistently evaluated against ecological integrity and long-term sustainability criteria (Feng et al., 2024; Brenckman et al., 2025).

8 Concluding Remarks

The research on harmful algal blooms has evolved from focusing only on individual cases in the early stage to a