

Automation is also broadening from water-quality regulation to behavior-linked and vision-based management. Reviews of recent RAS developments describe AIoT systems that reduce manpower and machine-vision tools that detect altered swimming behavior as an early warning of suboptimal water conditions, including hydrogen sulfide exposure below the known toxicity threshold (Gupta et al., 2024). Together with smart feeding systems that improve feed conversion and growth while reducing waste, these tools indicate that the next phase of RAS automation will combine environmental control with behavioral sensing and production optimization rather than focusing on physicochemical variables alone (Huang and Khabusi, 2025).

7.3 Challenges and future perspectives

The main barriers to intelligent RAS adoption remain economic, technical, and organizational rather than conceptual. Recent reviews describe high installation cost, connectivity problems in rural areas, and demanding calibration and maintenance requirements as major obstacles to smart RAS implementation, while earlier industry analysis identified poor system design and weak management capacity, especially the shortage of skilled personnel responsible for water quality and mechanical issues, as persistent constraints on RAS performance. These barriers explain why intelligent technologies have advanced faster in research and prototypes than in broad commercial uptake (Grandez-Yoplac et al., 2025).

A second major challenge is scale, robustness, and data quality. AI and IoT reviews emphasize that widespread deployment is still limited by restricted access to representative datasets, expensive sensor and AI infrastructure, and technical complexity, while water-quality management reviews further note persistent issues with sensor biofouling, recalibration, and performance across diverse environments (Aung et al., 2024). The future direction is therefore not simply more algorithm development, but more transferable systems that are resilient under real farm variability and that can operate reliably with local maintenance capacity (Huang and Khabusi, 2025).

Energy use and sustainability will also shape the future of intelligent RAS management. Although RAS are highly water-efficient and relatively insulated from climate variability, energy consumption and greenhouse gas emissions remain major limiting factors, and broader systems analyses argue that renewable energy integration combined with advanced monitoring and process optimization could improve both environmental and economic feasibility. Future intelligent RAS will therefore likely be judged not only by how well they stabilize water quality and fish health, but also by how effectively they reduce energy demand through system-wide optimization (Ahmed and Turchini, 2021).

The strongest near-term development pathway combines better sensing, tighter automation, and broader biological data integration. Proposed priorities include self-calibrating multi-parameter sensors, low-power communication technologies such as LoRaWAN and NB-IoT, and expansion of monitored variables to include microbiological and emerging-contaminant indicators, all of which would support more comprehensive and autonomous environmental control (Baena-Navarro et al., 2025). More broadly, recent RAS reviews describe a thematic shift from classical engineering variables toward proteomics, transcriptomics, and molecular techniques, suggesting that future intelligent management will increasingly fuse environmental monitoring with microbial and genomic evidence for disease control, growth optimization, and precision aquaculture (Grandez-Yoplac et al., 2025).

8 Conclusions

Recent advances in water quality control technologies for RAS show a clear transition from conventional treatment and intermittent measurement toward integrated, real-time, and more intelligent control systems. Current RAS performance depends on coordinated use of mechanical and biological filtration, gas regulation, disinfection, and monitoring tools that remove suspended solids, nitrogenous wastes, carbon dioxide, and other hazardous compounds while maintaining conditions suitable for fish growth. At the same time, modern monitoring has expanded from labor-intensive handheld sampling to sensor-based surveillance, IoT connectivity, and AI-assisted warning systems that improve the speed and precision of operational responses.

Technological progress is also moving beyond basic recirculation toward process intensification and adaptive optimization. Dynamic and reinforcement-learning models now link feeding, oxygenation, biofilter behavior, and