

exceeded (Malandrakis, 2025). This architecture is especially valuable in RAS because equipment failures or rapid water-quality deterioration can escalate quickly, making immediate alerts and remote access more useful than retrospective records alone.

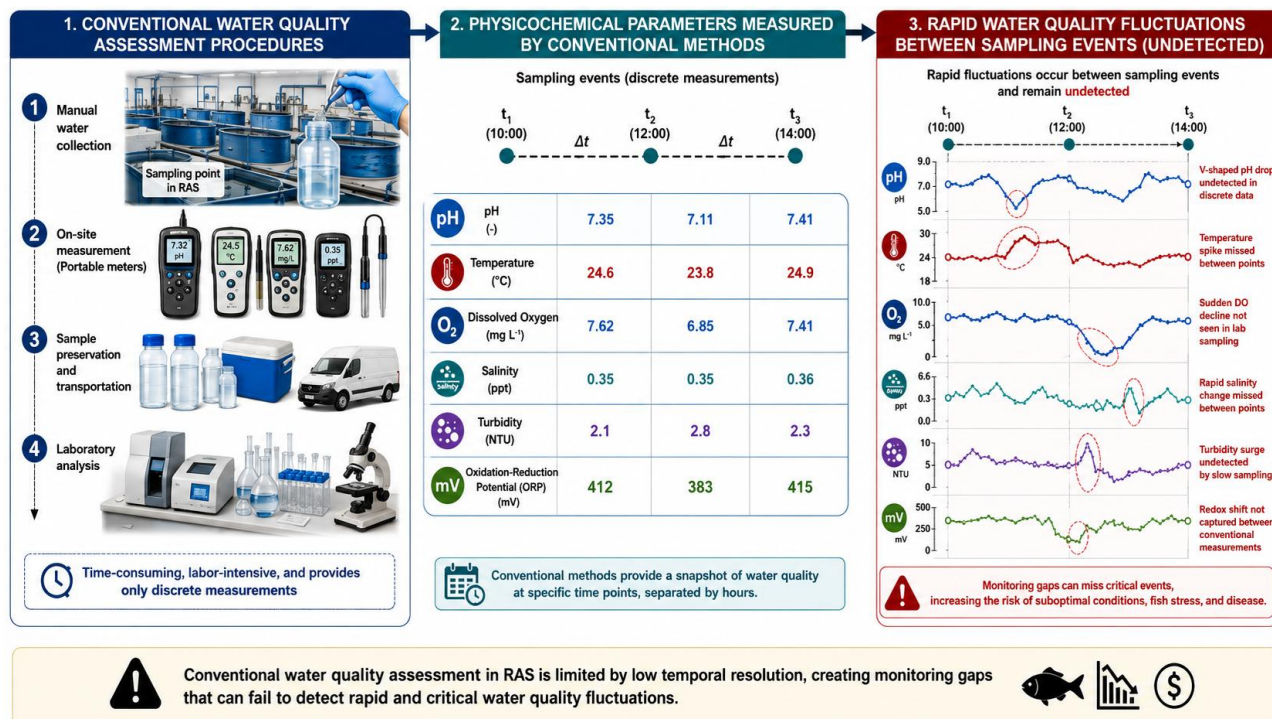


Figure 1 Conventional water quality assessment workflow and temporal limitations in recirculating aquaculture systems

Recent implementations show that IoT-enabled monitoring is becoming more accurate, more distributed, and more operationally practical across aquaculture settings. NB-IoT systems have achieved stable long-distance transmission and accurate control of temperature, dissolved oxygen, and pH, while review evidence shows that real-time monitoring remains the dominant delivered function and that temperature, dissolved oxygen, and pH are the most frequently prioritized variables in IoT-based aquaculture platforms. Even so, these systems still face practical constraints involving calibration, maintenance, automation depth, and performance in remote areas, which explains why many platforms remain focused on monitoring and alerts rather than fully autonomous control (Lindholm-Lehto, 2023; Flores-Iwasaki et al., 2025).

3.3 Data integration and feature extraction for aquaculture management

The next stage of RAS monitoring is not simply collecting more data, but integrating heterogeneous sensor streams into models that can extract useful features for management. Water quality in aquaculture is shaped by nonlinear interactions among fish density, feeding, climate, and interdependent parameters, so predictive systems increasingly use machine learning to capture temporal patterns and forecast variables such as dissolved oxygen and pH before harmful shifts occur (Baena-Navarro et al., 2025). This transition turns data acquisition into decision support by linking real-time monitoring with early warning, trend detection, and operational planning.

Feature extraction is central to this transition because raw time-series signals are often noisy, redundant, and difficult to interpret directly. Hybrid deep-learning frameworks now use convolutional layers to extract local features from timestamped water-quality data and recurrent units such as GRU or LSTM to learn sequential dependencies, while intelligent RAS analytics systems also use relational data analysis to detect sensor faults and infer relative parameter changes with lower hardware requirements (Yang et al., 2023). More broadly, machine learning in aquaculture has expanded beyond water-quality prediction alone to include biomass estimation, fish identification, and behavioral analysis, suggesting that future RAS management will depend on integrated data pipelines that combine environmental sensing with biological response indicators (Singh et al., 2024).