

2.2 Biological processes maintaining water quality in ras

The core biological mechanism maintaining water quality in RAS is microbial nitrogen conversion within biofilters, where toxic ammonium is oxidized into nitrite and then nitrate, reducing acute toxicity in the culture water (Lindholm-Lehto et al., 2020). This process is now understood as more complex than the classical two-step nitrification model, because coupled nitrogen removal can also involve aerobic denitrifiers, anammox organisms, and comammox microorganisms that together improve total nitrogen removal under low-water-exchange conditions (Preena et al., 2021).

Biological regulation also depends on community structure and engineered enhancement of microbial function rather than on nitrification alone. In recirculating pond systems, bacteria-microalgae associations with biofilm carriers reduced total nitrogen, TAN, and nitrite while increasing functional genes linked to ammonia oxidation and denitrification, and biofloc biofilters similarly concentrated denitrifiers, nitrifiers, and phosphorus-removing microorganisms in the reaction zones where most nutrient removal occurred.

2.3 Effects of water quality fluctuations on fish physiological responses

Water quality fluctuations affect fish first through stress physiology, and dissolved oxygen depletion is one of the most immediate threats in intensive systems. Hypoxia below about 1-2 mg/L for even a few hours can suppress growth and cause mortality, while broader reviews of RAS species responses show that excessively low dissolved oxygen disrupts system balance and produces losses that can quickly become unacceptable under intensive culture conditions (Dai et al., 2025).

Nitrogenous waste accumulation produces a second major physiological pathway of harm because elevated ammonia alters biochemical, physiological, immunological, and homeostatic processes, increasing disease susceptibility. This toxicity is not fixed, since its severity rises or falls with pH, temperature, salinity, dissolved oxygen, species, and life stage, and RAS observations confirm that even when overall water quality remains acceptable, fluctuations such as unstable pH and low alkalinity can still generate measurable fish stress (Pepe-Victoriano et al., 2025).

3 Water Quality Monitoring Technologies and Data Acquisition in RAS

3.1 Conventional methods for water quality assessment

Conventional water quality assessment in RAS has relied mainly on periodic manual sampling, portable meters, and laboratory analysis of key physicochemical variables. These approaches remain foundational because they are used to track core indicators such as pH, temperature, dissolved oxygen, salinity, turbidity, and oxidation-reduction conditions, but they are labor-intensive and provide only intermittent snapshots of system status rather than continuous process awareness (Lindholm-Lehto, 2023). In intensive recirculating systems, that sampling logic is useful for routine compliance and baseline husbandry, yet it is inherently limited when water quality shifts rapidly between observation intervals.

The main weakness of conventional assessment is therefore not analytical validity but delayed detection of critical change. Manual sampling and laboratory workflows are costly in labor and time, do not support immediate intervention, and can miss off-hour excursions in dissolved oxygen, pH, or temperature that affect fish performance before personnel become aware of them (Figure 1) (Flores-Iwasaki et al., 2025). At the same time, RAS water assessment increasingly extends beyond basic field measurements to more specialized analyses, including in situ ion chromatography for continuous nitrite and nitrate monitoring and HPLSEC-fluorescence methods for tracking dissolved organic matter under oxidative treatment conditions.

3.2 Application of sensor networks and IoT technologies

Sensor networks and IoT technologies have shifted RAS monitoring from interval-based observation to real-time acquisition and remote supervision. Current systems integrate sensors for temperature, pH, dissolved oxygen, turbidity, salinity, conductivity, or water level with wireless communication modules and cloud-connected dashboards, allowing farmers to visualize conditions continuously and receive warning signals when thresholds are