

3.2 Remote sensing and drone-based monitoring technologies

Satellite and airborne remote sensing have transformed HAB monitoring by providing synoptic, repeated observations of bloom extent and intensity over large spatial scales. Optical remote sensing, including multispectral, hyperspectral, and emerging high-performance sensors, retrieves proxies such as chlorophyll-a, phycocyanin, and water color, enabling the detection and mapping of surface blooms in both inland and coastal waters (Figure 2) (Zahir et al., 2024). Meta-analyses of hundreds of studies show rapid growth in remote-sensing-based HAB monitoring, while also highlighting needs for standardized methods, improved atmospheric correction (especially in turbid waters), and harmonized multi-sensor constellations to increase spatial-temporal resolution (Wang et al., 2025). Hyperspectral imaging in particular can discriminate algal groups with high classification accuracy and support robust early-warning applications when coupled with suitable algorithms (Arias et al., 2025; Wang and Qin, 2025).

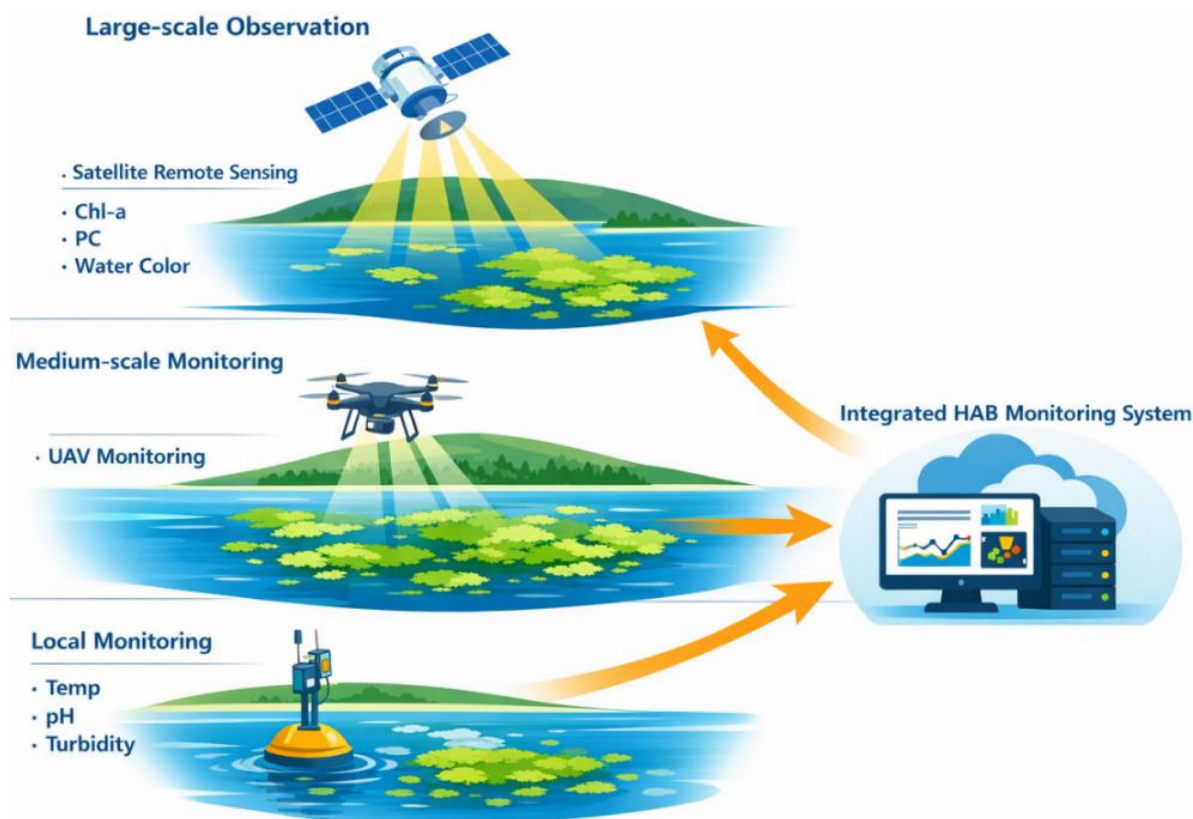


Figure 2 Conceptual framework for harmful algal bloom monitoring (Adopted from Zahir et al., 2024)

Unmanned aerial vehicles (UAVs) provide flexible, high-resolution coverage that bridges scales between in situ sampling and satellites. UAV platforms equipped with RGB, multispectral, hyperspectral, or thermal sensors can rapidly map fine-scale bloom patches, validate satellite products, and guide targeted sampling or public-health interventions (Arias et al., 2025; Wang and Qin, 2025). Recent systems integrate onboard water-quality sensors (e.g., temperature, pH, turbidity) and real-time communications (e.g., LoRaWAN) to deliver immediate data streams for operational decision-making (Hagh et al., 2024). Nonetheless, UAV-based monitoring faces challenges including regulatory constraints, the need for robust calibration and validation, and integration with risk frameworks and other observing platforms (Byrd et al., 2025). The emerging direction is coordinated, multi-platform observation networks that combine satellite, UAV, and in situ data for comprehensive HAB surveillance.

3.3 Prediction and early warning based on models and artificial intelligence

Forecasting and early-warning systems have evolved from empirical statistical models toward sophisticated process-based, data-driven, and hybrid approaches that exploit growing environmental and monitoring datasets.