Author(s): Petra Lindholm-Lehto

Title: Water quality monitoring in recirculating aquaculture systems

Year: 2023

Version: Published version

Please cite the original version:

Lindholm-Lehto, P. (2023) Water quality monitoring in recirculating aquaculture systems. Aquaculture, Fish and Fisheries, 00, 1– 19. https://doi.org/10.1002/aff2.102

Received: 17 November 2022 | Revised: 12 January 2023 | Accepted: 5 February 2023

DOI: 10.1002/aff2.102

AQUACULTURE, FISH and FISHERIES Open Access

WILEY

REVIEW

Water quality monitoring in recirculating aquaculture systems

Petra Lindholm-Lehto

Natural Resources Institute Finland (Luke), Aquatic Production Systems, Jyväskylä, Finland

Correspondence
Petra Lindholm-Lehto, Natural Resources Institute Finland (Luke), Aquatic Production Systems, Survontie 9A, FI-40500 Jyväskylä, Finland.
Email: petra.lindholm-lehto@luke.fi

Funding information
NordForsk: Sustainable Aquaculture–Research and Innovation Projects, Grant/Award Number: No.102714

Abstract

Good water quality in recirculating aquaculture systems (RAS) is crucial for ensuring the successful growth and survival of reared species. So far, there are no regulations for which parameters should be measured in RAS, and each farmer decides which parameters to follow. Traditionally, water quality parameters have been measured at certain intervals with handheld sensors and laboratory analyses, which can be labour intensive. Currently, a variety of sensors and monitoring equipment is available, even for the real-time monitoring of water quality parameters. Internet of Things-based systems and artificial intelligence can be applied for the monitoring purposes which allows real-time measurements and warnings of critical situations. However, many of the modern systems need competent users and require regular maintenance and calibration. Changes in water quality also induces changes in fish behaviour, such as swimming activity, depth, acceleration and water quality can be assessed also based on these changes. In this review, water quality parameters, variety of sensors and monitoring technologies have been summarised to provide an overview of the current monitoring systems for water quality. Additionally, analytical methods for more advanced analyses have also been briefly summarised. Although there are several advanced options available for monitoring the basic water quality parameters, real-time measurements of more advanced parameters still required require further development.

KEYWORDS
aquaculture, fish behaviour, Internet of Things (IoT), monitoring equipment, recirculating aquaculture systems (RAS), water quality

1 | INTRODUCTION

Recirculating aquaculture systems (RAS) are land-based intensive aquaculture systems where water is re-used typically via mechanical and biological treatment to reduce the consumption of water and yet maintain adequate water quality (Martins et al., 2010). RAS utilises modern knowledge of biology, environmental sciences, mechanical engineering and information technology (Xiao et al., 2019). Circulating water is reused multiple times, and only a small proportion is replaced with clean water (Chun et al., 2018). Currently, variety of freshwater and marine species from hatchery to grow-out is reared in RAS. RAS have been used for several decades for fish production, although only a few very large (production over 10 million kg per year) systems are in operation (Molleda, 2007).

The idea of RAS originates from Japanese biological purification in the 1960s (Wu et al., 2008; Lin, 2011; Xiao et al., 2019). Since the 1990s, biological engineering, automation control, bottom discharge and controls of dissolved oxygen (DO) and temperature have been employed. Currently, the development of RAS focuses on improving of water purification technology and equipment, sustainability and the level of wastewater discharge (Becke et al., 2019). However, since RAS are often energy and cost intensive, and suggestions have been made to improve their economy.

Water quality can be divided into categories which include physical parameters, organic contaminants, biological contaminants and pathogens (Su et al., 2020). Physical parameters depend on climate and the surrounding conditions. Water quality control is a key aspect in any aquaculture management, but especially in RAS, where the water is circulated in the system. The main parameters for quality monitoring include pH, temperature, oxidation–reduction potential (ORP/Redox), turbidity, salinity and DO. In the ideal range, water quality can enhance the fish growth rate and reduce the occurrence of fish diseases (Stigebrandt et al., 2004; Tolentino et al., 2021). Technologies suitable for rapid, real-time and automated monitoring and data storing are therefore greatly needed.

Water quality in RAS is affected by feed loading and composition (Blancheton et al., 2013; von Ahnen et al., 2015). Dissolved compounds and particulate matter can be difficult to remove from the system and they can act as substrate material for bacterial growth. Some of these bacterial species can induce off-flavours in the system (Lindholm-Lehto et al., 2019; Suurnäkki et al., 2020). A high abundance of bacteria can also affect the fish, acting as pathogens or competing for oxygen (Michaud et al., 2014).

In RAS, water quality parameters are kept stable to ensure suitable conditions for the fish (Rojas-Tirado et al., 2018). It is therefore important to understand and control factors that change the water quality. Water quality needs to be monitored closely to maintain optimal growth conditions in RAS (Naughton et al., 2020). In RAS, fish are often reared in high densities, causing a build-up of organic material and nutrients (Bentzon-Tilia et al., 2016). These factors need to be controlled and monitored, but the available tools are often complex or include a considerable lag between sampling and the results (Rojas-Tirado, 2018). There are no regulations concerning which parameters to measure and each farmer has their own view of and possibilities for water quality measurements. Additionally, there are no guidelines for acceptable ranges and fluctuations.

Previous articles have comprehensively studied and discussed fish health, stress levels, diseases (Venugopal, 2002; Endo & Wu, 2019), pathogens (Adams & Thompson, 2011) and exposure to environmental contaminants such as polycyclic aromatic hydrocarbons (Srogi, 2007) and cyanotoxins (Vogiazi et al., 2019). Additionally, analytical technologies and biosensors used in aquaculture have recently also been reviewed (Hu et al., 2020; Su et al., 2020). However, a comprehensive study of current sensors, monitoring equipment and the typically monitored water quality variables has been missing.

In this study, it was hypothesised that only the very basic water quality parameters are typically monitored in commercial RAS, possibly with very traditional monitoring methods. However, in recent years, new possibilities are available due to many technical innovations. This review aims at (1) combining new technologies available for monitoring of water quality by using the most modern information technologies, (2) listing the technology-based possibilities in prediction of detrimental occurrences in water quality and (3) presenting which parameters can be measured by the modern online-measurement tools and which still need more advanced laboratory analyses. All this might encourage adopting new measurement equipment for monitoring of water quality at commercial aquaculture facilities.

2 | WATER QUALITY PARAMETERS

In aquaculture, several parameters need to be monitored and measured to understand the aquatic conditions (Tziortzioti et al., 2019). These include pH, temperature, DO, salinity and turbidity (Mwegoha et al., 2010). DO is the most crucial parameter for aquatic species. Oxygen is not readily soluble in water, and its ability to dissolve decreases rapidly as the temperature and salinity increase (Timmons et al., 2018; Chumkiew et al., 2019).

The fluctuation of physical parameters directly affects the health, growth and feed utilisation of the raised species. For example, DO affects feed consumption, feeding efficiency, metabolism and growth in fish (Buentello et al., 2000; Zhang et al., 2011). Fish use oxygen to convert feed to biomass and depending on the species, varies from 5 mg L^{-1} (warm water species) to 7 mg L^{-1} (cold water species) (Pillay & Kutty, 2005). However, some species (silver catfish, *Rhamdia quelen*) can tolerate DO levels below 3 mg L^{-1} but DO levels below 5 mg L^{-1} affect their behaviour, survival and growth (Braun et al., 2006). For salmonids, oxygen saturation should be at least at 70–80% (above 6 mg L^{-1}). Fluctuations or suboptimal temperatures affect feed use (lower FCR at temperatures above optimal, Timmons et al., 2018) and induce stress which can lead to disease outbreaks. Additionally, organic material consumes oxygen (biological oxygen demand, BOD) via bacterial degradation.

Water conductivity is related to the ionic content of water and salinity, but it also depends on temperature and pressure (for a 1°C increase, conductivity increases by 2–4%) due to increased ion mobility and solubility (Tziortzioti et al., 2019). Hydrogen ion concentration and relative acidity are measured as pH. Aquatic species generally require a neutral pH, but for example, the optimum pH for chichlids (Cichlidae; Takahashi-Kariyazono et al., 2017) and for tilapia (*Oreochromis* sp.; Milud et al., 2013) can be in mildly basic conditions. A biofilter achieves its best performance in mildly basic conditions. The pH can be affected by, for example, bacteria, CO_2 content and chemicals in the system. Water with a low pH can be harmful to aquatic species but can also corrode pipes or release lead, cadmium, copper and zinc into water.

Turbidity means the degree of cloudiness in water due to suspended organic or inorganic particles (silt, clay, organic matter, plankton, etc.) and is a valuable parameter for evaluating water quality (Tziortzioti et al., 2019). The degree of turbidity is based on scattering of light from the suspended particles. High turbidity reduces the depth of light can penetrate which can prevent or decrease the efficiency of UV light treatment.

2.1 | Nitrogen species

In RAS, nitrogen compounds can accumulate in water (ammonium-N, nitrite), which are toxic to fish even at low concentrations (Timmons et al., 2018). Intensified production in RAS leads to an increase in dissolved waste, including ammonia (NH_3) (Ip et al., 2001). Ammonia (NH_3) is highly toxic to fish and can deteriorate gills and result in mortality (Wicks et al., 2002). Typically, the upper safe limit for NH_3-N for salmonids is 0.0125 mg L^{-1} (Timmons et al., 2018).

Ammonia can exist in two forms: NH_3 and in the ionised form NH_4^+, which are in equilibrium in water based on temperature and pH (Timmons et al., 2018). Together, they are referred to as total ammonia nitrogen (TAN). The proportion of free ammonia (NH_3) increases with increasing temperature and pH. Fish excrete nitrogen mainly as ammonia-N (53–68%), but also as urea-N (6–10%), amino acids (4–10%) and as protein (3–11%) (Kajimura et al., 2004). Fish have varying tolerance of ammonia-nitrogen, depending on species, age and physiological status. For example, adult fish are more tolerant to ammonia than juveniles and fingerlings (Dauda et al., 2019). Generally, levels of ammonia below 1 mg L^{-1} and of TAN below 5 mg L^{-1} are recommended (Table 1) (Boyd, 2003; Ajani et al., 2011). However, in some studies, increased concentrations of ammonium have been beneficial in terms of growth rate and sublethal NH_3-N (Kolarevic et al., 2013).

In RAS, ammonia is converted by certain bacteria to less toxic nitrite (ammonia-oxidising bacteria: AOB, e.g., *Nitrosomonas*) and further to nitrate (nitrite-oxidising bacteria: NOB, e.g., *Nitrospira*, *Nitrobacter*) via nitrification process which allows lower water use rates (Suurnäkki et al., 2020). Typically, this is performed in nitrifying bioreactors, such as moving bed bioreactors (Kamstra *et al*., 2017) or fixed bed bioreactors (Pedersen *et al*., 2015) where biofilm containing the nitrifying bacteria, is formed on plastic carrier material or on natural material, such as sand particles.

Nitrite is toxic to fish, and concentrations below 0.5 mg L^{-1} are recommended (Ajani et al., 2011). Nitrate is a less toxic oxidation product, and most fish species can tolerate levels up to 200 mg L^{-1} (Dauda & Akinwole, 2015), although NO_3-N concentrations of 100–1000 mg L^{-1} are not uncommon (Preena et al., 2021). However, high concentrations of nitrate can inhibit fish growth and increase mortality (Table 1) (Davidson et al., 2014). Typically, nitrate concentrations in RAS are controlled by adjusting the water exchange rate and biofilters, adding denitrification, or even phytoremediation into the system (Martins et al., 2010; Schipper *et al*., 2010; Pulkkinen et al., 2021).

Fish feeds and feed load are important factors when dimensioning ammonia removal capacity in RAS. TAN production in fish depends on the feeding interval (Pedersen et al., 2012) and digestibility (Médale et al., 1995) and it may increase if the amino acid profile in the fish feed is not balanced (Bureau & Hua, 2010). It is beneficial to disperse the feed throughout the day in RAS to ensure a steady ammonia load into the bioreactors.

The feed loading (kg feed per m^3 make-up water) reflects the intensity of recirculation which is the main critical parameter that influences water quality deterioration (Pedersen et al., 2012). Upper limits of feed loading are determined based on the raised fish species, the prevailing environmental conditions, the type of feed and the used water treatment equipment. Higher feed loads are possible with increased biofilter nitrification capacity, when fish performance is not restricted by nitrate accumulation or by deteriorated water quality in general (Davidson et al., 2011a). For example, declined health of rainbow trout (*Oncorhynchus mykiss*) and increased mortality were observed in a commercial RAS with 1.3–2.0 kg m^{-3} feed loads (Davidson et al., 2009). At very high feed loads, even abnormal swimming behaviour, side swimming and deformities in rainbow trout have been observed (Davidson et al., 2011b).

When aiming for very low water exchange rates in RAS or even zero-discharge systems, nitrate need to be removed from the system. Nitrogen removal is most commonly achieved via heterotrophic denitrification which converts nitrate to nitrogen gas and uses carbon as the electron donor and for microbial growth (Schipper *et al*., 2010). There are other options for denitrification, such as anaerobic ammonium oxidation (Anammox) and chemo-autotrophic denitrification (Burgin & Hamilton, 2007). Additionally, biofloc system or biofloc technology absorbs inorganic nitrogen from the circulating water and improves water quality. In Biofloc system, microbial protein is produced for the raised species which improves feed conversion ratio, FCR (Khanjani & Sharifinia, 2020). Biofloc has been widely studied in recent decades for example in shrimp and finfish farming (Abbaszadeh et al., 2019; Ebrahimi et al., 2020).

Aquaponic systems are also able to remove nitrogen species via denitrification and utilise nitrogen formed in aquaculture for the needs of plant growth (Wongkiew *et al*., 2017). Denitrification is carried out in anoxic conditions by various archaea and heterotrophic bacteria, such as *Aerobacter*, *Acinetobacter* and *Pseudomonas* (Wonkiew *et al*., 2017). Organic material in circulating water acts as electron donor and the source of carbon. However, sufficient carbon source need to be maintained to avoid accumulation of intermediate products NO and N_2O.

The most detrimental problems experienced in RAS have been associated with both low DO and high concentrations of metabolic waste, such as TAN, ammonia (NH_3-N), nitrite (NO_2-N) and CO_2 (Molleda, 2007). Typically, fish produce 1.0–1.4 mg L^{-1} TAN, 13–14 mg L^{-1} CO_2 and 10–20 mg L^{-1} total suspended solids (TSS) per every 10 mg L^{-1} of consumed DO (Hagopian & Riley, 1998; Molleda, 2007).

2.2 | Carbon dioxide

Carbon dioxide (CO_2) is toxic to fish and is a limiting factor in intensive systems. In RAS, fish density is much higher than with more traditional aquaculture methods. High fish density leads to a significant increase in CO_2 content in water. Additionally, nitrifying bacteria produce CO_2 in nitrification (Xiao et al., 2019). A high CO_2 level in water reduces the diffusion gradient between fish blood and water, resulting in blood acidification and reduction in oxygen uptake (Sanni & Forsberg, 1996;

TABLE 1 Limit concentrations of alkalinity (mg L^{-1}), CO_2 (mg L^{-1}), DO (mg L^{-1}), H_2S ($\mu g\ L^{-1}$), nitrogen species (mg L^{-1}), pH, selected metals ($\mu g\ L^{-1}$) and temperature (°C)

Parameter	Limit concentration	Species/additional info	References
Alkalinity (as $CaCO_3$), mg L^{-1}	50–300 70–200	Atlantic salmon	Timmons et al. (2018)Summerfelt et al. (2015)
CO_2, mg L^{-1}	15–20 7–10 <20 <80	Salmonids in freshwater; salmonids in seawater-sensitive species, salmonids-tolerant species, tilapia	Molleda (2007)Timmons et al. (2018)
Dissolved oxygen (DO), mg L^{-1}	6–9 (70–80%) <5 (70%)		Molleda (2007)Timmons et al. (2018)
H_2S, $\mu g\ L^{-1}$	2 5	In freshwater in marine	Hjeltnes et al. (2019) Sommerset et al. (2020)
NO_3-N, mg L^{-1}	100 200 0–400		Chen et al. (2002)Molleda (2007)Timmons et al. (2018)
NO_2-N, mg L^{-1}	<0.1 0.1	In soft water	Timmons et al. (2018)
NH_3-N, mg L^{-1}	0.03 0.32 2.2 <0.0125–0.03	Arctic charr; rainbow trout; common carp salmonids	Molleda (2007)Timmons et al. (2018)Summerfelt et al. (2015)
TAN (NH_3-N +NH_4-N), mg L^{-1}	<1.0 <3.0	Long-term, cool-water fish warm-water fish, Arctic charr	Molleda (2007)Timmons et al. (2018)
Temperature, °C	<15 15–20 >20 14–16 28–32	Cold-water species cool-water species warm-water species rainbow trout tilapia	Timmons et al. (2018)
pH	4.2 6.5–8.5	Rainbow trout, roach LC 8-day median general suitable pH range	Alabaster and Lloyd (1980)Timmons et al. (2018)
Cadmium (Cd), $\mu g\ L^{-1}$	11	Salmonid juveniles and adults, (hardness 4 mg L^{-1} as $CaCO_3$)	Alabaster and Lloyd (1980)
Copper (Cu), $\mu g\ L^{-1}$	5.0 <30	Rainbow trout (hardness 10 mg L^{-1} as $CaCO_3$)	Alabaster and Lloyd (1980)Davidson et al. (2009)
Zinc (Zn), $\mu g\ L^{-1}$	30 <269	Salmonids (hardness 10 mg L^{-1} as $CaCO_3$)	Alabaster and Lloyd (1980)Davidson et al. (2009)

Molleda, 2007). Fish ventilate CO_2 via the gills as molecular CO_2 gas, which forms carbonic acid H_2CO_3, bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) in water which are in equilibrium, based on pH and partial pressure of CO_2 (Fig. 1) (Boyd, 2000; Molleda, 2007). For rainbow trout (*Oncorhynchus mykiss*), excretion of CO_2 has been estimated to 1–2 mg CO_2 kg^{-1} min^{-1}. Typically, a limit value for CO_2 is 20 mg L^{-1} in water, but tilapia (*Oreochromis niloticus*), for example, can tolerate as much as 60 mg CO_2 L^{-1} (Timmons et al., 2018).

Excessively high concentrations can damage the respiratory system of fish or even result in mortality (Fivelstad et al., 2003) and decrease biofilter efficiency (Ren, 2014; Xiao et al., 2019). Removal of CO_2 also affects the water pH. For example, an 80% decrease of CO_2 can lead to a significant increase of pH (Chen et al., 2009). The rate of CO_2 removal is affected by the initial CO_2 content, water flow, gas-water volume ratio, type and structure of equipment and the inlet air flow rate (Gong et al., 2017).

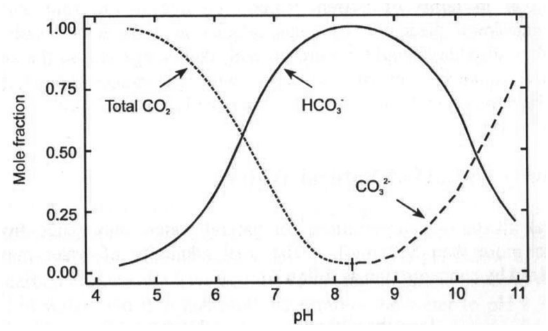

FIGURE 1 Mole fractions as a function of pH on proportions of CO_2, HCO^{3-} and CO_3^{2-} (Boyd, 2000; Molleda, 2007).

Over the years, a variety of equipment has been used for CO_2 removal. CO_2 degassing towers have been used since the 1980s and their effect has been evaluated by (Summerfelt et al., 2003). Additionally, the injection of micron-sized air bubbles into a foam fractionator increases aeration and CO_2 removal (Barrut et al., 2013). For example, an airlift pump with CO_2-stripping can remove 13-20 g CO_2 kWh^{-1} (Loyless & Malone, 1998) and paddlewheels 1.2 kg CO_2 kWh^{-1} (Eshchar et al., 2003).

2.3 | Alkalinity

Total alkalinity is described as the concentration of bases in water which can react with a hydrogen ion (H^+). Several compounds can react in water with hydrogen ion and the total alkalinity describes the contribution of different ions to alkalinity (Boyd et al., 2016). However, in natural waters alkalinity is mostly derived from HCO_3^-, CO_3^{2-} and OH^- (Eq. 1, Boyd et al., 2016). Traditionally, alkalinity has been expressed as mg $CaCO_3$ L^{-1} because alkalinity mainly originates from limestone (mixture of $CaCO_3$ and $MgCO_3$) or as milliequivalents per litre of calcium oxide (CaO). Limestone composition varies from $CaCO_3$ (calcite), $MgCO_3{\cdot}CaCO_3$ (dolomite) to mixture of $CaCO_3$ and $MgCO_3$ (Boyd et al., 2016). Besides alkalinity, limestone is a major source of hardness, the term used to describe the ability of water to precipitate soap and defined as the concentrations of primarily calcium (Ca^{2+}) and magnesium (Mg^{2+}; Timmons et al., 2018).

$$\text{Alkalinity} = \left[HCO_3^-\right] + 2\left[CO_3^{2-}\right] + \left[OH^-\right] - \left[H^+\right] \tag{1}$$

Alkalinity is also connected to buffering capacity. A buffer includes a mixture of a weak acid and its conjugate base (salt) or a weak base and its conjugate acid, such as acetic acid and its conjugate base sodium acetate or ammonium hydroxide and its conjugate acid ammonium chloride (Boyd et al., 2016). Dissolved CO_2, HCO_3^- and CO_3^{2-} buffer water against sudden changes in pH and water with low alkalinity will lead to greater fluctuation in pH (Boyd et al., 2016).

The pH of most freshwaters is based on HCO_3^- ions and dissolved acid CO_2 from air, excluding effects of biological activities and pollution. Typical alkalinity in freshwater ranges from below 5 mg L^{-1} to over 500 mg $CaCO_3$ L^{-1}, based the geology of the aquifer, while the alkalinity of seawater is about 120 mg $CaCO_3$ L^{-1} (Timmons et al., 2018).

In aquaculture, acids and bases may be added in circulating water which leads to change in alkalinity and pH. For example, removal of CO_2 from water increases pH, and at pH 8.3 the concentration of CO_2 is reduced to negligible (Boyd et al., 2016). Besides total alkalinity and pH, concentration of dissolved CO_2 is affected by temperate; its concentration decreases with increasing pH and temperature. Variety of bases, for example, $CaCO_3$, Na_2CO_3 and NaOH, can be added as alkalinity supplements (Timmons et al., 2018).

Maintaining adequate alkalinity concentrations has been reported to be critical for nitrification. For example, alkalinities of 40–80 mg $CaCO_3$ L^{-1} have been reported for wastewater. For aquaculture, Chen et al. (2006) recommend maintaining an alkalinity level at 200 mg $CaCO_3$ L^{-1} to support nitrification. Summerfelt et al. (2015) suggested alkalinity of 70 mg $CaCO_3$ L^{-1}, while a wide range of 50–300 mg $CaCO_3$ L^{-1} has also been reported (Timmons et al., 2018).

2.4 | Temperature

Each aquaculture farm has a unique optimum temperature range. Fish can be classified into three classifications depending on their temperature preference: cold-water, cool-water and warm-water species. For cold-water species, optimum water temperatures are below 15°C, for cool-water species between 15 and 20°C, and for warm-water species above 20°C (Timmons et al., 2018, Table 1). Temperature affects the physiological processes of the reared species, such as respiration rate, efficiency of feeding, growth, behaviour, reproduction and depuration (Drake et al., 2010). Additionally, several factors affect the tolerance of fish to different temperatures, including species, age, size and past thermal history (Timmons et al., 2018).

In RAS, temperature should be measured from several locations such as in rearing tank water and slaughtered fish (Lekang, 2013). Especially, measurement of inlet water temperature is important for designing and selecting a suitable heating equipment and for operating a RAS. The control of rearing temperature allows maintaining good rearing conditions for optimum growth and feed utilisation, although the inlet water temperature may vary considerably between seasons (Dalsgaard et al., 2013). A monitoring equipment based on a programmable logic controller (PLC) for real-time monitoring of recirculating water and water level was reported by Wu et al. (2011). On the other hand, water source heat pumps generate low-grade heat from natural sources and can be used for heating and cooling.

For heating, four different heating methods are typically used; boilers, geothermal energy, factory waste heat and heat pumps or other equipment (Xiao et al., 2019). Industrial heat is limited by geographical conditions. Heating by boilers is common, but increasing attention to environmental pollution is likely to reduce the attractiveness of boiler heating. So far, only a limited number of studies have been related to temperature control in RAS (Good et al., 2011; Davidson et al., 2014; Xin et al., 2017).

Water source heat pumps have been used to heat aquaculture water and to maintain stable temperature around the year (Xin et al., 2017), while Good et al. (2011) used a heat exchanger in RAS rearing rainbow trout (*O. mykiss*) and Davidson et al. (2014) a geothermal heat exchanger. Geothermal energy has been used for heating in RAS farms producing salmon, trout, tropical fish, lobsters, shrimp and prawns (Ragnarsson, 2014). Waste heat from industry has been used for commercial oyster, penaeid shrimp and salmon farming (Rickard, 1998), while heat from power plants has been used for eel and salmonid fingerlings production (Lemercier & Serene, 1980; Ingebrigtsen & Torrissen, 1980). Additionally, ground heat has been used as a heat source for temperature control in RAS (Jiang et al., 2017). In recent years, there has been interest in solar technologies to maintain selected water temperature in RAS, but only a simulation model regarding solar heating systems in RAS has so far been published (Fuller, 2007).

2.5 | Salinity

Salinity represents a content of dissolved salt in water, including calcium, sodium, potassium, bicarbonate, chloride and sulphate ions (Timmons et al., 2018). Water is commonly described as fresh, brackish or saltwater based on its salinity.

Cl^- and Na^+ ions are predominant in sea water, while carbonates and HCO^{3-} in fresh water. Typically, sea water contains 35 g L^{-1} salt (mainly 77.8% NaCl and 10.9% $MgCl_2$; Boeuf & Payan, 2001). It is more difficult to determine general values for fresh water, but 0.32 g L^{-1} (35.1% $CO_3{}^{2-}$, 20.4% $HCO_2{}^{3-}$, 12.1% $SO_4{}^{2-}$, 11.7% SiO_2 and 5.8% Na^+) have been reported (Boeuf & Payan, 2001).

Fish maintain concentrations of dissolved salts in their body fluids via osmoregulation by regulating the uptake of ions from the environment and through the restriction of ion loss (Timmons et al., 2018). For example, the best salinity range on growth for Atlantic salmon *Salmo salar* is 22–28 ppt or g L^{-1} (0–35 tolerated), 8 for tilapia *O. niloticus* (0–16 tolerated) and 0 g L^{-1} for rainbow trout *O. mykiss* (0–34 tolerated) (Boeuf & Payan, 2001). Most freshwater fish reproduce and grow well at salinities up to at least 4–5 g L^{-1}. Freshwater aquaculture systems are generally maintained at 2–3 g L^{-1} salinity (Timmons et al., 2018).

Seawater RAS may have higher operating costs compared with freshwater or brackish water RAS because of the lower efficiency of CO_2 (Moran, 2010) and ammonia removal in seawater and requirement to increased scale of equipment (Bakke et al., 2017). On the other hand, problems related to accumulation of off-flavours have been observed less often in saline water (15–33 g L^{-1}; Tucker, 2000).

Salinity affects reaction rates for ammonia oxidising (AOB) and NOB in brackish or saltwater conditions (NaCl above 5 g L^{-1}; Kinyage et al., 2019). At very low salinity, NaCl below 3.7 g L^{-1}, only minor effects have reported whereas complete inhibition was observed at a salinity of NaCl above 24 g L^{-1} (Cortés-Lorenzo et al., 2015).

Feed intake, feed conversion and growth rate are improved in brackish conditions (8–20 g L^{-1}) due to reduced energy expenditure on osmoregulation and lower standard metabolic rate (Árnason et al., 2013). Furthermore, brackish water (12 g L^{-1}) combined with moderate exercise (water velocity of minimum 1 body lengths s^{-1}) has shown a positive effect on salmon growth, survival and welfare in RAS (Ytrestøyl et al., 2020).

2.6 | Hydrogen sulphide

The smell of hydrogen sulphide (H_2S) resembles rotten eggs. It is highly soluble in water (4000 mg L^{-1} at 20°C (Barton et al., 2014). H_2S gas is also colourless, somewhat heavier than air (1.19 at 15°C) and flammable (Rubright et al., 2017). In water, H_2S equilibrates with bisulphide (HS^-) and sulphide (S^{2-}) (Eq. 2). H_2S and S^{2-} are toxic, while HS^- is not (Tanudjaja, 2021). The dissociation of H_2S greatly depends on pH, and HS^- formation begins at pH 5 (Fig. 2). In marine water systems, pH below 6.8 is a matter of concern due to sulphides, which can trigger the production of H_2S (Rojas-Tirado, 2018).

$$H_2S\,(g) \Leftrightarrow H_2S\,(aq) \Leftrightarrow HS^- + H^+ \Leftrightarrow S^{2-} + 2H^+ \tag{2}$$

H_2S is toxic to all aquatic species at very low concentrations (Lien et al., 2022). Long-term exposure can cause growth reduction and great stress on fish due to disruption of the respiration process and cellular anoxia (Kiemer et al., 1995). In marine water, sulphate concentration is about 1000 times higher than in freshwater (Letelier-Gordo et al., 2020), which can lead to H_2S formation. Marine RAS are therefore vulnerable to H_2S outbreaks. In recent years, H_2S poisoning has caused severe fish mortalities and resulted in high economic losses (Hjeltnes et al., 2019; Sommerset et al., 2020).

Although H_2S is known to be toxic, toxicity levels have not been set by the authorities. However, for freshwater species, over 2 μg L^{-1} and marine species, over 5 μg L^{-1} are not recommended (Table 1) (Boyd, 2014; Hjeltnes et al., 2019; Sommerset et al., 2020). The 96-h lethal concentration for H_2S in freshwater ranges from 20 to 50 μg L^{-1}, and in a marine environment from 50 to 500 μg L^{-1} (Boyd, 2014).

H_2S poisoning occurs and harms the fish quickly (Lien et al., 2022). Frequent measurements are therefore required to obtain specific information regarding H_2S formation. Unfortunately, the monitoring of H_2S levels may not be enough, and the prediction of potential occurrences is required to prevent the problems in advance.

Possible factors leading to H_2S formation are sulphate content in water (freshwater 5–50 mg L^{-1}, sea water 2700 mg L^{-1}), the presence of carbon-based compounds in water, biodegradation reactions in anoxic conditions with accumulated organic material and bacteria, for example, sulphate-reducing bacteria or methane-reducing bacteria (Li & Lancaster, 2013; Letelier-Gordo et al., 2020). Certain physical properties such as high turbidity, sedimentation of organic matter and low water flow rate can also affect H_2S formation (Yu & Bishop, 2001). Additionally, carbon-based material from uneaten feed or faeces can react with sulphate, forming HS^- and later toxic H_2S (Eq. 3). Organic matter can also participate in H_2S production via biodegradation which occurs via oxidation and reduction reactions; electrons are transferred from organic carbon donor to electron acceptor (Lien et al., 2022).

$$CH_4 + SO_4^{2-} \rightarrow HCO_3^- + HS^- + H_2O \tag{3}$$

2.7 | Ozone

Ozone is an environmentally safe disinfectant (Hansen et al., 2016) which improves water quality in RAS due to the oxidisation reactions of nitrite, organic material, chemical oxygen demand, colour and suspended solids (Summerfelt et al., 2009; Davidson et al., 2011a). Ozone can also attack off-flavour-causing compounds such as geosmin, bacteria and fish pathogens (Summerfelt et al., 2009). Ozone reacts rapidly with any organic matter, but residual ozone fed directly to a rearing tank severely threatens farmed species (Powell & Scolding, 2018).

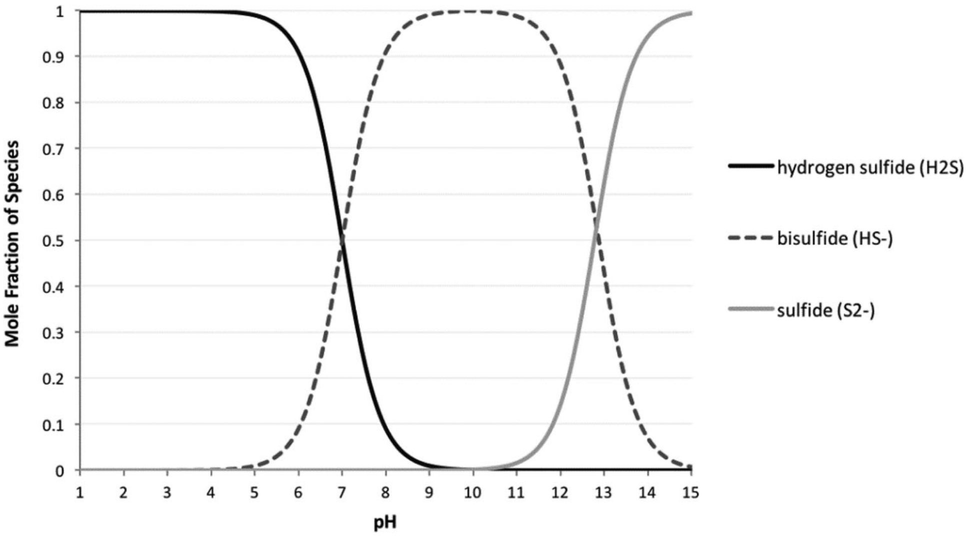

FIGURE 2 Mole fractions of hydrogen sulphide (H_2S), bisulphide (HS^-) and sulphide (S^{2-}) as a function of pH (Applied analytics, 2022).

Several commercial ozone sensors are available. However, they can be very expensive or unreliable or do not show the changes in ozone concentration. ORP is therefore widely used to monitor the ozone addition (Davidson et al., 2011a; Powell & Scolding, 2018). ORP records the readiness of substances in solution to give or receive electrons. In RAS, an ORP sensor should be placed at a point where ozone is completely consumed and downstream of the ozone addition point to prevent ozone damaging the sensors (Bullock et al., 1997). However, ORP gives only an indirect result by the difference in readings before and after the ozone treatment, and other methods such as mediated electrochemical oxidation and changes in UV absorbance at 254 nm or at 272 nm have been suggested (Hansen et al., 2010; Wenk et al., 2013).

The ozone production result can be determined by titration with an iodometric standard method (IOA Standardization Committee Europe, 001/87 (F), 1987), while dissolved ozone in water with the standard colorimetric indigo -method (IOA Standardization Committee – Europe, 006/ 89 (F), 1989), as recently reported in Pettersson et al. (2022).

3 | MEASUREMENTS

3.1 | Measurements of water quality

Successful intensive aquaculture requires the monitoring of several water quality parameters, such as DO, salinity, temperature, pH and electrical conductivity (EC) (Jamroen et al., 2023). Traditionally, water quality parameters have been measured at certain intervals with handheld sensors. However, this requires staff, can be time consuming and is possible only during working hours. In recent years, instrumentation, automation and monitoring systems have developed and become more common and many of the basic measurements can be carried out by online instrumentation (Lekang, 2013). The development of information technology and low-cost sensors has increased the feasibility of monitoring via wireless sensor networks (WSN). The special conditions in aquaculture must be considered when designing and installing instruments (Lekang, 2013). Besides the price of instrumentation, maintenance, running costs and calibration are required, and sensors may require changing at fixed intervals.

Real-time and efficient monitoring of water quality is essential to ensure cost-effective RAS management. For example, Zhu et al. (2010) reported an online water monitoring system which was able to monitor DO, pH, temperature and EC. Zhang et al. (2011) used an Orion5-Star Portable pH/ORP/DO/EC Multimeter to measure these factors in a RAS. Later, Odey and Li (2013) used an AquaMesh wireless mesh sensor network to measure pH, DO, temperature and EC. Several studies have reported methods to measure these variables online in aquaculture (Odey & Li, 2013; Schmidt et al., 2018 Danh *et al*., 2020) but they all measured the basic variables of water quality.

The most common basic water quality parameters, such as temperature, pH and DO, can be measured with portable instruments such as Multi 3410 (WTW GmbH) (Chun et al., 2018). Although portable alternatives are available, nitrite, nitrate and phosphate are often measured more accurately in a laboratory, using an ion-exchange chromatograph and suppressed conductivity detector (e.g., Dionex DX-500, Dionex ICS1600, Dionex Integrion HPIC; Chun et al., 2018; Lindholm-Lehto et al., 2020, 2021).

Instruments applying laboratory methods have been modified for aquaculture facilities. A typical detector is a spectrophotometer, which measures the absorption of light in a sample. Integration of monitoring equipment and intelligent data management have been commercially available, for example, from Greenspan and Fleck in Australia, Gimat in Germany, and Isoc, Hydrolab and Emnet in the USA (Zhang, 2007; Lv, 2015). Additionally, Siemens has developed a YSI5200 monitoring systems (Shi et al., 2011). YSI has designed monitoring and control systems specifically for aquaculture with sophisticated alarm modes (Timmons et al., 2018). Model 5200A can continuously monitor and log DO, pH, conductivity, ORP, salinity and temperature, and Model 5400 for four

DO probes and four additional inputs such as temperature, pH and ORP.

As a result of the development of online instruments, CO_2, ammonia and nitrate sensors are widely available (Pulkkinen et al., 2018). The sensors can be for individual parameters or several sensors included in one instrument (Lekang, 2013). For example, automatic monitoring of DO, pH and temperature in a RAS was performed with WATT TriO Matic 700IQ (SW), WATT Sensolyt 700 IQ (SW) and WATT TrioxyTherm sensors (Zhang, 2007). WSN equipment greatly reduces the requirement for maintenance and costs, but especially in marine systems, coating of sensors is required to prevent corrosion (Hu et al., 2020).

Water quality can also be monitored by electrochemical analysis. This includes salinity, pH, DO, total organic carbon (TOC), temperature, BOD, dissolved carbon and reduction potential (Bergheim & Fivelstad, 2014; Kolarevic et al., 2014). For example, companies supplying electrochemical sensors commercially include Oxygard Pacific (OxyGuard International A/S, Denmark) and Pentair Point Four (Pentair, UK). These sensorst' measurements are not specific but give a rough indication of water quality, and more accurate analyses for specific quantification can be performed in the laboratory (da Silva et al., 2018).

Tziortzioti *et al.* (2019) reported an inexpensive, portable device for water quality measurements without the need for a communications infrastructure and network connection. The Arduino device was equipped with SD card reader and an Ethernet module, and the measurement data were stored on the SD card (Tziorzioti *et al.*, 2019). The card can be removed and connected to a laptop or a smart phone for data transfer if necessary. The device included a digital temperature sensor, a total dissolved solids meter, an analogue turbidity sensor for measuring suspended particles, an analogue DO meter and an analogue pH Meter.

Santos et al. (2022) reported a pilot design of electrochemical oxidation of ammonium nitrogen in marine RAS water rearing gilthead sea bream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*). They measured TAN, fish growth (specific growth rate SGR, FCR, specific feed rate SFR), microbial count (FCU mL^{-1}) and water and energy consumption (Santos et al., 2022). The system included incorporated automatic online analysers for monitoring pH, DO, temperature, ORP, TAN and chlorine content. The TAN concentration was monitored in real time, while the other parameters were periodically measured.

Lien et al. (2022) developed a sensor to detect H_2S at sub $\mu g\ L^{-1}$ levels. The AquaSense system was a mobile wireless and a real-time monitoring system which consisted of units in different locations in a RAS. The sensors measured H_2S ($\mu g\ L^{-1}$), DO (% saturation), CO_2 (mg L^{-1}), pH, salinity (‰), alkalinity (mg L^{-1}), turbidity (NTU) and temperature (°C) (Lien et al., 2022). The sensors are not exposed to water. The system was automatically calibrated by feeding calibration gas to sensors at selected intervals. The sensors in a RAS communicated via an open network and collected the data for storage locally or stored in the cloud service. The H_2S sensor covered the 0–80 $\mu g\ L^{-1}$ range (Lien et al., 2022).

A future trend in aquaculture is an automatic remote monitoring and computer control of systems. For example, Zhu et al. (2010) used a Code Division Multiple Access (CDMA) service and an IPsec-based virtual private network to monitor water quality. CDMA is a competing cell phone service technology to GSM. The system consisted of water quality control components, data acquisition and data transformation and transmission. It was able to monitor water and room temperature, DO saturation, DO concentration, pH, EC and salinity, and notify any abnormalities (Zhu et al., 2010).

3.2 | Measurement frequency

Monitoring of water quality should include many parameters (Table 2). Some of them require constant monitoring (e.g., DO, CO_2, pH) to avoid detrimental disturbances in RAS, while others can be monitored less frequently (e.g., off-flavours, trace elements and metals). However, effective online monitoring systems are unavailable for all parameters, especially not at reasonable cost.

To maintain water quality at optimal range, quality parameter data need to be gathered regularly. Traditionally, water quality has been monitored by manually taking samples and sent for analysis in a laboratory (Pasika & Gandla, 2020). This takes time, requires analytical equipment and can be labour intensive (Pasika & Gandla, 2020), but does not provide real-time data. There are various opinions for, how often water quality parameters should be measured (Jamroen et al., 2023). For example, Ferreira et al. (2011) suggested daily monitoring of DO and temperature, and salinity, but weekly monitoring of pH and turbidity. However, dramatic changes in water quality can be missed which can lead to major fish mortalities and financial losses. New sensor technology and wireless communication for remote monitoring is possible in real-time (Jamroen et al., 2023). Real-time monitoring of selected water quality parameters is required for farmers to recognise low water quality and make management decisions (Oberle et al., 2019).

In aquaculture, economic constrains, high costs of human resources and real-time monitoring of all the important water quality parameters have long been real challenges for farmers (Rashid et al., 2021). It is impossible to monitor water quality based only on experience, but an intelligent system can monitor water quality parameters in real time and help maintain good water quality (Saha et al., 2019; Rashid et al., 2021). A water quality prediction model can be useful for predicting dynamic changes in water. Furthermore, a smart aquaculture system can reduce labour costs and be beneficial for fish health (Ghose, 2014).

A monitoring system with sensors and a microcontroller can monitor pH, turbidity, water level, temperature and humidity (Pasika & Gandla, 2020). The data were collected continuously and in real time sent wirelessly to the monitoring station. The system included a microcontroller unit with a sensor network for sampling every 10 s from the water tank (Pasika & Gandla, 2020). Additionally, an algorithm was used to monitor the changes in water quality parameters.

3.3 | Real-time measurements

Various methods for water quality monitoring have been reported (Zhu et al., 2010; Huan et al., 2020; Lin et al., 2021). Typically, they can

TABLE 2 Selected water quality parameters (alkalinity, DO, CO_2, EC, nitrite-N, nitrate-N, pH, ORP, salinity TAN, temperature and TOC) typically monitored in RAS, examples of their analysis methods and instrumentation

Parameter	Method of analysis	Instrumentation	References
Alkalinity	Standard titration method (ISO 9963—1:1994) Hach Method 8203–Sulfuric Acid Digital Titration	TitraLab AT1000, Hach	Lindholm-Lehto et al. (2021)Davidson et al. (2017)Pulkkinen et al. (2018)
Dissolved oxygen (DO)	Portable instruments online-monitoring, electrochemical analysis	Orion5-Star Portable pH/ORP/DO/EC Multimeter Oxygard Pacific	Zhang et al. (2011)Schmidt et al. (2018)Danh et al. (2020)
Carbon dioxide (CO_2)	Online-monitoring quick spectrophotometric tests	Franatech Hach Method 8223	Pulkkinen et al. (2018)Davidson et al. (2019)
Electrical conductivity (EC)	Portable instruments online-monitoring	Orion5-Star Portable pH/ORP/DO/EC Multimeter AquaMesh network Oxygard Pacific	Zhang et al. (2011)Odey and Li (2013)da Silva et al. (2018)
Hydrogen sulphide (H_2S)	Wireless online monitoring system	AquaSense system	Lien et al. (2022)
Nitrite-N Nitrate-N	Ion chromatography, IC portable instruments online- monitoring quick spectrophotometric tests	Dionex DX-500 (Dionex) Multi 3410 (WTW GmbH) LCK340, LCK341,	Chun et al. (2018)Lindholm-Lehto et al. (2020, 2021) Pulkkinen et al. (2018)
Oxidative reduction potential (ORP/Redox)	Portable instruments online-monitoring electrochemical analysis	LAQUAact, Horiba scientific D-74 LoRaWAN (Long Range Wide Area Network),	Tolentino et al. (2021)Pettersson et al. (2022)Schmidt et al. (2018)Danh et al. (2020)
pH	Portable instruments online-monitoring electrochemical analysis	AquaMesh network Oxygard Pacific ProMinent	Zhu et al. (2010)Odey and Li (2013)Pulkkinen et al. (2018)
Salinity	Ion chromatography, IC portable instruments	Dionex DX-500 Oxygard Pacific YSI 30 Salinity Meter	Danh et al. (2020)Lindholm-Lehto et al. (2020, 2021)
Total nitrogen (TAN)	Quick spectrophotometric tests	Hach Method 8038 USEPA Nessler	Davidson et al. (2019)
Temperature	Electrochemical analysis portable instruments online-monitoring	Oxygard Pacific Temperature Meter	Danh et al. (2020)Bergheim and Fivelstad (2014) Kolarevic et al. (2014)
Total organic carbon (TOC)	Electrochemical analysis	Oxygard Pacific	Bergheim and Fivelstad (2014) Kolarevic et al. (2014)

measure the basic water quality factors (e.g., DO, pH, temperature) which greatly affect the survival of the reared species.

In recent years, a variety of monitoring systems has been reported, such as a remote monitoring system for aquaculture (Wang et al., 2012), WSN (Nam et al., 2015) and a WSN automatic monitoring system for fisheries that combines WiFi and ZigBee technologies (Chen et al., 2016). Zigbee is built for control and sensor networks for wireless personal area networks (WPANs) and operates on 2.4 GHz, 900 MHz and 868 MHz frequencies. WSN consists of self-organised sensors that measure, collect, transmit and process data in real time. The information is displayed on a computer or conveyed for remote monitoring (Chen et al., 2016). Over the last decade, WSN has been widely used in aquaculture (Zhang et al., 2011; Huang et al., 2013; Cario et al., 2017).

Odey and Li (2013) used an AquaMesh wireless mesh sensor network to measure pH, DO and EC. Later, WSN and a general packet radio service (GPRS) were applied to remotely monitor water quality parameters and feed consumption (Lorena *et al*., 2018). Lin et al. (2021) used online monitoring of temperature, pH, DO and EC in an intensive culture system. They used a portable pH/ORP/DO/EC Multimeter to measure these variables in a RAS connected with a constructed wetland. The applications have been in used in variety of industries, also in fish farms (Zhang et al., 2011; Huang et al., 2013; Chandanapalli, 2014; Luo et al., 2015; Cario et al., 2017). Physical water quality parameters were measured in real time and stored in a database. However, these systems included only the most basic variables (temperature, DO, pH, water level). A responsible person was informed of a problem by SMS or email (Zhang et al., 2011). Graphical display of real-time data was available (Huang et al., 2013), while solar and lithium cells have also been used as power supply (Luo et al., 2015).

Long transmission distance, fast communication and high transmission distance quality have been achieved with the 4G technology. In future, 5G technology will be applied to further enhance the data transfer. Addition of data processing to support subsequent analysis can improve data quality. It consists of data cleaning, integration, transformation and data reduction (Fang, 2009). This usually means data repair and noise reduction. Several different data repairing mechanisms have been suggested, such as request retransmission mechanism (Li et al., 2014a), distributed storage mechanism (Omiwade & Zheng, 2012), multi-path disjoint data transmission (Li et al., 2014b) and data redundancy backup (Srouji et al., 2011). Additionally, a compression sensing algorithm can be incorporated (Zhao, 2015).

Many noise reduction methods have been proposed, such as least square method, quadratic bilinear time frequency analysis, Fourier transform and wavelet transform, to eliminate noise interference in measurements (Wickersham et al., 2014; Hu et al., 2020). The wavelet analysis can realise the separation and extraction of frequencies for water quality signals (Wickersham et al., 2014). It is a convenient tool which has been used, for example, in hydrological and water quality prediction (Ebrahimi et al., 2013; Yu et al., 2014).

Tolentino et al. (2021) reported a system which monitored and automatically corrected water quality parameters in an intensive system rearing Nile tilapia (*O. niloticus*). They developed a monitoring system for pH, ORP, turbidity, temperature, salinity and DO in water. Furthermore, the system included an internet-based access and online-applications to monitor the status of the system and parameters (Tolentino et al., 2021). The system consisted of sensors, microcontrollers, a Long Range Wide Area Network (LoRaWAN), and correcting devices: a microcontroller, water pump, heater, water bottle and drum. Water quality was improved by adding new replacement water, while pH was corrected by adding sodium bicarbonate solution.

3.4 | Internet of Things in aquaculture

In recent years, Internet of Things (IoT) has become increasingly common. In aquaculture, the IoT has been applied in real-time monitoring and adjusting of water levels and pumping (Kassem et al., 2021). Anand and Regi (2018) used a Narrow Band (NB)-IoT system for remote monitoring of water levels in rearing tanks. This technology had low costs, low power consumption and wide coverage which is suitable for aquaculture. For example, an IoT-based water quality monitoring system for temperature, pH, DO and salinity (Dahn *et al*., 2020). Lin et al. (2021) showed that a wireless multi-sensor IoT integrated with sensors measuring pH, temperature, DO and EC with WiFi communication for aquaculture, showing good accuracy and confidence.

Huan et al. (2020) reported a monitoring system for aquaculture water quality based on NB-IoT with chip and sensor technology to collect aquatic environment information. It was applied for the non-gateway data report through the NB module and a cloud platform to save the received data. Temperature, pH and DO sensor devices collected the water quality data and encoded them for the data frame format. Additionally, the system enabled the remote control of equipment.

In the study of Kassem et al. (2021), the RAS monitoring system consisted of three components: monitoring of the most vital water quality parameters, monitoring the water sampling inlets connected to basin water, and the components responsible for cleaning pipes. No cleaning fluid was fed into the rearing tanks. The sensor case contained a separate cleaning mechanism to ensure the cleaning of sensors and their calibration (Kassem et al., 2021). The system run-time depended on the distance from the sampling point to the sensor and controller (about two hours, including the cleaning sequence). The systems showed high accuracy due to automated sampling and cleaning. It was run non-stop to ensure multiple measurements per day (Kassem et al., 2021). A decreased labour requirement led to decreased costs, but it could still measure a wide range of parameters: ammonia, nitrite, pH, total vibrio (cfu mL^{-1}), alkalinity, temperature, salinity and DO.

Rashid et al. (2021) reported a system applying an IoT-based monitoring system for real-time water quality, which focused on water level parameters. They collected data via sensors, analysed the data with machine learning tools to study and monitor the water quality. The water quality parameters included pH, temperature and TSS, and the correlation between the parameters was also studied (Rashid et al., 2021). The prediction model was trained based on the collected data. They showed that the system increased efficiency, reduced labour requirements and ensured more sustainable and economical production. They also reported good testing accuracy and performance but still wished to improve it in the future.

IoT systems in aquaculture typically use WSN with wide coverage area and good scalability (Pule et al., 2017). These technologies include Zigbee, Bluetooth (Hu et al., 2020) and General Packet Radio Services (GPRS)/CDMA/long-term evolution (Zhu et al., 2010). Zigbee is widely used in WSN for water quality monitoring. However, sensitive systems can easily malfunction and have high energy consumption in long distance transmission.

A fusion of digital technologies and use of IoT can transform a traditional farming model into smart farming (Narwane et al., 2022). WSNs have made significant contribution to various farming applications (Jamroen et al., 2020, 2023). Wang et al. (2012) designed a remote monitoring system to increase the level of automation and used a 3G cellular technology with an Android-based mobile operating architecture. Nam et al. (2015) developed a WSN-based remote water quality monitoring system by combining a ZigBee network protocol and CDMA technology. Postolache et al. (2014) proposed an IoT-based system for water quality monitoring (EC, temperature and turbidity) in aquaculture, using WSN architecture. Recently, a photovoltaic (PV)/battery energy storage (BES)-powered water quality monitoring system was introduced, based on the NB-IoT (Jamroen et al., 2023). The system could measure DO, pH, temperature, turbidity and salinity, as well as electrical parameters' PV power, system consumption, BES power and state of charge for system functionality.

Besides the real-time information they provide on water quality parameters, early warning signs are also valuable for farmers in detecting abnormalities (Hu et al., 2020). In smart aquaculture, the integration of artificial intelligence and IoT systems can control the risks and improve the quality of aquatic production and ensure the survival of the reared species. This requires real-time collection and processing of reliable water quality data.

3.5 | More advanced analyses

Organic compounds such as veterinary drugs, antibiotics, off-flavour compounds and ozonation by-products in marine systems can enter the system, for example, via inlet water, or are formed in the system. Medications can also be needed in aquaculture, including anaesthetics, vaccines and antibiotics (Costello et al., 2001; Dauda et al., 2019). However, these chemicals are important for aquaculture purposes but are used in low concentrations. Additionally, the detection of cortisol levels and other hormones in aquaculture water and fish have become more important for fish welfare studies (Rollo et al., 2006; Mota et al., 2017; Hanke et al., 2019; Höglund et al., 2022;). Some compounds may be undesirable in fish products (e.g., off-flavours geosmin and 2-methylisoborneol), or they can pose a risk to the raised species (e.g., ozonation by-products). They need to be reliably detected, identified and quantified. This usually requires more advanced chemical knowledge and equipment, and these analyses are therefore performed in a laboratory instead of on a fish farm (Table 3).

Trace metals such as zinc and copper can be led in the system via feed or by erosion of materials, or via inlet water (Kristensen et al., 2009; Bergheim & Fivelstad, 2014). Heavy metals are toxic to fish, as they can interact with osmoregulation and the accumulation of other toxic compounds such as ammonia, or remain in fish flesh, posing a risk to fish consumers (da Silva et al., 2018). This highlights the importance of monitoring trace metals and elements in RAS.

Compound can be analysed with techniques based on liquid (LC) or gas chromatography (GC) based on its properties. Additionally, for the detection of low concentrations of analytes in complex RAS water matrix, a variety of pretreatment methods is required, including solid phase extraction (Gorito et al., 2022; Höglund et al., 2022), solid phase micro extraction (Lindholm-Lehto, 2022) and dynamic headspace (HS) (Podduturi et al., 2017), to name a few (Table 3). In the case of volatile and semi-volatile compounds, GC-based methods are preferred (Lindholm-Lehto et al., 2019; Lindholm-Lehto, 2022), while LC with tandem mass spectrometry (MS/MS) detection is more suitable for antibiotics (Freitas et al., 2014).

4 | EFFECTS OF WATER QUALITY

4.1 | Water quality and fish behaviour

The stress response of fish is related to water quality (Iryna et al., 2013; Hu et al., 2020). Stress in fish can lead to inhibited growth, a weaker immune system and changes in fish behaviour (Hjeltnes et al., 2022). These changes can be crucial, especially as optimal growth is highly desirable (da Silva et al., 2018). For example, stressed zebrafish (*Danio rerio*) showed increased body temperature (2–4°C) which can be considered as a fever response (Rey et al., 2015). Rey et al. (2015) suggested that the observed emotional fever is associated with consciousness in fish. The zebrafish clearly showed the capacity for emotional fever but the link between consciousness is still debated. On the other hand, water properties (temperature) can affect fish growth and genetic sex determination based on temperature (Santi et al., 2017). High temperatures (36°C) led to masculinisation of African catfish (*Clarias gariepinus*) when exposed 6–8 days after hatching. The exposure during the short thermosensitive period led to 90–100% males (Santi et al., 2017).

Certain pollutants can change the movement behaviour of fish, and by measuring the intensity of this behaviour, pollutant concentration can be calculated (Zhang et al., 2013). For a pollutant, models can show if the water quality is polluted or unpolluted but not determine a specific concentration (Peng, 2017). So far, more advanced interactions remain subjects for further studies.

Water quality has been evaluated by studying the average movement speed, height, distant and position distribution of fish (Bernatowicz et al., 2009). Fen (2014) on the other hand, used group behaviour parameters: swimming speed and distance to nearest neighbor, to quantify normal and abnormal water quality. However, all these methods are applicable only in certain conditions, and only a few studies

TABLE 3 Selected water quality parameters measured in RAS which require more advanced analyses in the laboratory and examples of instrumentation required for their analysis

Parameter	Instrumentation	References
Antibiotics	LC-MS/MS[a]	Gorito et al. (2022)Shi et al. (2022)
Cortisol	LC-MS/MS[a]radioimmunoassay (RIA) Cortisol EIA kit	Hanke et al. (2019)Mota et al. (2017)Höglund et al. (2022)Rollo et al. (2006)
DOC, TOC[b]	Aurora 1030 W TOC analyzer Shimdadzu TOC-L analyzer	Li et al. (2016)Pettersson et al. (2022)
Metals	ICP-OES[c]: Perkin-Elmer Optima 8300 ICP-MS[d]: Perkin Elmer NexION® 350D	Lindholm-Lehto et al. (2020, 2021)
Molecular mass of NOM[e]	HPSEC-EEM[f]/UV	Jokubauskaite et al. (2015)Ignatev and Tuhkanen (2019)
Molecular mass of NOM[e]	HPSEC-DAD/FLD[g]EEM-PARAFAC[h]	Li et al. (2014c, 2016)
Off-flavours[i]	Dynamic HS[j-G]C-MS SPME-GC-MS SPME-GC-MS/MS	Podduturi et al. (2017)Lindholm-Lehto et al. (2019)Lindholm-Lehto (2022)
Trihalomethanes Brominated oxidation by-products	GC-MS USEPA Method 524.2 DR/2800 Spectrophotometer	Schroeder et al. (2011)Li et al. (2016)

[a] Liquid chromatography (LC)–tandem mass spectrometry (MS/MS).

[b] Dissolved organic matter (DOC), total organic carbon (TOC).

[c] Inductively coupled plasma optical emission spectrometer (ICP-OES).

[d] Inductively coupled plasma mass spectrometry (ICP-MS).

[e] Organic material, including humic and fulvic acids, protein-like compounds (NOM).

[f] Excitation emission matrix (EEM).

[g] High performance size exclusion chromatography (HPSEC)-diode array detector (DAD)/fluorescence detector (FLD).

[h] Fluorescence excitation-emission-matrix combined with parallel factor analysis (EEM-PARAFAC).

[i] Off-flavours include a variety of compounds, such as geosmin, 2-methylisoborneol and other terpenes, aldehydes, fatty acids and so on.

[j] Dynamic HS Dynamic Headspace sampling of volatiles in Tenax TA traps.

report interactions between multiple water quality parameter and behavioural characteristics of fish.

Based on fish behaviour, it is possible to obtain and predict changes in water quality. The detection of fish behaviour can be based on video imaging, and includes characteristics' shape, texture, background, colour, swimming speed and direction, fin beating frequency, feeding condition and metabolic rate (Yang et al., 2013; Cook et al., 2014). However, video imaging may be unsuitable for aquaculture environment, for example, in the case of high turbidity. Fish can be separated from their backgrounds, based on background modelling, temporal difference method and optical flow method (Hu et al., 2020). For example, Zhang et al. (2015) used a computer vision algorithm to measure pectoral fin and background subtraction to obtain fish location more accurately.

Changes in swimming activity, swimming depth and acceleration can reflect the response of fish to its surroundings (Martins et al., 2012; Kolarevic et al., 2021). Although water quality parameters are frequently monitored in RAS, fish behaviour is not typically as an integral part of the systems (Kolarevic et al., 2016, 2021), and the conditions in RAS on welfare and performance of the raised species need to be improved.

A variety of water quality parameters (DO, CO_2, nitrate, pH) and feeding regimes can affect the swimming behaviour of fish (Davidson et al., 2011a; Martins et al., 2012). Techniques applying biotelemetry have been used to monitor the behaviour of individual farmed and wild fish (Kolarevic et al., 2016, 2021; Sinisalo, 2022). With tags, algorithms of acceleration and gravity forces can be measured accurately and transmitted to acoustic receivers (AccelTag; Thelma Biotel, Norway) (Martins et al., 2012). This technology has been used to monitor swimming activity in sea cages (Føre et al., 2011).

An acoustic acceleration tag, AccelTag, allows real-time monitoring of fish behaviour (Kolarevic et al., 2016). However, they are limited by the available tag sizes (7 and 11 g). The tag size should be about 2%/body mass (Jepsen et al., 2004). By tagging Atlantic salmon post smolts in RAS, swimming behaviour of fish can be monitored and observe changes in water quality and stress events (Kolarevic et al., 2016). Acoustic acceleration tags can therefore be a suitable tool for welfare and management practice studies and for responses to changes in water quality and chronic thresholds of water quality parameters.

Fish movement in good water quality differs from those in abnormal water quality. Cheng et al. (2019) monitored fish movements by two cameras combined a three-dimensional motion trajectory system with a Kuhn-Munkres algorithm. They showed that the learning model successfully reflected the water quality. However, they could not assess water quality in time and were not able to show which water quality parameter caused the abnormal behaviour.

WSNs have also been applied for monitoring of fish behaviour and water quality. For example, Parra et al. (2018) used a WSN to monitor feeding of fish and water quality in rearing tanks. Sensors were used to monitor temperature, turbidity, water level and conductivity, while monitoring of fish behaviour included swimming depth and velocity. Based on the monitored variables and fish behaviour, system was able to control the changes in water quality.

4.2 | Feeding

Fish appetite can be affected by water quality, especially temperature and DO (Sun et al., 2016). Several issues affect feed intake, which can be due to physiological, nutritional or environmental issues (Zhou et al., 2018). Frequency and time of feeding affects feeding intensity, and fish behaviour can vary based on how feed is sprinkled in the tank (Martins et al., 2012).

Excessive feeding increases costs and faeces and uneaten feed lead to increased solid waste in the system and affect the water quality and microbial abundance in the system (Rojas-Tirado et al., 2018; Zhou et al., 2018). Currently, automated feeding systems are widely used in aquaculture. However, predicting when feeding should be stopped is often based on subjective experience (Zhou et al., 2018).

Feeding can be automatically adjusted based on fish appetite (Zhou et al., 2017a). There are feeding systems that can calculate feed demand real-time based on the quantity of fish. Fish behaviour is monitored by machine vision, underwater acoustic technology and water quality sensors. For example, acoustic sensors can detect feed (Juell et al., 1993) and count the pellets by computer vision (Li et al., 2017) to assess the fish appetite. Computer vision has been widely used because it is relatively inexpensive and does not harm the fish (Sadoul et al., 2014; Lin et al., 2018).

An intelligent feedback control can observe fish behaviour and based on specific control algorithm, stop feeding in the case of aggregation behaviour (Chang et al., 2005). However, computer vision often requires good illumination conditions which can be challenging in turbid water. A near infrared machine vision is more suitable, and with image enhancement algorithms good results can be achieved, also in poorly illuminated conditions (Zhou et al., 2017b). Zhou et al. (2018) reported an automatic feeding control method based on near infrared computer vision and a neuro-fuzzy model for on-demand feeding. They found significant increase in fish growth and the FCR was reduced by 10%, and water quality was improved (Zhou et al., 2018).

5 | CONCLUSIONS

In aquaculture, several water quality parameters need to be monitored to understand the aquatic conditions. There are currently no regulations for which parameters to measure, and each farmer has their own view of and possibilities for water quality measurements. So far, there are no guidelines for acceptable ranges and fluctuations. These have been listed in this study. Although suitable ranges vary between different species, certain guidelines would be a valuable tool for designing and running a RAS facility.

1. Traditionally, water quality parameters have been measured at certain intervals with handheld sensors and quick laboratory tests, but this can time-consuming and possible only during working hours. In recent years, the development of information technology and low-cost sensors has enabled monitoring via WSNs, online monitoring systems and applications of IoT which allow real-time monitoring, automatic data collection and storing.
2. Intelligent systems may include the prediction of problems beforehand based on changes in water quality. Early warning signs are valuable for farmers to detect abnormalities and act before major issues occur. However, many of the modern sensors and monitoring systems need competent users and regular maintenance and calibration. The effects of water quality can also be observed by monitoring fish behaviour such as swimming activity, depth, acceleration and feeding. Fish behaviour can be monitored by, for example, acoustic acceleration tags and computer vision. This can be a valuable addition to the monitoring regime with the more traditional parameters.
3. All the new IoT-based monitoring systems can monitor the basic water quality parameters (DO, pH, temperature, turbidity and salinity), which can be sufficient for regular monitoring purposes. However, the more advanced analyses (e.g., off-flavours, cortisol levels) still need to be performed in a laboratory and cannot be performed in real-time. These may also require more advanced analysis equipment and can only be performed by trained personnel. Development of new techniques which allows real-time monitoring of the more advanced water quality parameters remains as a subject of future studies.

AUTHOR CONTRIBUTION

Petra Lindholm-Lehto: Formal analysis, investigation, writing – original draft, resources

ACKNOWLEDGEMENTS

Financial support from the NordForsk: Sustainable Aquaculture – Research and Innovation Projects is gratefully acknowledged.

CONFLICT OF INTEREST STATEMENT

The author of this research project would like to disclose the absence any personal or financial relationship with people or organisations that may inappropriately influence this work. This naturally includes all grant and sources of funding described in the paper.

DATA AVAILABILITY STATEMENT

Not applicable.

ETHICS STATEMENT

This material is the authors' own original work, which has not been previously published elsewhere.

ORCID

Petra Lindholm-Lehto https://orcid.org/0000-0003-1807-8116

REFERENCES

Abbaszadeh, A., Keyvanshokooh, S., Yavari, V. & Naderi, M. (2019) Proteome modifications of Pacific white shrimp (*Litopenaeusvannamei*) muscle under biofloc system. *Aquaculture Nutrition*, 25, 358366.

Adams, A. & Thompson, K.D. (2011) Development of diagnostics for aquaculture: challenges and opportunities. *Aquaculture Research*, 42, 93102.

Ajani, E.K., Akinwole, A.O. & Ayodele, I.A. (2011) Fundamentals of fish farming in Nigeria. *Walecrown publishers*, Ibadan, Nigeria.

Alabaster, J.S. & Lloyd, R. (1980) *Water quality criteria for freshwater fish*. FAO, Butterworths, London.

Anand, S. & Regi, R. (2018) Remote monitoring of water level in industrial storage tanks using NB-IoT. 2018 International Conference on Communication Information and Computing Technology (ICCICT). IEEE, 14.

Applied analytics: Concept: pH-independent analysis. Available online: https://aai.solutions/concepts/pH-independent-analysis (accessed on 8.10.2022).

Árnason, T., Magnadóttir, B., Björnsson, B., Steinarsson, A. & Björnsson, B.T. (2013) Effects of salinity and temperature on growth, plasma ions, cortisol and immune parameters of juvenile Atlantic cod (*Gadus morhua*). *Aquaculture*, 380, 70-79.

Bakke, I., Am, A.L., Kolarevic, J., Ytrestøyl, T., Vadstein, O., Attramadal, K.J.K. et al. (2017) Microbial community dynamics in semi-commercial RAS for production of Atlantic salmon post-smolts at different salinities. *Aquacultural Engineering*, 78, 42-49.

Barrut, B., Blancheton, J.P., Callier, M., Champagne, J.Y. & Grasmick, A. (2013) Foam fractionation efficiency of a vacuum airlift—application to particulate matter removal in recirculating systems. *Aquacultural Engineering*, 54, 1621.

Barton, L.L., Fardeau, M.L. & Fauque, G.D. (2014) Hydrogen sulfide: A Toxic gas produced by dissimilatory sulfate and sulfur reduction and consumed by microbial oxidation. *Mets. Ions Life Sciences*, 14, 237277. https://doi.org/10.1007/978-94-017-9269-1

Becke, C., Schumann, M., Steinhagen, D., Rojas-Tirado, P., Geist, J. & Brinker, A. (2019) Effects of unionized ammonia and suspended solids on rainbow trout (*Oncorhynchus mykiss*) in recirculating aquaculture systems. *Aquaculture*, 499, 348357.

Bentzon-Tilia, M., Sonnenschien, E.C. & Gram, L. (2016) Monitoring and managing microbes in aquaculture -Towards a sustainable industry. *Microbial Biotechnology*, 9, 567584.

Bergheim, A. & Fivelstad, S. (2014) Atlantic salmon (*Salmo salar* L.) in aquaculture: Metabolic rate and water flow requirements. *Salmon: Biology, Ecological Impacts and Economic Importance*, 8, 155171.

Bernatowicz, W., Weiss, A. & Matschullat, J. (2009) Linking biological and physicochemical water quality. *Environmental Monitoring and Assessment*, 159, 311330.

Blancheton, J.P., Attramadal, K.J.K., Michaud, L., Roque d'Orbcastel, E. & Vadstein, O. (2013) Insight into bacterial population in aquaculture systems and its implication. *Aquacultural Engineering*, 53, 3039.

Boeuf, G. & Payan, P. (2001) How should salinity influence fish growth? *Comp. Biochem. Physiol. Part C*, 130, 411423.

Boyd, C.E. (2000) *Water Quality. An Introduction*. Kluwer Academic Publishers, Dordrecht, London, 325 p.

Boyd, C.E. (2003) Guidelines for aquaculture effluent management at the farm-level. *Aquaculture*, 226, 101112.

Boyd, C.E. (2014) Hydrogen sulfide, toxic but manageable. *Global aquaculture advocate*, Auburn, Alabama USA.

Boyd, C.E., Tucker, C.S. & Somridhivej, B. (2016) Alkalinity and hardness: Critical but elusive concepts in aquaculture. *Journal of the World Aquaculture Society*, 47(1). https://doi.org/10.1111/jwas.12241

Braun, N., de Lima, R.L., Moraes, B., Loro, V.L. & Baldisserotto, B. (2006) Survival, growth and biochemical parameters of silver catfish, *Rhamdia quelen* (Quoy & Gaimard, 1824), juveniles exposed to different dissolved oxygen levels. *Aquaculture Research*, 37, 15241531.

Buentello, J.A., Gatlin, D.M. & Neill, W.H. (2000) Effects of water temperature and dissolved oxygen on daily feed consumption, feed utilization and growth of channel catfish (*Ictalurus punctatus*). *Aquaculture*, 182, 339352.

Bullock, G.L., Summerfelt, S.T., Noble, A.C., Weber, A.L., Durant, M.D. & Hankins, J.A. (1997) Ozonation of a recirculating rainbow trout culture system. I. Effects on bacterial gill disease and heterotrophic bacteria. *Aquaculture*, 158, 4355. https://doi.org/10.1016/S0044-8486(97)00063-X

Bureau, D.P. & Hua, K. (2010) Towards effective nutritional management of waste outputs in aquaculture, with particular reference to salmonid aquaculture operations. *Aquaculture Research*, 41, 777-792.

Burgin, A.J., Hamilton, S.K., (2007). Have we overemphasized the role of denitrification in aquatic ecosystems? A review of nitrate removal pathways. *Front. Ecol. Environ.* 5, 89–96.

Cario, G., Casavola, A., Gjanci, P., Lupia, M., Petrioli, C., Spaccini, D. (2017) *Long lasting underwater wireless sensors network for water quality monitoring in fish farms*. OCEANS, Aberdeen, UK.

Chandanapalli, S.B. (2014) Design and deployment of aqua monitoring system using wireless sensor networks and IAR-Kick. *Journal of Aquaculture Research & Development*, 5, 7.

Chang, C.M., Fang, W., Jao, R.C., Shyu, C.Z. & Liao, I.C. (2005) Development of an intelligent feeding controller for indoor intensive culturing of eel. *Aquacultural Engineering*, 32, 343353.

Chen, S., Summerfelt, S., Losordo, T. & Malone, R. (2002) Recirculating systems effluents, and treatment. In *Aquaculture and the environment in the United States*. Tomasso, J. (Ed.), US Aquaculture Society, Baton Rouge, pp. 119140.

Chen, S., Ling, J. & Blancheton, J.-P. (2006) Nitrification kinetics of biofilm as affected by water quality factors. *Aquacultural Engineering*, 34, 179-197.

Chen, Q.Y., Ni, Q., Guan, C.W., Zhen, Z.X., Liu, H. & Liu, P. (2009) Experimental study of carbon dioxide removal technology in aquaculture waters. *Fishery Modern*, 36, 611.

Chen, J.H., Sung, W.T. & Lin, G.Y. (2016) Automated monitoring system for the fish farm aquaculture environment. *IEEE International Conference on Systems*, 1–6.

Cheng, S., Zhao, K. & Zhang, D. (2019) Abnormal water quality monitoring based on visual sensing of three-dimensional motion behavior of fish. *Symmetry*, 11, 1179. https://doi.org/10.3390/sym11091179

Chumkiew, S., Jaroensutasinee, M., Tina, F.W., Jaroensutasinee, K. & Koad, P. (2019) Physical factors affecting oyster diversity and distribution in Southern Thailand. *Journal of Environmental Biology*, 40, 0308.

Chun, S.-J., Cui, Y., Ahn, C.-Y. & Oh, H.-M. (2018) Improving water quality using settleable microalga *Ettlia* sp. and the bacterial community in freshwater recirculating aquaculture system of *Danio rerio*. *Water Research*, 135, 112121.

Cook, D.G., Brown, E.J., Lefevre, S., Domenici, P. & Steffensen, J.F. (2014) The response of striped surfperch Embiotoca lateralis, to progressive hypoxia: Swimming activity, shoal structure, and estimated metabolic expenditure. *Journal of Experimental Marine Biology and Ecology*, 460, 162169.

Cortés-Lorenzo, C., Rodríguez-Díaz, M., Sipkema, D., Juárez-Jiménez, B., Rodelas, B., Smidt, H. et al. (2015) Effect of salinity on nitrification efficiency and structure of ammonia-oxidizing bacterial communities in a submerged fixed bed bioreactor. *Chemical Engineering Journal*, 266, 233-240.

Costello, M.J., Grant, A., Davies, I.M., Cecchini, S., Papoutsoglou, S., Quigley, D. et al. (2001) The control of chemicals used in aquaculture in Europe. *Journal of Applied Ichthyology*, 17, 173180.

da Silva, L.F.B.A., Yang, Z., Pires, N.M.M., Dong, T., Teien, H.-C., Storebakken, T. et al. (2018) Monitoring aquaculture water quality: Design of an early warning sensor with *Aliivibrio fischeri* and predictive models. *Sensors*, 18, 2848. https://doi.org/10.3390/s18092848

Dalsgaard, J., Lunda, I., Thorarinsdottir, R., Drengstig, A., Arvonen, K. & Bovbjerg Pedersen, P. (2013) Farming different species in RAS in Nordic countries: Current status and future perspectives. *Aquacultural Engineering*, 53, 2-13.

Danh, L.V.Q., Dung, D.V.M., Danh, T.H. & Ngon, N.C. (2020) Design and deployment of an IoT-based water quality monitoring system for aquaculture in Mekong Delta. *International Journal of Mechanical Engineering Robotics Research*, 9, 11701175.

Dauda, A.B. & Akinwole, A.O. (2015) Evaluation of polypropylene and palm kernel shell as biofilter media for denitrification of fish culture wastewater. *NSUK JST*, 5, 207213.

Dauda, A.B., Ajadi, A., Tola-Fabunmi, A.S. & Akinwole, A.O. (2019) Waste production in aquaculture: Sources, components and managements in different culture systems. *Aquaculture Fish*, 4, 8188.

Davidson, J., Good, C., Welsh, C., Brazil, B. & Summerfelt, S. (2009) Heavy metal and waste metabolite accumulation and their potential effect on rainbow trout performance in a replicated water reuse system operated at low or high system flushing rates. *Aquacultural Engineering*, 41, 136145.

Davidson, J., Good, C., Welsh, C. & Summerfelt, S. (2011a) The effects of ozone and water exchange rates on water quality and rainbow trout Oncorhynchus mykiss performance in replicated water recirculating systems. *Aquacultural Engineering*, 44, 80-96. doi.org/10.1016/j.aquaeng.2011.04.001

Davidson, J., Good, C., Welsh, C. & Summerfelt, S. (2011b) Abnormal swimming behavior and increased deformities in rainbow trout *Oncorhynchus mykiss* cultured in low exchange water recirculating aquaculture systems. *Aquacultural Engineering*, 45, 109-117.

Davidson, J., Good, C., Welsh, C. & Summerfelt, S. (2014) Comparing the effects of high vs. low nitrate on the health, performance, and welfare of juvenile rainbow trout *Oncorhynchus mykiss* within water recirculating aquaculture systems. *Aquacultural Engineering*, 59, 3040.

Davidson, J., Good, C., Williams, C. & Summerfelt, S.T. (2017) Evaluating the chronic effects of nitrate on the health and performance of post-smolt Atlantic salmon *Salmo salar* in freshwater recirculation aquaculture systems. *Aquacultural Engineering*, 79, 18.

Davidson, J., Summerfelt, S., Straus, D.L., Schrader, K.K. & Good, C. (2019) Evaluating the effects of prolonged peracetic acid dosing on water quality and rainbow trout *Oncorhynchus mykiss* performance in recirculation aquaculture systems. *Aquacultural Engineering*, 84, 117127.

Drake, S.L., Drake, M.A., Sanderson, R., Daniels, H.V. & Yates, M.D. (2010) The effect of purging time on the sensory properties of aquacultured southern flounder (*Paralichthys lethostigma*). *J. Sens. Stud*, 25, 246-259.

Ebrahimi, F., Setarehdan, S.K., Ayala-Moyeda, J. & Nazeran, H. (2013) Automatic sleep staging using empirical mode decomposition, discrete wavelet transform, time-domain, and nonlinear dynamics features of heart rate variability signals. *Comput. Meth. Progr. Biomedic*, 112, 4757.

Ebrahimi, A., Akrami, R., Najdegerami, E.H., Ghiasvand, Z. & Koohsari, H. (2020) Effects of different protein levels and carbon sources on water quality, antioxidant status and performance of common carp (*Cyprinus carpio*) juveniles raised in biofloc based system. *Aquaculture*, 516, 734639.

Endo, H. & Wu, H. (2019) Biosensors for the assessment of fish health: a review. *Fisheries Science*, 85, 641654.

Eshchar, M., Mozes, N. & Fediuk, M. (2003) Carbon dioxide removal rate by aeration devices in marine fish tanks. *Israeli J. Aquacult. (= Bamidgeh)*, 55, 7985.

Fang, H.Y. (2009) *Data preprocessing method of dimensionless*. Southwest University.

Fen, M. (2014) *Dynamic model of fish behavior and its application in water quality monitoring*. Zhejiang University of Technology.

Ferreira, N., Bonetti, C. & Seiffert, W. (2011) Hydrological and water quality indices as management tools in marine shrimp culture. *Aquaculture*, 318, 425433.

Fivelstad, S., Waagbo, R., Zeitz, S.F., Hosfeld, A.C.D., Olsen, A.B. et al. (2003) A major water quality problem in smolt farms: combined effects of carbon dioxide, reduced pH and aluminium on Atlantic salmon (*Salmo salar* L.) smolts: physiology and growth. *Aquaculture*, 215, 339357.

Freitas, A., Barbosa, J. & Ramos, F. (2014) Multi-residue and multi-class method for the determination of antibiotics in bovine muscle by ultra-high-performance liquid chromatography tandem mass spectrometry. *Meat Science*, 98, 5864.

Føre, M., Alfredsen, J.A. & Gronningsater, A. (2011) Development of twotelemetry-based systems for monitoring the feeding behaviour of Atlantic salmon (*Salmo salar* L.) in aquaculture sea-cages. *Computers and Electronics in Agriculture*, 76, 240251.

Fuller, R.J. (2007) Solar heating systems for recirculation aquaculture. *Aquacultural Engineering*, 36, 250260.

Ghose, B. (2014) Fisheries and aquaculture in Bangladesh: Challenges and opportunities. *Ann. Aquacult. Res*, 1, 1001.

Gong, J.H., Cao, X. & Xu, S.L. (2017) The effect of carbon dioxide removal device on pH level of recirculating aquaculture system. *Fishery Modern*, 44, 1014.

Good, C., Davidson, J., Welsh, C., Brazil, B., Snekvik, K. & Summerfelt, S. (2011) The impact of water exchange rate on the health and performance of rainbow trout Oncorhynchus mykiss in water recirculation aquaculture systems. *Aquaculture*, 294, 8085.

Gorito, A.M., Ribeiro, A.R.L., Rodrigues, P., Fernando, M., Pereira, R., Guimarães, L. et al. (2022) Antibiotics removal from aquaculture effluents by ozonation: chemical and toxicity descriptors. *Water Research*, 218, 118497.

Hagopian, D.S. & Riley, J.G. (1998) A closer look at the bacteriology of nitrification. *Aquacultural Engineering*, 18, 223244.

Hanke, I., Ampe, B., Kunzmann, A., Gärdes, A. & Aerts, J. (2019) Thermal stress response of juvenile milkfish (*Chanos chanos*) quantified by ontogenetic and regenerated scale cortisol. *Aquaculture*, 500, 2430.

Hansen, K.M.S., Andersen, H.R. & Ledin, A. (2010) Ozonation of estrogenic chemicals in biologically treated sewage. *Water Science and Technology*, 62, 649657. doi.org/10.2166/wst.2010.919

Hansen, K.M.S., Spiliotopoulou, A., Chhetri, R.K., Escola Casas, M., Bester, K. & Andersen, H.R. (2016) Ozonation for source treatment of pharmaceuticals in hospital wastewater – ozone lifetime and required ozone dose. *Chemical Engineering Journal*, 290, 507514. doi.org/10.1016/j.cej.2016.01.027

Hjeltnes, B., Bang-Jensen, B., Bornø, G., Haukaas, A. & Walde, C. (2019) *The health situation in Norwegian aquaculture 2018*. Norwegian Veterinary Institute, Ås, Norway.

Hjeltnes, B., Baeverfjord, G., Erikson, U., Mortensen, S., Rosten, T. & Østergård, P. Norwegian scientific committee for food safety (VKM) opinion of the panel on animal health and welfare of the Norwegian scientific committee for food safety. Risk Assessment of recirculation systems in salmonid hatcheries. Available online: https://vkm.no/english/riskassessments/allpublications/risk *assessment of recirculation systems in salmonid hatcheries.4.72c3261615e09f2472f46f9b.html* (accessed on 13 October 2022).

Hu, Z., Li, R., Xia, X., Yu, C., Fan, X. & Zhao, Y. (2020) A method overview in smart aquaculture. *Environmental Monitoring and Assessment*, 192, 493. https://doi.org/10.1007/s10661-020-08409-9

Huan, J., Li, H., Wu, F. & Cao, W. (2020) Design of water quality monitoring system for aquaculture ponds based on NB-IoT. *Aquacultural Engineering*, 90, 102088.

Huang, J., Wang, W., Jiang, S., Sun, D., Ou, G. & Lu, K. (2013) Development and test of aquacultural water quality monitoring system based on wireless sensor network. *Transactions of the Chinese Society of Agricultural Engineering*, 29, 183190.

Höglund, E., Fernandes, P., Rojas-Tirado, P., Rundberget, J.T. & Hess-Erga, O.-C. (2022) Assessing stress resilience after smolt transportation by waterborne cortisol and feeding behavior in a commercial Atlantic salmon (*Salmo salar*) grow-out recirculating aquaculture system. *Frontiers in Physiology*, 12, 771951. https://doi.org/10.3389/fphys.2021.771951

Ignatev, A. & Tuhkanen, T. (2019) Monitoring WWTP performance using size-exclusion chromatography with simultaneous UV and fluorescence detection to track recalcitrant wastewater fractions. *Chemosphere*, 214, 587597. https://doi.org/10.1016/j.chemosphere.2018.09.099

Ingebrigtsen, O. & Torrissen, O. (1980) The use of effluent water from Matre power plant for raising salmonid fingerlings at Matre aquaculture system. Symposium on New Developments in the Utilization of Heated Effluents and Recirculation Systems for Intensive Aquaculture. Stavanger (Norway).

Ip, Y., Chew, S. & Randall, D. (2001) Ammonia toxicity, tolerance, and excretion. *Fish Physiology*, 20, 109148.

Iryna, K., Antonín, K. & Pavel, K. (2013) Real-time monitoring of water quality using fish and crayfish as bio-indicators: A review. *Environmental Monitoring and Assessment*, 185, 50435053.

Jamroen, C., Komkum, P., Fongkerd, C. & Krongpha, W. (2020) An intelligent irrigation scheduling system using low-cost wireless sensor network toward sustainable and precision agriculture. *IEEE*, 8, 172756172769.

Jamroen, C., Yonsiri, N., Odthon, T., Wisitthiwong, N. & Janreung, S. (2023) A standalone photovoltaic/battery energy-powered water quality monitoring system based on narrowband internet of things for aquaculture: Design and implementation. *Smart Agricultural Technology*, 3, 100072.

Jepsen, N., Schreck, C., Clements, S. & Thorstad, E.B. (2004) A brief discussion of the 2%tag/bodyweight rule of thumb. In Spedicato, M.T., & Lembo, M.G. (Eds.), *Aquatic Telemetry Advances and Applications* (pp. 255259). FAO-COISPA, Rome.

Jiang, Y.L., Dong, X.L., Cui, C.M. & Yang, T. (2017) Discussion on temperature control technology of factory aquaculture circulating water system. *Journal of Aquaculture*, 38, 812.

Jokubauskaite, I., Amaleviciute, K., Lepane, V., Slepetiene, A., Slepetys, J., Liaudanskiene, I. et al. (2015) High-performance liquid chromatography (HPLC)-size exclusion chromatography (SEC) for qualitative detection of humic substances and dissolved organic matter in mineral soils and peats in Lithuania. *International Journal of Environmental Analytical Chemistry*, 95, 508519. http://doi.org/10.1080/03067319.2015.1048435

Juell, J.E., Furevik, D.M. & Bjordal, Å. (1993) Demand feeding in salmon farming by hydroacoustic food detection. *Aquacultural Engineering*, 12, 155167.

Kamstra, A., Blom, E., & Terjesen, B.F. (2017). Mixing and scale affect moving bed biofilm reactor (MBBR) performance. *Aquacult. Eng.*, 78, 9–17.

Kajimura, M., Croke, S.J., Glover, C.N. & Wood, C.M. (2004) Dogmas and controversies in the handling of nitrogenous wastes: The effect of feeding and fasting on the excretion of ammonia, urea and other nitrogenous waste products in rainbow trout. *The Journal of Experimental Biology*, 207, 1993-2002.

Kassem, T., Shahrour, I., Khattabi, J.E. & Raslan, A. (2021) Smart and sustainable aquaculture farms. *Sustainability*, 13, 10685. http://doi.org/10.3390/su131910685

Khanjani, M.H. & Sharifinia, M. (2020) Biofloc technology as a promising tool to improve aquaculture production. *Reviews in Aquaculture*, 12, 1836–1850.

Kiemer, M.C., Black, K.D., Lussot, D., Bullock, A.M. & Ezzi, I. (1995) The Effects of chronic and acute exposure to hydrogen sulphide on Atlantic salmon (*Salmo Salar* L.). *Aquaculture*, 135, 311327. http://doi.org/10.1016/0044-8486(95)01025-4

Kinyage, J.P.H., Bovbjerg Pedersen, P. & Pedersen, L.-F. (2019) Effects of abrupt salinity increase on nitrification processes in a freshwater moving bed biofilter. *Aquacultural Engineering*, 84, 91-98.

Kolarevic, J., Selset, R., Felip, O., Good, C., Snekvik, K., Takle, H., et al. (2013) Influence of long term ammonia exposure on Atlantic salmon (*Salmo salar* L.) parr growth and welfare. *Aquaculture Research*, 44, 16491664.

Kolarevic, J., Baeverfjord, G., Takle, H., Ytteborg, E., Megård Reiten, B.K., Nergård, S. & Fyhn Terjesen, B. (2014) Performance and welfare of Atlantic salmon smolt reared in recirculating or flow through aquaculture systems. *Aquaculture*, 432, 1525.

Kolarevic, J., Aas-Hansen, Ø., Espmark, Å., Baeverfjord, G., Fyhn Terjesen, B. & Damsgård, B. (2016) The use of acoustic acceleration transmitter tags for monitoring of Atlantic salmon swimming activity in recirculating aquaculture systems (RAS). *Aquacultural Engineering*, 7273, 3039.

Kolarevic, J., Calduch-Giner, J., Espmark, Å.M., Evensen, T., Sosa, J. & Pérez-Sánchez, J. (2021) A Novel miniaturized biosensor for monitoring Atlantic salmon swimming activity and respiratory frequency. *Animals*, 11, 2403. http://doi.org/10.3390/ani11082403

Kristensen, T., Åtland, Å., Rosten, T., Urke, H.A. & Rosseland, B.O. (2009) Important influent-water quality parameters at freshwater production sites in two salmon producing countries. *Aquacultural Engineering*, 41, 5359.

Lekang, O.-D. (2013) *Instrumentation and monitoring in Aquaculture engineering* (2nd Ed.). John Wiley & Sons Ltd.

Lemercier, P. & Serene, P. (1980) Commercial eel farming using heated effluent in France. Symposium on New Developments in the Utilization of Heated Effluents and Recirculation Systems for In-tensive Aquaculture. Stavanger (Norway).

Letelier-Gordo, C.O., Aalto, S.L., Suurnäkki, S. & Pedersen, P.B. (2020) Increased sulfate availability in saline water promotes dydrogen sulfide production in fish organic waste. *Aquacultural Engineering*, 89, 102062. http://doi.org/10.1016/J.AQUAENG.2020.102062

Li, Q. & Lancaster, J.R. Jr. (2013) Chemical foundations of hydrogen sulfide biology. *Nitric. Oxide*, 35, 2134. http://doi.org/10.1016/J.NIOX.2013.07.001

Li, H., Xiong, Q., Shi, W. & Cheng, Z. (2014a) Gradient based multipath reliable transmission strategy with fault tolerance for wireless sensor networks. *International Journal of Distributed Sensor Networks*, 1, 1–13.

Li, P.Y., Wu, J.-H. & Qian, H. (2014b) Influences of the modelinitial value of Holt exponential smoothing model on the water quality prediction accuracy. *Geotech. Invest. Surv*, 42, 4750.

Li, W.-T., Chen, S.-Y., Xu, Z.-X., Li, Y., Shuang, C.-D. & Li, A.-M. (2014c) Characterization of dissolved organic matter in municipal wastewater using fluorescence PARAFAC analysis and chromatography multi-excitation/emission scan: a comparative study. *Environmental Science & Technology*, 48, 26032609.

Li, W.-T., Jin, J., Li, Q., Wu, C.-F., Lu, H., Zhou, Q. et al. (2016) Developing LED UV fluorescence sensors for online monitoring DOM and predicting DBPs formation potential during water treatment. *Water Research*, 93, 19.

Li, D., Xu, L. & Liu, H. (2017) Detection of uneaten fish food pellets in underwater images for aquaculture. *Aquacultural Engineering*, 78, 8594.

Lien, E., Valsvik, G., Nordstrand, J.V., Martinez, V., Rogne, V., Hafsås, O. et al. (2022) The SeaRAS AquaSense™ System: Real-time monitoring of H_2S at sub μg/L levels in recirculating aquaculture systems (RAS). *Frontiers in Marine Science*, 9, 894414. http://doi.org/10.3389/fmars.2022.894414

Lin, Y.L. (2011) Studies on construction and operation performance of an ecological indoor recirculating aquaculture system. MSc. thesis, Huazhong Agricultural University, Wu Han, Hu Bei Province, China.

Lin, K., Zhou, C., Xu, D., Guo, Q., Yang, X. & Sun, C. (2018) Three-dimensional location of target fish by monocular infrared imaging sensor based on a L–z correlation model. *Infrared Physics and Technology*, 88, 106113.

Lin, J.-Y., Tsai, H.-L. & Lyu, W.-H. (2021) An integrated wireless multi-sensor system for monitoring the water quality of aquaculture. *Sensors*, 21, 8179. http://doi.org/10.3390/s21248179

Lindholm-Lehto, P.C., Suurnäkki, S., Pulkkinen, J.T., Aalto, S.L., Tiirola, M. & Vielma, J. (2019) Effect of peracetic acid on levels of geosmin, 2-methylisoborneol, and their potential producers in a recirculating aquaculture system for rearing rainbow trout (*Oncorhynchus mykiss*). *Aquacultural Engineering*, 85, 5664.

Lindholm-Lehto, P., Pulkkinen, J., Kiuru, T., Koskela, J. & Vielma, J. (2020) Water quality in recirculating aquaculture system using woodchip denitrification and slow sand filtration. *Environmental Science and Pollution Research*, 27, 1731417328.

Lindholm-Lehto, P.C., Pulkkinen, J.T., Kiuru, T., Koskela, J. & Vielma, J. (2021) Efficient water treatment achieved in recirculating aquaculture system using woodchip denitrification and slow sand filtration. *Environmental Science and Pollution Research*, 28, 6533365348.

Lindholm-Lehto, P.C. (2022) Developing a robust and sensitive analytical method to detect off-flavor compounds in fish. *Environmental Science and Pollution Research*, 29, 5586655876. http://doi.org/10.1007/s11356-022-19738-2

Loyless, J.C. & Malone, R.F. (1998) Evaluation of air-lift pump capabilities for water delivery, aeration, and degasification for application to recirculating aquaculture systems. *Aquacultural Engineering*, 18, 117133.

Lorena, P., Sandra, S., Laura, G., & Jaime, L., (2018). Design and deployment of low-cost sensors for monitoring the water quality and fish behavior in aquaculture tanks during the feeding process. *Sensors*, 18(3), 750–772.

Luo, H., Li, G., Peng, W., Song, J. & Bai, Q. (2015) Real-time remote monitoring system for aquaculture water quality. *International Journal of Agricultural and Biological Engineering*, 8, 136143.

Lv, X. (2015) Research on key technology of water resources monitoring system based on wireless sensor network. *Wirel. Int. Technol*, 12, 1718.

Martins, C.I.M., Eding, E.H., Verdegem, M.C.J., Heinsbroek, L.T.N., Schneider, O., Blancheton, J.P. et al. (2010) New developments in recirculating aquaculture systems in Europe: a perspective on environmental sustainability. *Aquacultural Engineering*, 43, 8393.

Martins, C.I.M., Galhardo, L., Noble, C., Damsgard, B., Spedicato, M.T., Zupa, W. et al. (2012) Behavioural indicators of welfare in farmed fish. *Fish Physiology and Biochemistry*, 38, 1741.

Médale, F., Brauge, C., Vallée, F. & Kaushik, S.J. (1995) Effects of dietary protein/energy ratio, ration size, dietary energy source and water temperature on nitrogen excretion in rainbow trout. *Water Science and Technology*, 31, 185-194.

Michaud, L., Lo Giudice, A., Interdonato, F., Triplet, S., Ying, L. & Blancheton, J.P. (2014) C/N ratio-induced structural shift of bacterial communities inside lab-scale aquaculture biofilters. *Aquacultural Engineering*, 58, 7787.

Milud, A., Hassan, D., Noordin, M., Siti Khairani, B., Yasser, M. & Ali, A. (2013) Environmental factors influencing the susceptibility of red hybrid tilapia (*Orechromis* sp.) to *Streptococcus agalactiae* infection. *Advanced Science Letters*, 19, 36003604.

Molleda, M.I. (2007) Water quality in recirculating aquaculture systems for arctic charr (*Salvelinus alpinus* L.) culture. Fisheries training programme, Final Project, Reykjavik, Iceland.

Moran, D. (2010) Carbon dioxide degassing in fresh and saline water. I: Degassing performance of a cascade column. *Aquacultural Engineering*, 43, 29-36.

Mota, V.C., Martins, C.I.M., Eding, E.H., Canário, A.V.M. & Verreth, J.A.J. (2017) Water cortisol and testosterone in Nile tilapia (*Oreochromis niloticus*) recirculating aquaculture systems. *Aquaculture*, 468, 255261.

Mwegoha, W.J.S., Kaseva, M.E. & Sabai, S.M.M. (2010) Mathematical modeling of dissolved oxygen in fish ponds. *African Journal of Environmental Science and Technology*, 4, 623638.

Nam, H., An, S., Kim, C.H., Park, S.H., Kim, Y.W. & Lim, S.H. (2015) Remote monitoring system based on ocean sensor networks for offshore aquaculture. *Oceans*, 17.

Narwane, V.S., Gunasekaran, A. & Gardas, B.B. (2022) Unlocking adoption challenges of IoT in Indian agricultural and food supply chain. *Smart Agricultural Technology*, 2, 100035. http://doi.org/10.1016/j.atech.2022.100035

Naughton, S., Kavanagh, S., Lynch, M. & Rowan, N.J. (2020) Synchronizing use of sophisticated wet-laboratory and in-field handheld technologies for real-time monitoring of key microalgae, bacteria and physicochemical parameters influencing efficacy of water quality in a freshwater aquaculture recirculation system: A case study from the Republic of Ireland. *Aquaculture*, 526, 735377.

Oberle, M., Salomon, S., Ehrmaier, B., Richter, P., Lebert, M. & Strauch, S.M. (2019) Diurnal stratification of oxygen in shallow aquaculture ponds in central Europe and recommendations for optimal aeration. *Aquaculture*, 501, 482487.

Odey, A.J. & Li, D. (2013) AquaMesh—design and implementation of smart wireless mesh sensor networks for aquaculture. *American Journal of Networks and Communications*, 2, 8187.

Omiwade, S. & Zheng, R. (2012) *Online data recovery in wireless sensor networks*. Sensor, Mesh and Ad Hoc Communications and Networks, pp. 200208.

Parra, L., Sendra, S., García, L. & Lloret, J. (2018) Design and deployment of low-cost sensors for monitoring the water quality and fish behavior in aquaculture tanks during the feeding process. *Sensors*, 18, 750. http://doi.org/10.3390/s18030750

Pasika, S. & Gandla, S.T. (2020) Smart water quality monitoring system with cost-effective using IoT. *Heliyon*, 6, e04096.

Pedersen, L.-F., Suhr, K.I., Dalsgaard, J., Pedersen, P.B. & Arvin, E. (2012) Effects of feed loading on nitro-gen balances and fish performance in replicated recirculating aquaculture systems. *Aquaculture*, 338-341, 237-245.

Pedersen, L.-F., Oosterveld, R., & Pedersen, P.B. (2015). Nitrification performance and robustness of fixed and moving bed biofilters having identical carrier elements. *Aquacult. Eng.*, 65, 37–45.

Peng, H.M. (2017) *Research on fish movement state detection system based on biological water quality monitoring*. Xi'an University of Posts and Telecommunications, pp. 16.

Pettersson, S.J., Lindholm-Lehto, P.C., Pulkkinen, J.T., Kiuru, T. & Vielma, J. (2022) Effect of ozone and hydrogen peroxide on off-flavor compounds and water quality in a recirculating aquaculture system. *Aquacultural Engineering*, 98, 102277.

Pillay, T.V.R. & Kutty, M.N. (2005) *Aquaculture Principles and Practices*, 2nd ed.; Blackwell Publishing Ltd, Oxford, UK, 630 p.

Podduturi, R., Petersen, M.A., Mahmud, S., Rahman, M.M. & Jørgensen, N.O.G. (2017) Potential contribution of fish feed and phytoplankton to the content of volatile terpenes in cultured pangasius (*Pangasianodon hypophthalmus*) and Tilapia (*Oreochromis niloticus*). *Journal of Agricultural and Food Chemistry*, 65, 37303736. http://doi.org/10.1021/acs.jafc.7b00497

Postolache, O., Pereira, J.D. & Girão, P.S. (2014) Wireless sensor network-based solution for environmental monitoring: water quality assessment case study. *IET Science, Measurement & Technology*, 8, 610616.

Powell, A. & Scolding, J.W.S. (2018) Direct application of ozone in aquaculture systems. *Reviews in Aquaculture*, 10, 424438. http://doi.org/10.1111/raq.12169

Preena, P.G., Kumar, V.J.R. & Singh, I.S.B. (2021) Nitrification and denitrification in recirculating aquaculture systems: the processes and players. *Reviews in Aquaculture*, 13, 20532075.

Pule, M., Yahya, A. & Chuma, J. (2017) Wireless sensor networks: A survey on monitoring water quality. *Journal of Applied Research and Technology*, 15, 562570. http://doi.org/10.1016/j.jart.2017.07.004

Pulkkinen, J.T., Kiuru, T., Aalto, S.L., Koskela, J. & Vielma, J. (2018) Startup and effects of relative water renewal rate on water quality and growth of rainbow trout (*Oncorhynchus mykiss*) in a unique RAS research platform. *Aquacultural Engineering*, 82, 3845.

Pulkkinen, J.T., Ronkanen, A.-K., Pasanen, A., Kiani, S., Kiuru, T., Koskela, J. et al. (2021) Start-up of a "zero-discharge" recirculating aquaculture system using woodchip denitrification, constructed wetland, and sand infiltration. *Aquacultural Engineering*, 93, 102161.

Ragnarsson, A. (2014) *Geothermal energy in aquaculture*. Short course VI on utilization of low- and medium-enthalpy geothermal resources and financial aspects of utilization. Santa Tecla, El Salvador.

Rashid, M., Nayan, A.-A., Simi, S.A., Saha, J., Md Rahman, O. & Kibria, M.G. (2021) IoT based smart water quality prediction for Biofloc aquaculture. *International Journal of Advanced Computer Science and Applications*, 12, 6.

Ren, X. (2014) Research of carbon dioxide accumulation and its impacts on biological aerated filter in marine recirculating aquaculture systems. MSc. Thesis, University of Chinese Academy of Sciences, Beijing, China.

Rey, S., Huntingford, F.A., Boltaña, S., Vargas, R., Knowles, T.G. & Mackenzie, S. (2015) Fish can show emotional fever: stress-induced hyperthermia in zebrafish. *Proceedings of the Royal Society*, 282, 20152266.

Rickard, B.J. (1998) Solar and fuel oil heating in fingerling production: issues in growth modelling and financial feasibilty. Thesis for Master of Science, The Faculty of Graduate Studies of The University of Guelph. National Library of Canada.

Rojas-Tirado, P.A. Microbial water quality within recirculating aquaculture systems. PhD Thesis, Technical University of Denmark, 1.3.2018.

Rojas-Tirado, P., Bovbjerg Pedersen, P., Vadstein, O. & Pedersen, L.-F. (2018) Changes in microbial water quality in RAS following altered feed loading. *Aquacultural Engineering*, 81, 8088.

Rollo, A., Sulpizio, R., Nardi, M., Silvi, S., Orpianesi, C., Caggiano, M. et al. (2006) Live microbial feed supplement in aquaculture for improvement of stress tolerance. *Fish Physiology and Biochemistry*, 32, 167177. http://doi.org/10.1007/s10695-006-0009-2

Rubright, S.L.M., Pearce, L.L. & Peterson, J. (2017) Environmental toxicology of hydrogen sulfide. *Nitric. oxide: Biol. Chem*, 71, 1. http://doi.org/10.1016/J.NIOX.2017.09.011

Sadoul, B., Evouna Mengues, P., Friggens, N.C. & Prunet, P., Colson, V. (2014) A new method for measuring group behaviours of fish shoals from recorded videos taken in near aquaculture conditions. *Aquaculture*, 430, 179187.

Saha, S., Hasan, R. & Kabir, S. (2019) IoT based smart farm monitoring system. *International Journal of Recent Technology and Engineering*, 8, 54905494. doi: 10.35940/ijrte.d8806.118419

Sanni, S. & Forsberg, O.I. (1996) Modelling pH and carbon dioxide in single-pass seawater aquaculture systems. *Aquacultural Engineering*, 15, 91110.

Santi, S., Rougeot, C., Toguyeni, A., Gennotte, V., Kebe, I. & Melard, C. (2017) Temperature preference and sex differentiation in African catfish, *Clarias gariepinus*. *Journal of Experimental Zoology*, 327A, 28-37.

Santos, G., Ortiz-Gándara, I., Castillo, A.D., Arruti, A., Gómez, P., Ibáñez, R. et al. (2022) Intensified fish farming. performance of electrochemical remediation of marine RAS waters. *Science of the Total Environment*, 847, 157368.

Schipper, L. A., Robertson, W.D., Gold, A.J., Jaynes, D.B., Cameron, S.C. (2010) Denitrifying bioreactors—An approach for reducing nitrate loads to receiving waters. *Ecological Engineering*, 36, 1532–1543.

Schmidt, W., Raymond, D., Parish, D., Ashton, I.G.C., Miller, P.I., Campos, C.J.A. et al. (2018) Design and operation of a low-cost and compact autonomous buoy system for use in coastal aquaculture and water quality monitoring. *Aquacultural Engineering*, 80, 2836.

Schroeder, J.P., Croot, P.L., Von Dewitz, B., Waller, U. & Hanel, R. (2011) Potential and limitations of ozone for the removal of ammonia, nitrite, and yellow substances in marine recirculating aquaculture systems. *Aquacultural Engineering*, 45, 3541.

Shi, B., Zhao, D.A., Liu, X.Q., Jiang, J.M. & Sun, Y.P. (2011) Intelligent monitoring system of large-scale aquaculture based on wireless sensor network. *Transactions of the Chinese Society of Agricultural Engineering*, 09, 136140.

Shi, B.-S., Cheng, X.-J., Chen, H.-Z., Xie, J., Zhou, Z.-H., Jiang, S.-Q. et al. (2022) Occurrence, source tracking and removal of antibiotics in recirculating aquaculture systems (RAS) in southern China. *Journal of Environmental Management*, 324, 116311.

Sinisalo, K. (2022) Kirjolohen käyttäytymisen havainnointi telemetriajärjestelmällä. Käyttökokeet kalankasvatuslaitoksella Saaristomerellä 2021. (In Finnish). Research on natural resources and bioeconomy, Natural Resources Institute Finland (Luke).

Sommerset, I., Bang Jensen, B., Bornø, G., Haukaas, A. & Brun, E. (2020) *The health situation in Norwegian aquaculture 2020*. Norwegian Veterinary Institute, Ås, Norway.

Srogi, K. (2007) Monitoring of environmental exposure to polycyclic aromatic hydrocarbons: a review. *Environmental Chemistry Letters*, 5, 169195.

Srouji, M.S., Wang, Z. & Henkel, J. (2011) RDTS: A reliable erasure-coding based data transfer scheme for wireless sensor networks. IInternational Conference on Parallel and Distributed Systems, IEEE Computer Society, pp. 481488.

Stigebrandt, A., Aure, J., Ervik, A. & Hansen, P. (2004) Regulating the local environmental impact of intensive marine fish farming: Iii. A model for estimation of the holding capacity in the modelling ongrowing fish farm-monitoring system. *Aquaculture*, 234, 239261.

Su, X., Sutarlie, L. & Loh, X.J. (2020) Sensors, biosensors, and analytical technologies for aquaculture water quality. *Research*, 8272705, 15 p. http://doi.org/10.34133/2020/8272705

Summerfelt, S.T., Davidson, J. & Waldrop, T. (2003) Evaluation of full-scale carbon dioxide stripping columns in a coldwater recirculating system. *Aquacultural Engineering*, 28, 155169.

Summerfelt, S.T., Sharrer, M.J., Tsukuda, S.M. & Gearheart, M. (2009) Process requirements for achieving full-flow disinfection of recirculating water using ozonation and UV irradiation. *Aquacultural Engineering*, 40, 1727. http://doi.org/10.1016/j.aquaeng.2008.10.002

Summerfelt, S.T., Zühlke, A., Kolarevic, J., Megård Reiten, B.K., Selset, R., Gutierrez, X. & Fyhn Terjesen, B. (2015) Effects of alkalinity on ammonia removal, carbon dioxide stripping, and system pH in semi-commercial scale water recirculating aquaculture systems operated with moving bed bioreactors. *Aquacultural Engineering*, 65, 4654.

Sun, M., Hassan, S.G. & Li, D. (2016) Models for estimating feed intake in aquaculture: A review. *Comput. Electron. Agric*, 127, 425438.

Suurnäkki, S., Pulkkinen, J.T., Lindholm-Lehto, P.C., Tiirola, M. & Aalto, S.L. (2020) The effect of peracetic acid on microbial community, water quality, nitrification and rainbow trout (*Oncorhynchus mykiss*) performance in recirculating aquaculture systems. *Aquaculture*, 516, 734534.

Takahashi-Kariyazono, S., Tanaka, H. & Terai, Y. (2017) Gene duplications and the evolution of c-type lysozyme during adaptive radiation of East African cichlid fish. *Hydrobiologia*, 791, 720.

Tanudjaja, Y. (2021) *Early warning signs and dynamics of* H_2S *production in recirculating aquaculture system*, Norwegian University of Science and Technology, Trondheim.

Timmons, M.B., Guerdat, T. & Vinci, B.J. (2018) Water quality. In *Recirculating Aquaculture* 4th ed.; Publisher: Ithaca Publishing Company LLC, Ithaca, NY, USA, pp. 2758.

Tolentino, L.K.S., De Pedro, C.P., Icamina, J.D., Navarro, J.B.E., Salvacion, L.J.D., Sobrevilla, G.C.D. et al. (2021) Development of an IoT-based intensive aquaculture monitoring system with automatic water correction. *Int. J. Comput. Dig. Sys*, 10, 1. http://doi.org/10.12785/ijcds/100-1120

Tucker, C.S. (2000) Off-flavor problems in aquaculture. *Reviews in Fisheries Science*, 8, 45-88.

Tziortzioti, C., Amaxilatis, D., Mavrommati, I., & Chatzigiannakis, I. (2019) IoT sensors in sea water environment: Ahoy! Experiences from a short summer trial. *Electronic Notes in Theoretical Computer Science*, 343, 117–130.

Venugopal, V. (2002) Biosensors in fish production and quality control. *Biosensors and Bioelectronics*, 17, 147157.

Vogiazi, V., de la Cruz, A., Mishra, S., Shanov, V., Heineman, W.R. & Dionysiou, D.D. (2019) A comprehensive review: development of electrochemical biosensors for detection of cyanotoxins in freshwater. *ACS Sensors*, 4, 11511173.

von Ahnen, M., Pedersen, L.-F., Pedersen, P.B. & Dalsgaard, J. (2015) Degradation of urea, ammonia and nitrite in moving bed biofilters operated at different feed loadings. *Aquacultural Engineering*, 69, 5059.

Wang, Y., Qi, C. & Pan, H. (2012) Design of remote monitoring system for aquaculture cages based on 3 g networks and arm-android embedded system. *Procedia Engineering*, 29, 7983.

Wenk, J., Aeschbacher, M., Salhi, E., Canonica, S., Von Gunten, U. & Sander, M. (2013) Chemical oxidation of dissolved organic matter by chlorine dioxide, chlorine, and ozone: effects on its optical and antioxidant properties. *Environmental Science & Technology*, 47, 1114711156. http://doi.org/10.1021/es402516b

Wickersham, A.J., Li, X. & Ma, L. (2014) Comparison of Fourier, principal component and wavelet analyses for high speed flame measurements. *Computer Physics Communications*, 185, 12371245.

Wicks, B.J., Joensen, R., Tang, Q. & Randall, D.J. (2002) Swimming and ammonia toxicity in salmonids: the effect of sub lethal ammonia exposure on the swimming performance of coho salmon and the acute toxicity of ammonia in swimming and resting rainbow trout. *Aquatic Toxicology*, 59, 5569.

Wongkiew, S., Hu, Z., Chandran, K., Lee, J.W. & Khanal, S.K. (2017) Nitrogen transformations in aqua-ponic systems: A review. *Aquacultural Engineering*, 76, 9-19.

Wu, F., Liu, H. & Su, M. (2008) Current status and trend for the development of industrialized recirculating aquaculture. *Sci. Fish Farm*, 9, 7274.

Wu, Y.X., Hu, Y.M. & Liu, Y.Q. (2011) The design of recirculating aquaculture temperature control system based on PLC. *Sci. Technol. Eng*, 11, 47344739.

Xiao, R., Wei, Y., An, D., Li, D., Ta, X., Wu, Y.et al. (2019) A review on the research status and development trend of equipment in water treatment processes of recirculating aquaculture systems. *Reviews in Aquaculture*, 11, 863895.

Xin, N.H., Peng, L.Q., Yu, X.Q., Yang, Y.M. & Zhang, S.S. (2017) Research on application of recirculating aquaculture system and water source heat pump for grouper. *Fishery Modern*, 44, 914.

Yang, H., Cao, Z.D. & Fu, S.J. (2013) The effects of dielcycling hypoxia acclimation on the hypoxia tolerance, swimming capacity and growth performance of southern catfish (*Silurus meridionalis*). *Compar. Biochem. Physiol. Part A Molec. Integrat. Physiol*, 165, 131138.

Ytrestøyl, T., Takle, H., Kolarevic, J., Calabrese, S., Timmerhaus, G., Rosseland, B.O. et al. (2020) Performance and welfare of Atlantic salmon, *Salmo salar* L. post-smolts in recirculating aquaculture systems: Importance of salinity and water velocity. *Journal of the World Aquaculture Society*, 51, 373-392.

Yu, T. & Bishop, P.L. (2001) Stratification and oxidation–reduction potential change in an aerobic and sulfate-reducing biofilm studied using microelectrodes. *Water Environment Research*, 73, 368373. http://doi.org/10.2175/106143001x139399

Yu, X., Hou, X.J., Lu, H.D., Yu, X.J., Fan, L.Z. & Liu, Y. (2014) Anomaly detection of fish school behavior based on features statistical and optical flow methods. *Transactions of the Chinese Society of Agricultural Engineering*, 30, 162168.

Zhang, L.B. (2007) *Research on on-line multi-parameter water quality monitoring system*. Qingdao University.

Zhang, S.-Y., Li, G., Wu, H.-B., Liu, X.-G., Yao, Y.-H., Tao, L. et al. (2011) An integrated recirculating aquaculture system (RAS) for land-based fish farming: The effects on water quality and fish production. *Aquacultural Engineering*, 45, 93102.

Zhang, J.S., Huang, Y., Han, X.B. & Huang, Y.T. (2013) Application of changes of the fish behavior in the water quality monitoring. *Water Waste. Eng*, 39, 166170.

Zhang, R., Zheng, H.Y., Li, L. & Rao, K.F. (2015) A computer vision algorithm which was used for measuring the oscillation frequency of the Japanese Medaka's pectoral fin and caudal fin. *Asian J. Ecotoxicol*, 10, 154161.

Zhao, J.G. (2015) Data recovery algorithms based on multiattribute assist and compressed sensing in WSN. *Comput. Appl. Softw*, 32, 137142.

Zhou, C., Xu, D., Lin, K., Sun, C. & Yang, X. (2017a) Intelligent feeding control methods in aquaculture with an emphasis on fish: a review. *Reviews in Aquaculture*, 10, 975993. http://doi.org/10.1111/raq.12218

Zhou, C., Yang, X., Zhang, B., Lin, K., Xu, D., Guo, Q. & Sun, C. (2017b) An adaptive image enhancement method for a recirculating aquaculture system. *Scientific Reports*, 7, 6243.

Zhou, C., Lina, K., Xua, D., Chen, L., Guo, Q., Sun, C. et al. (2018) Near infrared computer vision and neuro-fuzzy model-based feeding decision system for fish in aquaculture. *Computers and Electronics in Agriculture*, 146, 114124.

Zhu, X., Li, D., He, D., Wang, J., Ma, D. & Li, F. (2010) A remote wireless system for water quality online monitoring in intensive fish culture. *Computers and Electronics in Agriculture*, 71S, S3S9.

How to cite this article: Lindholm-Lehto, P. (2023) Water quality monitoring in recirculating aquaculture systems. *Aquaculture, Fish and Fisheries*, 1–19. https://doi.org/10.1002/aff2.102