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Water quality management in aquaculture

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Review

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Abstract

The aquaculture industry requires good water quality for its successful operation but produces wastes that can cause environmental deterioration and pose high risks to the sector. Adequate waste treatment and recycling are necessary to make aquaculture a sustainable and profitable industry and contribute to the circular economy. Polluted water sources, excess feeding, overstocking, use of antibiotics/chemicals and harmful algal blooms are major causes of water quality deterioration and low production in aquaculture systems. Discharges of untreated wastes would have serious impacts on the receiving water bodies, and eventually on the aquaculture industry itself. Possible solutions include technological innovations in environmentally friendly production systems, use of efficient processes in water quality management and improved legislation and governance. Environmentally feasible aquaculture production technologies such as recycling aquaculture system, integrated multi-trophic aquaculture and aquaponics including features of waste recycling are viable options in aquaculture schemes. Best aquaculture practices integrating advanced water quality treatment processes and technologies, supported by automation and sensors, modeling and artificial intelligence-internet of things are necessary for a sustainable aquaculture environment, production and stable value chain. In general, low-cost technologies for aquaculture waste treatment and environmental impact reduction through good governance are crucial for achieving sustainability in the aquaculture industry and natural environmental management.

Impact statement

Good water quality is mandatory in different phases of a successful aquaculture production, water intake, water use and waste discharges. However, unsustainable aquaculture practices can result in low yields and cause negative impacts on the environment and the human community. This review provides assessments of water quality in different aquaculture systems, and the impacts of their effluents on the natural water bodies. To optimize aquaculture production, and minimize their impacts on the environment, effective management of the water quality and wastes in aquaculture is needed. Major constraints in adequate aquaculture wastewater treatment, including high capital and operation costs of waste treatment systems, lack of incentives for waste treatment and lack of legislation and enforcement in discharges of raw aquaculture wastes, should be overcome. Possible solutions include technological innovations in production systems and wastewater treatments, increased professionals in water quality control and waste management, improved legislation, certification, financial assistance and incentives to farmers along the aquaculture industrial chains can be applied for a sustainable aquaculture sector. If water quality management can be effectively carried out, it would have a great long-term impact on the aquaculture industry.

Introduction

Aquaculture is the fastest-growing food-production sector, and its sustainable growth is vital to food security, ecosystem health, uninterrupted natural resource utilization, biodiversity conservation and socioeconomic resilience. In the face of declining capture fishery resources and rising demand for fish and fishery products, aquaculture has become the main source of aquatic food/protein supply and contributes to the food security of the global population (Boyd et al., 2022; Troell et al., 2023). However, there are concerns about the impacts of aquaculture activities on the environment and natural resources, such as habitat destruction, exploitation of wild fish stocks, fishmeal/fish oil requirements and waste disposal (Bull et al., 2021; Klootwijk et al., 2021). Different aquaculture systems (extensive, semi-intensive and intensive); types of systems (closed, semi-open and open); different cultured species and stocking densities can generate different

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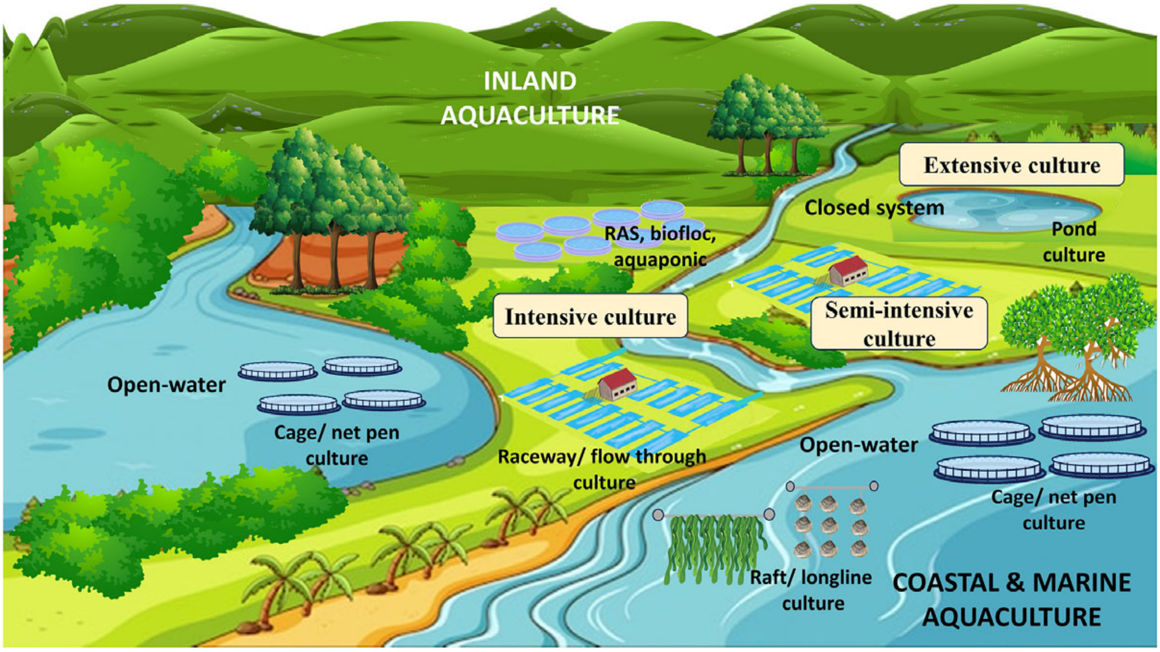

Figure 1. Different aquaculture production systems in closed (tanks, ponds, and raceways) and open ecosystems (cages and extractive culture systems in lakes, rivers, and coastal waters).

environmental impacts (Figure 1). Environmental impacts can occur through three different processes such as consumption of natural resources, culture procedures/practices and generation of wastes. Each ecosystem has its own carrying capacity, and working within the limit is crucial to avoid negative impacts. The transition of traditional cultural practices to an intensified cultural system involves increased waste that requires proper treatment to avoid pollution and deleterious impacts on the environment (da Silva et al., 2022). With the high demand for aquaculture products, more farms are opting for intensive culture systems, which tend to affect the environment more than extensive and semi-intensive systems due to large amounts of waste containing toxins, drugs and chemicals in the former system (Zhang et al., 2021; Nagaraju et al., 2022). Thus, unsustainable aquaculture activities could result in widespread habitat destruction, loss of biodiversity, declined fishery and other aquatic resources in the surrounding area (Valiela et al., 2001; Polidoro et al., 2010; Herbeck et al., 2013; Cardoso-Mohedano et al., 2018).

In aquaculture production systems, poor water quality due to accumulation of toxic compounds, including ammonia, nitrite and hydrogen sulfide, together with low dissolved oxygen, hypoxic conditions, harmful algal blooms (HABs) and pathogenic bacteria can greatly affect the fish health through bacterial infections, poor growth and stress rendering them less tolerant to handling. Diseases in aquaculture systems are closely related to the environmental health. Uncontrolled diseases can rapidly decimate operations and can cause high mortality in aquaculture systems. Lusiastuti et al. (2020) attributed the disease outbreaks, mass fish mortality and low aquaculture production to poor water quality associated with environmental degradation and climate change. Climate change can affect the aquaculture industry through flooding (too much water), drought (too little water) and changes in water quality. Decline in pH due to ocean acidification could seriously affect aquaculture, especially those in the coastal areas (Guo et al., 2023). Hassan et al. (2022) noted that improving water quality, maintaining stable environmental factors and controlling water exchange would reduce the occurrence of fish diseases in aquaculture production systems.

Untreated or improperly treated aquaculture discharges with high nutrient concentrations can cause eutrophication and water quality deterioration, hypoxia and HABs in adjacent water bodies (Zhang et al., 2018; Purnomo et al., 2022). HABs can be a serious concern in coastal and inland waters (rivers, lakes and reservoirs) that receive aquaculture effluents. Lukassen et al. (2019a) reported that the off-flavor compounds produced by the HABs especially geosmin in tilapia produced in cage aquaculture increased the risk of decreasing fish quality and value. Hu et al. (2022) reported that Lake Datong, a shallow lake in China, became eutrophic and its water quality deteriorated after the introduction of aquaculture.

Extraction of ground water for aquaculture can cause saltwater intrusion and salinization in coastal areas (Gopaiah et al., 2023). All these environmental changes could affect the livelihoods of the local communities (da Silva et al., 2022; Nagaraju et al., 2022; Menon et al., 2023). Kim et al. (2022a) reported that an increasing number of farms in the coastal area resulted in the release of organic wastes derived from excess feed and fish metabolites. Yang et al. (2021) and Chiquito-Contreras et al. (2022) reported that approximately 27% to 49% of the feeds supplied to aquaculture production ponds are converted to fish products while the rest goes to wastes that are usually discharged into the nearby water bodies, and eventually form one of the factors that negatively affect the aquaculture value chain.

Water treatment technologies that are technically feasible, environmentally promising and financially profitable can be integrated into different aquaculture systems to make aquaculture industry a sustainable sector and contributes to the circular economy. Aquaculture wastes can be recovered and recycled using various technologies such as bioremediation, aeration, biocoagulation and biofiltration applied in various production systems such as recirculating aquaculture system (RAS), integrated multi-trophic aquaculture (IMTA) and aquaponics (aquaculture and hydroponics). In these circular economic activities, aquaculture wastes can generate additional products such as seaweeds, herbs, vegetables, mollusks

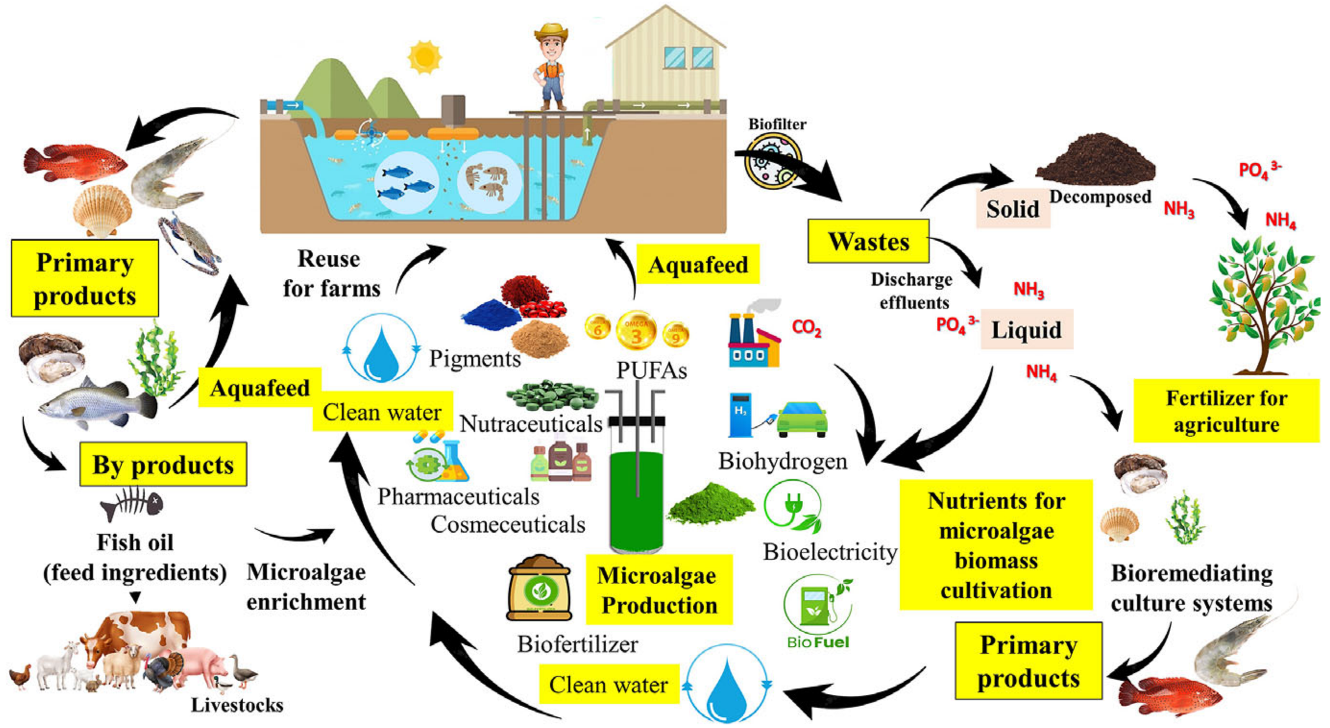

Figure 2. Recycling of aquaculture wastes to create various economically important outputs and maintain good water quality for aquaculture production.

and other by-products, while generating a clean water source that can be recycled and used for the fed culture (Figure 2). Legal instruments and authoritative interventions are also necessary for regulating aquaculture waste discharge and ensuring producers consider environmental impact and water quality management in their operations and practices. This review assessed the impacts of different production systems on the water quality and suggested possible approaches such as the use of environmentally friendly technological innovations and good governance in improving water quality management for a sustainable aquaculture industry.

Pollution and threats to water quality in aquaculture systems

Most aquaculture systems require a thorough understanding of water quality and waste management for accurate treatment decisions to ensure healthy cultured organisms with high yields (Davidson et al., 2022). Ssekyanzi et al. (2022) reported that in Sub-Saharan Africa, limited knowledge of water quality is one of the main factors contributing to low production (<1% of global production) and slow growth of the aquaculture sector.

Major factors contributing to the deteriorating environment and water quality in the aquaculture industry include nutrients (17%), other pollutants, including emerging pollutants (12%), habitat loss (16%), HABs (9%), lack of treatment technologies (8%) and socio-economic factors (38%) (Theuerkauf et al., 2019). Nutrients play a major role in eutrophication, resulting in massive proliferation of HABs, such as cyanobacteria and dinoflagellates and high mortality of cultured organisms in cultured systems (Table 1). Cyanobacterial blooms are also commonly associated with toxic–odor compounds such as geosmin and 2-methylisoborneol (2-MIB) which impart an unpleasant taste to water and cultured organisms. Marques et al. (2018) and Ryan et al. (2022) noted the negative impacts of an intensive aquaculture farm on effluent water quality due to excessive nutrients, especially phosphorus and nitrogen.

Emerging pollutants such as microplastics (Table 1) can cause health implications such as reduced feeding rate, gill malfunction, reduced reproductive capacity and immune suppression of cultured animals (Mallik et al., 2021). In aquaculture, plastic debris from aquaculture farms, rafts, cages, nets and other related production structures are sources of microplastics (Chen et al., 2018; Krüger et al., 2020). In addition, biofilms formed on microplastic particles are sources of pathogenic bacteria that can negatively affect aquaculture (Cholewińska et al., 2022).

Contamination in water sources for aquaculture production

Availability of clean water for aquaculture is an important consideration in site selection for aquaculture operation. In fact, suitable site selection for aquaculture activities is vital to alleviate potential problems associated with pollution and conflicting activities, and to ensure that the selected water body would be a conducive growing environment without jeopardizing the existing ecosystems (Table 1). Brigolin et al. (2015) and Jayanthi et al. (2021) used remote sensing, geospatial tools and mathematical models in combination with water quality factors, environmental characteristics and socioeconomic data to identify suitable areas for cage aquaculture in estuaries and coastal areas. Vaz et al. (2021) and Arega et al. (2022) developed a habitat suitability model based on water quality, hydrodynamics and biogeochemistry for aquaculture site selection.

In aquaculture systems, pollutants can originate from both allochthonous sources (such as feeds, fertilizers and/or polluted water sources) and autochthonous sources (phytoplankton biomass, metabolites). Polluted water from rivers and coastal waters can seriously affect the health and growth of the culture species,

Table 1. Major problems and mitigating measures in water quality management in aquaculture production systems

Problems	Aquaculture system	Mitigating measures/technologies	Benefits	References
Nutrients from excess feeds and metabolites (phosphorus and nitrogen) – Eutrophication	Intensive culture systems with high stocking rates – generate large amounts of wastes (liquid and solid wastes)	Integrated/restorative aquaculture – use of combined species of mollusks and seaweeds. Water treatment plants; removal of soluble reactive P (SRP) by adsorption to particulate organic matter	Improved water quality, improved aquaculture production and enhanced sustainability	Falconer et al., 2018; Zhang et al., 2018; Theuerkauf et al., 2019; Pu et al., 2021; Purnomo et al., 2022
		Installation of seaweed farms	Extract pollutants and improve water quality. Improved ecosystem services	Cabral et al., 2016
Harmful algal blooms (HABs) – taste and odor (T/O) compounds mainly due to geosmin and 2–MIB (2–methyl isoborneol)	Open water systems (Cage aquaculture, extractive aquaculture) and land–based production systems (e.g., recirculating aquaculture systems [RAS], integrated multi–trophic aquaculture [IMTA])	Monitoring, early detection and prevention of geosmin–producing cyanobacteria and other T/O compounds using PCR–based method. Reduce external nutrient loads	Degradation of geosmin and 2–MIB by UV/chlorine process, maintains the water quality and enhances the quality of aquaculture products	Ma et al., 2018; John et al., 2020; Kibuye et al., 2021
	Fish cages – *Oreochromis niloticus*	Use of probiotics for management of the intestinal bacteria	Reduce geosmin and other off–flavor compounds and improve fish quality	Lukassen et al., 2019a
	RAS – off flavor compounds	Optimization of the depuration method with improved water treatment	Reduce the off–flavor compounds	Azaria and van Rijn, 2018
Microplastics – toxic to living organisms	Mariculture – rafts, cages and nets are sources of microplastics.	Monitoring microplastic concentrations in water bodies and aquaculture systems. Reduce the usage of plastics	Reduce harmful effects on organisms and human health; healthy and safe aquaculture production	Chen et al., 2018; Krüger et al., 2020; Mallik et al., 2021; Cholewińska et al., 2022
Unsuitable aquaculture sites	Ponds, fish cages	Use of models for selecting suitable sites	Avoid pollution, continuous supply of good quality water for culture	Jayanthi et al., 2021; Racine et al., 2021

resulting in high mortality and low yields. In closed culture systems such as ponds and tanks, the quality of the intake water can be controlled. Under limited circumstances, low-quality water can be first treated before use, although the production would still be lower compared to those with clean water intake. In aquaculture systems located in open waters such as lakes and coastal waters (Figure 1), yields are highly dependent on the *in situ* water quality. In these, natural waters where cage aquaculture or extractive aquaculture is common, pollutants are mainly associated with anthropogenic activities in the catchment and upstream areas. Kim et al. (2022a) used 15-N isotopic signatures to show that organic pollutants in estuaries and coastal areas were mainly contributed by sources related to anthropogenic activities, including organic fertilizers and aquaculture discharges exported through rivers.

To ensure the sustainability of aquaculture production through sound water quality management of open waters, Liu et al. (2023a) proposed a watershed management framework using economic-based and water quality-based protection strategies to manage catchment areas for sustainable development. To prevent nonpoint source pollution, interactions between land cover, landscape pattern and design and pollution loading should be assessed and optimized (Ouyang et al., 2014; Falconer et al., 2018; Rong et al., 2021).

Factors affecting water quality in aquaculture production systems

Water quality in aquaculture systems is influenced by various physical, chemical and biological factors such as temperature, light, pH, dissolved oxygen, organic matter/nutrients, microorganisms and various biological interactions (Table 2). Climate change could exert drastic fluctuations in these physical chemical factors that would affect water quality, increase the incidence of fish diseases and cause high fish mortality and production (Lusiastuti et al., 2020). Alam et al. (2021) reported that Nile tilapia, *Oreochromis niloticus*, produced fewer eggs under high temperatures associated with climate change, and suggested effective management strategies to overcome the low egg production in commercial fish hatcheries. Ocean acidification and decrease in pH caused problems in shellfish aquaculture, such as oysters (Abisha et al., 2022; Mayrand and Benhafid, 2023). Higher sea levels could cause positive consequences such as the creation of new habitats in the coastal waters or negative impacts like saltwater intrusion. Increased wind speed and waves caused sediment suspension and high turbidity that affected water quality and aquaculture activities (Shen et al., 2023). Mitigating measures to overcome impacts of physicochemical changes include adaptations in production systems, good culture strategies such as species diversification, and use of predictive models (Table 2). Abisha et al. (2022) suggested the development of climate-resilient aquaculture through adaptations to environmental factors that have negative impacts on organisms to minimize the impacts of climate change. Shen et al. (2023) used satellite remote sensing to assess the impacts of the environment and improve the ecological and environmental regulations to support the sustainable development of the coastal area.

High organic wastes in aquaculture systems, mainly from excess feeds and metabolites, caused water quality degradation

Table 2. Factors affecting water quality in aquaculture production systems and mitigation measures

Factors	Types of stressors/impacts	Mitigating measures	References
Physicochemical factors/climate change	Increased mortality, and low production – threaten food security	Developed climate–change resilient aquaculture through adaptation to environmental stressors, selective breeding; species diversification and innovative aquaculture system	Abisha et al., 2022
	Extreme fluctuations of environmental parameters with high rainfall – increased incidence of fish diseases	Formulate aquatic animal health strategies to reduce diseases and use fewer/less chemicals in aquaculture operation	Lusiastuti et al., 2020
	Light availability	Reduce/regulate the abundance and buoyancy of toxic cyanobacteria such as *Microcystis*	Xu et al., 2023
	Extreme temperature fluctuations – affect Atlantic salmon cage aquaculture	Predictive models to match aquaculture activities and climate change	Gamperl et al., 2020
	Increasing temperature: Hatchery – Nile tilapia (*Oreochromis niloticus*)	Management strategies – decrease light intensity and temperature	Alam et al., 2021
	Ocean acidification – decrease in pH; reduced calcification in shellfish	Reduce atmospheric CO_2	Guo et al., 2023
Organic matter	Excreta and excess feeding	Precision feeding; high–quality feeds, optimize stocking rate and effective waste removal	Kawasaki et al., 2016; Zhang et al., 2018; Liu et al., 2023b
	Types of feed – release nitrogenous compounds – contaminate water and cause health problems	Feeding technologies and management to improve water quality	Fiordelmondo et al., 2020
Age and pond bottom quality	Organic matter accumulation, increased C/N ratio result in low production	Proper pond management to reduce organic matter accumulation	Hasibuan et al., 2023
Toxic compounds	Ammonia – Effects on growth, survival and yields of Japanese sea–perch (*Lateolabrax japonicus*) culture	Reduce total ammonia nitrogen to <0.3 mg N L^{-1}	Zhang et al., 2022a
	Low dissolved oxygen – hypoxia in Atlantic Salmon (*Salmo salar*) Aquaculture	Aeration (especially in the bottom layers) to increase dissolved oxygen (DO) and decrease the amount of organic matter. Microbubbles can be used to increase DO in the bottom layers where oxygen consumption tends to be high. Advanced technologies such as internet-of-things can be applied to ensure adequate DO in all aquaculture systems all the time	Gamperl et al., 2020
	Hydrogen sulfide (H_2S) in RAS – cause sudden mass mortality	Addition of hydrogen peroxide (H_2O_2) for H_2S removal. Safe for fish.	Bergstedt et al., 2022
	Heavy metal pollution contaminates water and fish/shrimp	Good management practices and good governance to reduce heavy metal contamination	Le et al., 2022
	Methane and CO_2 release from aquaculture ponds	Reduce organic wastes, aerate ponds and/or dredge pond bottom to prevent hypoxia	Chen et al., 2016; Yang et al., 2018; Yuan et al., 2021; Zhao et al., 2021
Algal blooms	Cyanobacterial blooms, algal toxins	Prevent eutrophication and toxic algal blooms. High and stable pH and dissolved oxygen concentrations	Yñiguez et al., 2021; Xue et al., 2023
Chemicals	Antibiotics, chemicals (e.g., malachite green), heavy metals	Use high–quality water sources for culture. Avoid using antibiotics and chemicals; use their alternatives such as probiotics, remove antibiotics by UV–photolysis and degradation by microbial granules	Falconer et al., 2018; Pandey et al., 2022; Sha et al., 2022
	Development of antibiotic–resistant genes (ARGs) that would be harmful to aquaculture health. Most antibiotics are from aquaculture farms and/or domestic sewage	Minimal and regulated antibiotics use in farms. Development of technologies for antibiotic removal from wastewater. Development of biomarker for antibiotic monitoring	Han et al., 2020; Fernanda et al., 2022; Chen et al., 2022
	Sulfonamides – degradation from aquaculture wastewater	Remove sulfonamides – Use laccase–syringaldehyde mediator system through response surface optimization, degradation kinetics and degradation pathways	Lou et al., 2022
Microbial communities	Environmentally friendly bacteria/bioremediate ecosystem; pathogenic bacteria/diseases and related health problems	Monitoring the dynamics of bacterial populations in the aquaculture systems and its related processes (bio–filtration, biofilms)	Lukassen et al., 2019b
Diseases	Poor water quality – increased incidence of white spot disease – high mortality and low production.	Good farm management includes improving water quality, maintaining and stabilizing physical–chemical parameters and controlling water exchange to reduce the pathogen prevalence	Swathi et al., 2021; Hassan et al., 2022

characterized by high ammonia, nitrate and soluble reactive phosphorus, high biological oxygen demand (BOD), high chemical oxygen demand (COD) and low dissolved oxygen (Table 2). Phosphorus (P) can be a source of environmental contamination and eutrophication in aquaculture systems if not adequately removed from the wastewater. In terms of nitrogen, the proportion of toxic unionized ammonia (NH_3) depends on the total ammonia concentration (ionized ammonium ion) and NH_3 in the water column, which is in turn governed by water temperature and pH. Once ammonia concentrations in the water are high, fish are less able to excrete ammonia through gill diffusion resulting in the accumulation of ammonia in fish tissues, which would finally affect fish health and growth. Zhang et al. (2022a) reported that toxic ammonia can reduce the quality and yield of Japanese sea perch (*Lateolabrax japonicus*). Due to its adverse effects on aquaculture species, ammonia concentrations in production systems should be closely monitored. Yu et al. (2021) used a hybrid soft computing method to accurately predict ammonia concentrations in aquaculture water in real time. Temperature, dissolved organic carbon and redox potential are the primary drivers of chemical fluxes in freshwater aquaculture ponds (Yuan et al., 2021).

Accumulation of organic matter in the pond bottom can be the main cause of hypoxic conditions in enriched aquaculture ponds (Yang et al., 2021). Under anaerobic conditions, high organic matter accumulation can produce methane (CH_4), hydrogen sulfide (H_2S) and nitrous oxide (N_2O), which could adversely affect water quality (Table 2). Toxic H_2S, commonly found in production systems with low oxygen, could cause sudden fish/shrimp mass mortality. Wu et al. (2018b) reported that CH_4 and N_2O fluxes in inland aquaculture ponds were positively correlated to temperature and sediment organic carbon, and negatively correlated to dissolved oxygen concentration. Chen et al. (2016) and Yang et al. (2018) noted that substantial amounts of CH_4 and carbon dioxide were released from mariculture ponds. In freshwater aquaculture ponds, Zhao et al. (2021) reported that high concentrations of CH_4 were released and showed that dredging of the pond bottom as part of pond preparation was more effective in reducing CH_4 compared to aeration. Thus, there is a need for immediate and continuous removal of toxic compounds such as ammonia, nitrite, H_2S and CH_4 in aquaculture systems.

Nutrient-rich waters are also associated with cyanobacterial blooms that could produce toxic–odor compounds such as geosmin and 2-MIB, causing an unpleasant taste to water and cultured organisms. Although a variety of bacteria and fungi produce geosmin, cyanobacteria including planktonic and benthic species belonging to Nostocales, Oscillatoriales and Synechococcales are major producers of geosmin (Watson et al., 2016; John et al., 2018). Cyanobacterial toxins pose threats and risks to human and animal health. Cyanobacteria proliferate rapidly in eutrophic waters due to their ability to float and overcome light limitations (Table 2). Geosmin has been found to cause off-flavor in a wide range of environments including RAS (Azaria and van Rijn, 2018; Lukassen et al., 2019b). Lukassen et al. (2019a) reported that higher densities of geosmin-producing bacteria were found in the intestinal mucous layer and digestive system of tilapia (*O. niloticus*) compared to the water column, indicating that probiotics can be used to manage intestinal microflora to improve fish quality. Due to the detrimental impacts of HABs on aquaculture production systems, environmental and human health, and socioeconomics, microalgal toxic species distribution and abundance should be closely monitored for early detection and preventive action. In fact, reduction of the external nutrient load is the most fundamental aspect of cyanobacterial control (Kibuye et al., 2021). Derot et al. (2020) used two machine learning models with a long-term base to forecast HABs. Pal et al. (2020) suggested biological options such as bacteria, viruses, fungi and zooplankton for controlling HABs. John et al. (2018) developed a novel polymerase chain reaction method targeting the geosmin synthase gene (geoA) to assess all important sources of geosmin, while Ma et al. (2018) showed that chlorine aqueous solution under ultraviolet light could effectively remove geosmin and 2-MIB in acidic conditions.

In addition to nutrients, aquaculture systems can also be subjected to other pollutants such as antibiotics and heavy metals that could eventually affect the quality of the produce (Table 2). Le et al. (2022) noted heavy metal pollution in the aquaculture coastal area and emphasized the need for good management practices if sustainable aquaculture is to persist in the coastal area. The use of antibiotics and chemicals in aquaculture can also have far-reaching effects on ecological food pyramids. Fernanda et al. (2022) showed that water quality parameters in aquaculture ponds were significantly correlated with the abundance of antibiotic-resistant (AR) genes which were brought down by a river polluted by various sources from the cultivated and industrial lands. In the environment, the partitioning and distribution of antibiotics are positively correlated to salinity, suspended solids, pH, ammonia and zinc, and negatively correlated to temperature, dissolved oxygen, phosphate, COD, oil, copper and cadmium (Li et al., 2022a). Ecological and biological risks of antibiotics are high and can be detrimental to aquaculture products. Chen et al. (2022) developed a biomarker using cyanobacterial carbonic anhydrase for monitoring antibiotics. Chemicals used in aquaculture should also be removed before discharging wastewater into the surrounding environment. Sulfonamides from aquaculture wastewater can be degraded using laccase-syringaldehyde mediator system through response surface optimization, degradation kinetics and degradation pathways (Lou et al., 2022). Pandey et al. (2022) suggested the removal of malachite green, which is commonly used for disease treatment in aquaculture ponds, using laccase immobilized biochar. Yanuhar et al. (2022) reported that water quality in concrete ponds can be improved by aeration, filtration and reduction of organic matter by optimizing the feed.

In addition to physical and chemical parameters, disease agents such as bacteria, fungi and other pathogenic organisms can also affect water quality and aquaculture performance (Table 2). Microbial communities in aquaculture systems are shaped by the environmental conditions which are in turn influenced by inland discharges, climate changes and anthropogenic pressures. Swathi et al. (2021) reported that water quality parameters were closely related to the outbreak of white spot disease in shrimp culture ponds. Thus, regular monitoring and estimating microbial diversity would allow farmers to link water quality parameters to subsequent fish performance and assess the environmental health of the aquaculture systems and the vicinity for early detection of microbial conditions that could lead to impaired fish health.

Water quality management in aquaculture production systems and methods to enhance it

Water quality in aquaculture production systems

Aquaculture production systems including RAS, IMTA, aquaponics (aquaculture and hydroponics) and ecosystem-based approaches were designed and constantly improved to enhance water quality and production (Table 3). These integrated

Table 3. Aquaculture production systems for improving water quality in aquaculture

Approaches/methods/processes	Aquaculture species/systems	Supporting species/function	References
Aquaponics	Catfish (*Clarias gariepinus*)	Spinach and bacterial communities in the aquaponic system (A–RAS)	Ekawati et al., 2021
	European catfish (*Silurus glanis*)	Lettuce (*Lactuca sativa*) for nutrient removal from aquaculture wastewater, improved water quality, fish yields and plant biomass (A–RAS)	Calone et al., 2019
	Multiloop aquaponic system	RAS–hydroponic for better fish and plant production with flexible sizing	Goddek and Körner, 2019
	Pangas (*Pangasius hypophthalmus*)	Marigold (*Tagetes erecta*) in portable nutrient film technique (NFT) aquaponic system	Mohapatra et al., 2020
	Hydroponic–biofilm combined treatment system	Efficiently removed nutrients by both plants and biofilms. Biofilm promoted the removal of nitrogenous compounds by denitrification. Improved water quality, fish health and fish production	Li et al., 2022b; Sopawong et al., 2023
	Co–cultivation – Tilapia and microalgae in aquaponics	Microalgae (*Chlorella* sp.) were more efficient in ammonia removal compared to plants. An additional product of microalgae biomass	Addy et al., 2017
	Crayfish–rice integrated system (CRIS)	Less fertilizer for rice plants boosts farmers' production and economy	Liu et al., 2019
	Biochar–supplemented planting panel system; Laccase immobilized biochar	Water treatment for fish culture increase dissolved oxygen and convert toxic compounds to those beneficial for plant growth; bioremoval of toxic malachite green from aquaculture systems	Mopoung et al., 2020; Pandey et al., 2022
	Aeration and polylactic acid addition in aquaponics	Decrease of dissolved organic matter, improved water quality	Wu et al., 2018a
	Internet–of–things (IoT) in aquaponics	Cloud–based IoT monitoring and smart sensing systems. Improved water quality and fish production	Lee and Wang, 2020; Taha et al., 2022
Integrated multi–trophic aquaculture (IMTA)	Abalone (*Haliotis asinine*) and other bivalves	Mollusks and seaweeds. Seaweeds (*Gracilaria heteroclada* and *Eucheuma denticulatum*) extract nutrients (especially nitrate and ammonia) from the water column	Largo et al., 2016; Park et al., 2018
	Rainbow trout (*Oncorhynchus mykiss*) and European perch (*Perca fluviatilis*)	Duckweed species; *Lemna minor* and *L. gibba*/ enhanced nutrient removal and biomass production	Paolacci et al., 2022
	Hybrid grouper (*Epinephelus fiscoguttatus* x *E. lanceolatus*) and whiteleg shrimp (*Litopenaeus vannamei)*	Seaweed (*Gracilaria bailinae*)/removed inorganic nutrients, improved water quality, enhanced health and promoted the growth of cultured organisms	Zhang et al., 2022b
	Commercial shellfish species	Seaweed aquaculture (extractive species)/decrease or minimize impacts of pollution, habitat loss, ocean acidification and fishing pressures – restorative IMTA	Theuerkauf et al., 2019
Macroalgal–based IMTA	Salmon aquaculture	Macroalgal–based IMTA – Kelp farm (*Macrocystis pyrifera*). 3D ecosystem model used to quantify water quality changes. Reduce chlorophyll *a* concentrations	Hadley et al., 2018
Microalgal–based IMTA	Aquaculture systems – effluents; Binary microalgae culture system	Periphyton, microalgae–bacterial consortia, cell immobilization–alginate beads/reduce nutrients and other pollutants, improve water quality, production of algal biomass for feed, fertilizers and other valuable compounds	Milhazes–Cunha and Otero, 2017; Luo et al., 2019
	Microalgae cultivation – recycling of culture medium	Sequestering of nutrients by microalgae (autoflocculation); flocculating bacteria enhanced microalgae growth	Li et al., 2019; Nguyen et al., 2019b
Recirculating Aquaculture System (RAS)	Rainbow trout (*O. mykiss*) culture	Optimized relative water renewal rate, maintained good water quality with online water quality monitoring, low feed conversion ratio, high growth rate; single–sludge denitrification to remove organic matter and nitrate	Pulkkinen et al., 2018; Suhr et al., 2014
RAS – depuration system	Atlantic salmon, *Salmo salar* culture with depuration system	Additional depuration system in RAS improved water quality, low geosmin and 2–methylisoboreol levels	Davidson et al., 2022

(*Continued*)

Table 3. (*Continued*)

Approaches/methods/processes	Aquaculture species/systems	Supporting species/function	References
RAS –microalgae	Tilapia (*Oreochromis niloticus*) culture – Microalgae	Include microalgae (*Chlorella vulgaris* and *Tetradesmus obliquus*) for aquaculture effluent pretreatment – enhanced microalgal growth and nutrient removal	Ramli et al., 2017; Tejido–Nuñez et al., 2019
	Marine fish culture – Microalgae	Microalga, *Tetraselmis* sp. High nutrient removal (N and P). Production of microalgal biomass high in lipids and useful compounds suitable for fish feeds	de Alva and Pabello, 2021
	Shrimp culture – Microalgae	Immobilized microalga *Tetraselmis* sp. Reduction of nitrogenous and phosphorus compounds	Khatoon et al., 2021
RAS – microbes	Marine fish culture – Bacteria; immobilized bacterial granules	Nitrifying bacteria in RAS, oxidize ammonia to nitrate; removal of antibiotics – ultraviolet photolysis and biodegradation by immobilized bacterial granules	Sha et al., 2022
	Freshwater fish culture, Shrimp culture – Microbial communities	Microbial communities in RAS biofiltration system. The addition of carbon sources enhanced microbial communities in biofilters in RAS	Jiang et al., 2019; Chen et al., 2020
	Shrimp culture –Microbial community improvement	Water circulation on the microbial community/ improved water quality, better growth	Chen et al., 2019
	Aquaculture System – SNAD Bioreactor (Simultaneous partial nitrification, anammox and denitrification)	Effective removal of nitrogen and COD under high dissolved oxygen condition	Lu et al., 2020
	African catfish (*C. gariepinus*) culture – Near–zero discharge RAS	Recovery and reuse of phosphorus by microbes under anoxic and anaerobic treatments	Yogev et al., 2020
	Microalgae–bacteria consortia in RAS	Significant reduction of nitrogenous compounds, and improved water quality	Chun et al., 2018
	Moving–bed biofilm reactor (MBBR)	Ammonia removal by MBBR resulting in improved water quality	Ashkanani et al., 2019
Integrated RAS–IMTA	River prawn and tambaqui fish – RAS–IMTA	Improved system efficiencies, better yields	Flickinger et al., 2020
Ecosystem–based approach – Integration of aquaculture system extractive species (seaweed cultivation; mangrove forest)	Coastal aquaculture, shrimp farming, whiteleg shrimp (*L. vannamei*).	Eco–green approach. Integration of aquaculture and mangrove forest management/preserve and sustain mangrove forest, sustain aquaculture industry Integration of seaweed cultivation in aquaculture system	Racine et al., 2021; Musa et al., 2023
Physical–biological coupling ecosystem model	Integrated bivalve–seaweed culture	Increased production of kelp (*Saccharina japonica* – seaweed) and oysters (*Crassostrea gigas* – mollusks), improved water quality, sustainable ecosystem	Fan et al., 2020

production systems which have zero-water exchange and produce microorganisms as food sources, can be integrated with different types of biofiltration, biocoagulation, bioflocculation and biological interactions including bioflocs and bioremediation (Xu et al., 2021; Igwegbe et al., 2022) to enhance their wastewater treatment performance (Table 4).

Aquaponics

Aquaponics, the integration of aquaculture and hydroponics, is conceptually based on the efficient use of water and recycling of accumulated organic nutrients using plants, as one of the effective approaches in addressing the problems of aquaculture wastewater treatment, pollution in public waters, improved water quality in culture systems and sustainable aquaculture development (Yep and Zheng, 2019; Chiquito-Contreras et al., 2022); Okomoda et al., 2023). Essentially, aquaponics uses bacterial processes and enhances plant nutrient uptake to recover and recycle nutrients from aquaculture systems (Kalayci Kara et al., 2021; Chen et al., 2023). Sopawong et al. (2023) showed that integrating fish culture and plants in a bio-green floating system significantly improved water quality, fish health and aquaculture production. In addition, aquaponics overcomes the land scarcity for aquaculture as the system can be constructed and designed to fit any area available, such as in urban areas and water-scarce areas. Palm et al. (2018) and Obirikorang et al. (2021) demonstrated the increased efficiency of aquaculture production in aquaponics improvised for commercial aquaculture production and food security. To make the aquaponics more effective, Calone et al. (2019) and Ekawati et al. (2021) combined it with RAS as aquaponic-RAS (A-RAS), which proved to be effective in improving water quality, survival rate, feed conversion ratio (FCR) and yield in catfish aquaculture (Table 3). Based on the same principle, Goddek and Körner (2019) designed RAS-hydroponic multi-loop aquaponic system for better fish and plant production with flexible sizing. Liu et al. (2019) introduced crayfish integrated system for efficient use of waste for rice production. There are different combinations of fed and extractive species in

Table 4. Technologies and processes for improving water quality in aquaculture systems

Technologies/ processes	Applications/main features	Benefits	References
Bioremediation	Triangle sail mussel culture (*Hyriopsis cumingii*)	*Bacillus subtilis*, *Bacillus licheniformis* and microalga, *Chlorella vulgaris*/bioremediate aquaculture wastes, provide foods for the mussels (*H. cumingii*), enhance digestive enzyme activities of the mussel	Geng et al., 2022
	Intensive aquaculture ponds	*Bacillus megaterium* with high aerobic denitrification efficiency (>90% of NO_2–N removal). Development of biofilm enhanced denitrification (>95% nitrate removal)	Gao et al., 2018; Xu et al., 2019
	Tilapia culture – aquaculture wastewater	Bacterial consortium – *Bacillus cereus*, *Bacillus amyloliquefaciens* and *Pseudomonas stutzeri*	John et al., 2020
Phytoremediation – Microalgae–based Aquaculture	Aquaculture systems – fish, shrimp	Microalgae (*Nannochloropsis oculata*, *Tetraselmis suecica*) –highly efficient nutrient removal (from wastewater) with low cost, double crops (fish and algae) enhanced biomass production. Production of byproducts – bioethanol Immobilized marine microalgae biofilter Seaweed *Ulva lactuca*, bioremediate water and served as a food additive	Reyimu and Özçimen, 2017; Nie et al., 2020; Emparan et al., 2020; Elizondo–González et al., 2018; Kumar et al., 2016
	Flow–through system for Eurasian Perch (*Perca–fluviatilis*)	An alga, *Pseudokirchneriella subcapita*, improved water quality	O'Neill and Rowan, 2022
	Fishery wastewater	Microalgae co–culture of *Thalassiosira pseudonana* and *Isochrysis galbana.* Microalgae – improved water quality and enhanced algal growth	Wang et al., 2021; Kim et al., 2020
	Binary microalgae culture system	Microalgal–bacterial symbiotic system – synchronous wastewater treatment and nutrient recovery	Rashid et al., 2018; Bhatia et al., 2022; Sun et al., 2022; Wang et al., 2022
	Microalgae–bacteria symbiotic system	Integrated microalgae and bacteria system/ optimized carbon sources, enhanced nutrient removal	Nguyen et al., 2019a
	Biotic control: biological agents for HABs treatment	Species–specific mode of interactions with algal blooms (bacteria, viruses, fungi and zooplankton) through feeding (predation), lysis and/or competition	Pal et al., 2020
Bioflocs	Aquaculture systems – binary microalgae culture	Microalgae–bacterial flocs/nutrient removal and microalgae biomass	Rashid et al., 2018; Nguyen et al., 2019a
	Tilapia culture (*Oreochromis niloticus*)	Reduce inorganic nutrients by different biofloc starters (carbohydrates)/improve water quality	Luo et al., 2017; Putra et al., 2020
	Jade Perch RAS – biofloc with heterotrophic and nitrifying bacteria	Heterotrophic bacteria removed nitrate and soluble reactive P and nitrifying bacteria removed nitrite. Save carbon resources. Heterotrophic bacteria showed better performance than autotrophic bacteria in wastewater purification capacity	Kim et al., 2020; Liu et al., 2021b
	Shrimp culture – Penaeid shrimp *Litopenaeus vannamei*	Biofloc–based bacterio–plankton community/improve water quality, control pathogens and enhance shrimp immunity	Kim et al., 2022b; Ríos et al., 2023
Biological Filtration	Tank cultures – issues on emerging pollutants, antibiotic–resistant genes and organic micropollution	Environmentally friendly, recirculating aquaculture system, bio–enhanced biological filtration	Jin et al., 2023
	Catalytic ozonation–membrane filtration	Degradation of organic matter and decreased of ammonia	Chen et al., 2015
	Biological filters in common carp culture	Use of additional media such as wheat hay, rice husks as biological filters to improve water quality and fish growth	Hassan et al., 2022

(*Continued*)

Table 4. (*Continued*)

Technologies/ processes	Applications/main features	Benefits	References
Membrane filtration technology	Membrane filtration in RAS	Good sieving effect and solute removal mechanism, but has problems such as high cost and was subjected to high biofouling	Ng et al., 2018
Electrochemical Oxidation	Seabream (*Sparus aurata*) and sea bass (*Dicentrarchus labrax*) in recirculating aquaculture system (RAS)	No supporting species/improved water quality with high efficiency of ammonia removal and fish disinfection, reduction in water use; improved fish yields	Santos et al., 2022
Hybrid electrocoagulation filtration method	Wastewater of aquaculture system–electrocoagulation (EC) filtration system consisting of EC reactor, mixed flocculator, filtration equipment	Pretreatment of marine aquaculture wastewater	Xu et al., 2021
Bio–coagulation–flocculation/ adsorption – *Picralima nitida* seed extract	Catfish culture	Treatment of aquaculture effluent using *Picralima nitida* seed extract/improve waste biodegradability, significant pollutant removal, superior effluent quality	Igwegbe et al., 2022
	Marine and land–based RAS for salmon (*Salmo salar*)	Treatment of aquaculture effluents by coagulation of phosphorus and organic matter.	Letelier–Gordo and Fernandes, 2021
	Fresh and brackish water RAS – Organic flocculants/woodchip reactor/sand filtration	Removed P, N, geosmin and heavy metals from RAS. Improved water quality in RAS	Kujala et al., 2020; Lindholm–Lehto et al., 2020
Chemicals and veterinary medicine	Pacific whiteleg shrimp (*Litopenaeus. vannamei*)	Improved health, survival and production of cultured species	Patil et al., 2022
Development of green feeds	Freshwater aquaculture	Better feed conversion ratio (FCR), improved water quality	Farradia et al., 2022
Technologies: Internet of things (IoT), artificial intelligence (AI) and models	Wireless sensor network, artificial intelligence (AI)–web–based monitoring, automation and alert system	Water quality monitoring of aquaculture systems	Shi et al., 2018; Eze et al., 2021; Wei et al., 2023
	Machine learning approach for water quality assessment in aquaculture systems	Improve water quality and aquaculture yields	Rana et al., 2021; Rahman et al., 2021
	A hybrid neural network model for dissolved oxygen and other water quality parameters	For predicting dissolved oxygen concentration and other water quality parameters in aquaculture systems	Eze and Ajmal, 2020; Liu et al., 2021a; Ranjan et al., 2023
	Hybrid soft computing	Real–time measurement and monitoring of ammonia	Yu et al., 2021
	Low–to–high frequency data – autonomous data collection platform	Monitoring of water quality and fish production	Sampaio et al., 2021
	Long–range multistep water quality forecasting	Accurate water quality prediction for effective water quality monitoring	Islam et al., 2021
	Fuzzy comprehensive evaluation method	Improved water quality	You et al., 2021
	Bio–reaction kinetics model for assessing pollutant accumulation in fish tissue	Environmental quality and safety risk assessment for fish	Bai et al., 2021
	Machine learning models for predicting HABs	Prevention of HABs.	Derot et al., 2020
	Sentinel–2 satellites	Water quality and cyanoHABs monitoring	Caballero and Navarro, 2021
	Sentinel–2 satellite imagery for water quality index	Assessment of microphytobenthos using remote sensing to determine the health status of water bodies	Oiry and Barillé, 2021
	Machine learning models for predicting fish kills	Predicting fish kills and toxic blooms in aquaculture areas	Yñiguez and Ottong, 2020
	Intelligent IoT–based control and traceability system	Forecast and maintain water quality in the aquaculture system.	Gao et al., 2019
	Deep belief network (DBN) and variational mode decomposition (VDM) data processing – VMD–DBN model	VMD–DBM model for high prediction accuracy and stability of dissolved oxygen in aquaculture systems	Ren et al., 2020

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Table 4. (*Continued*)

Technologies/ processes	Applications/main features	Benefits	References
	AI techniques	Modeling daily dissolved oxygen. Least square support vector machine (LSSVM), multivariate adaptive regression splines and M5 model tree (M5T)	Heddam and Kisi, 2018
	Integrated AI–IoT	Integrates AI, IoT and smart sensors in aquaculture (water quality monitoring and feeding)/enhance water quality, precision feeding, increased survival and production	Danh et al., 2020; Huan et al., 2020; Pasika and Gandla, 2020; Chang et al., 2021
	Solar–powered semi–floating aeration system	Increase dissolved oxygen	Dayıoğlu, 2022
	Fish culture zone water quality model – taking into account interacting aquatic components: P cycle, N cycle, dissolved oxygen, phytoplankton and particulate organic carbon	For aquaculture site assessment	Arega et al., 2022
	Water quality modeling framework for antibiotic resistance in aquaculture systems	Evaluate AR bacteria and AR genes in aquaculture systems	Jampani et al., 2022
	Intelligent and unmanned equipment	Convenient and efficient applications of intelligent and unmanned equipment for water quality management, precision feeding and biomass estimation in aquaculture systems	Ubina and Cheng, 2022; Wu et al., 2022

different systems to improve water quality, such as catfish, plants and bacteria in hydroponic-biofilm and NFT systems (Mohapatra et al., 2020; Li et al., 2022b) to improve biofilter and ammonia removal efficiencies. Addy et al. (2017) showed that microalgae were more efficient in ammonia removal compared to plants in aquaponic co-cultivation. Other technologies such as biochar-supplemented planting panel system, polylactic acid addition and smart sensing systems have been integrated into the design of aquaponics to improve water quality (Table 3).

Integrated multi-trophic aquaculture

The concept of IMTA utilizes complementary aquaculture species along the food chain in the process of eating and being eaten such that wastes are fully recycled and minimal pollutants are released to the adjacent waters (Figure 3). In IMTA system, commercially important fed species (the main fish or invertebrates that consume given feeds) are cultured together with commercially important extractive species (aquatic species such as seaweeds or mollusks that feed/use the waste of other species) so that ecological balance and water quality in the system could be maintained (Figure 3). Since feeding is an important factor in an IMTA system, Flickinger et al. (2020) showed that feed management is important to determine the water quality that translates into prawn and fish production in IMTA.

The selection of the species from various trophic is based on their physiological and ecology functions to ensure a complete recycling of organic matter in the system with minimal wastes and good water quality, which contributes to the sustainability of the aquaculture industry (Table 3). Largo et al. (2016) reported the use of abalone (donkey's ear, *Haliotis asinina*) as fed species and seaweeds (*Gracilaria heteroclada* and *Eucheuma denticulatum*) as the inorganic nutrient extractive species. Seaweeds functioned effectively in sequestering nutrients in various fish and shellfish cultures to minimize the impacts of pollution and improve water quality not only in aquaculture systems, but also in the related water bodies (Table 3). Kelp (*Macrocystis pyifera*) farms in a macroalgae-based IMTA were used to sequester nitrogenous compounds from salmon aquaculture effluents resulting in low chlorophyll concentrations and improved water quality (Hadley et al., 2018). In freshwater IMTA, Paolacci et al. (2022) showed that duckweed, *Lemna* spp., could substantially remove total nitrogen and total phosphorus, maintain good water quality and increase aquaculture yields. In addition to macroalgae, microalgae can be introduced in IMTA in the form of periphyton and/or microalgae–bacterial consortia to reduce nutrients and other pollutants, improve water quality and produce algal biomass for enhancement of culture yields in the system (Milhazes-Cunha and Otero, 2017).

Recirculating aquaculture system

The RAS is a closed-circuit high-density aquatic animal farming where water from fish tanks is recirculated to remove solid and liquid wastes, and the purified water is returned to the aquaculture tanks (Figure 4). It is designed to provide a more controlled aquaculture system to reduce water usage and produce less wastes (both liquid and solid wastes), and thus it is more efficient and economical compared to the conventional flow-through and cage aquaculture systems (Table 3). In RAS, the relative water renewal rate can be optimized, the fish FCR decreased and the growth rate increased (Pulkkinen et al., 2018). As excess and poor-quality feeds can cause water quality problems in RAS, Kamali et al. (2022) took into account the effects of feeding regimes on the accumulation of ammonia and dissolved oxygen in designing a new RAS to enhance the sustainability of aquaculture.

The efficiency of RAS in water quality management could be enhanced by combining the system with other functional components such as depuration system to eliminate off-flavor, microalgae system to enhance nutrient removal and bacterial communities as in simultaneous partial nitrification, anammox and denitrification system to enhance organic–inorganic matter recycling (Table 3). Biofiltration in RAS functions to convert ammonia to the less toxic form, nitrate. According to Santos et al. (2022), nitrate is about 100–200 folds less toxic.

Other alternative methods of nutrient removal such as direct or indirect oxidation, adsorption by zeolites and activated carbon, air stripping and reverse osmosis have their own drawbacks in terms of

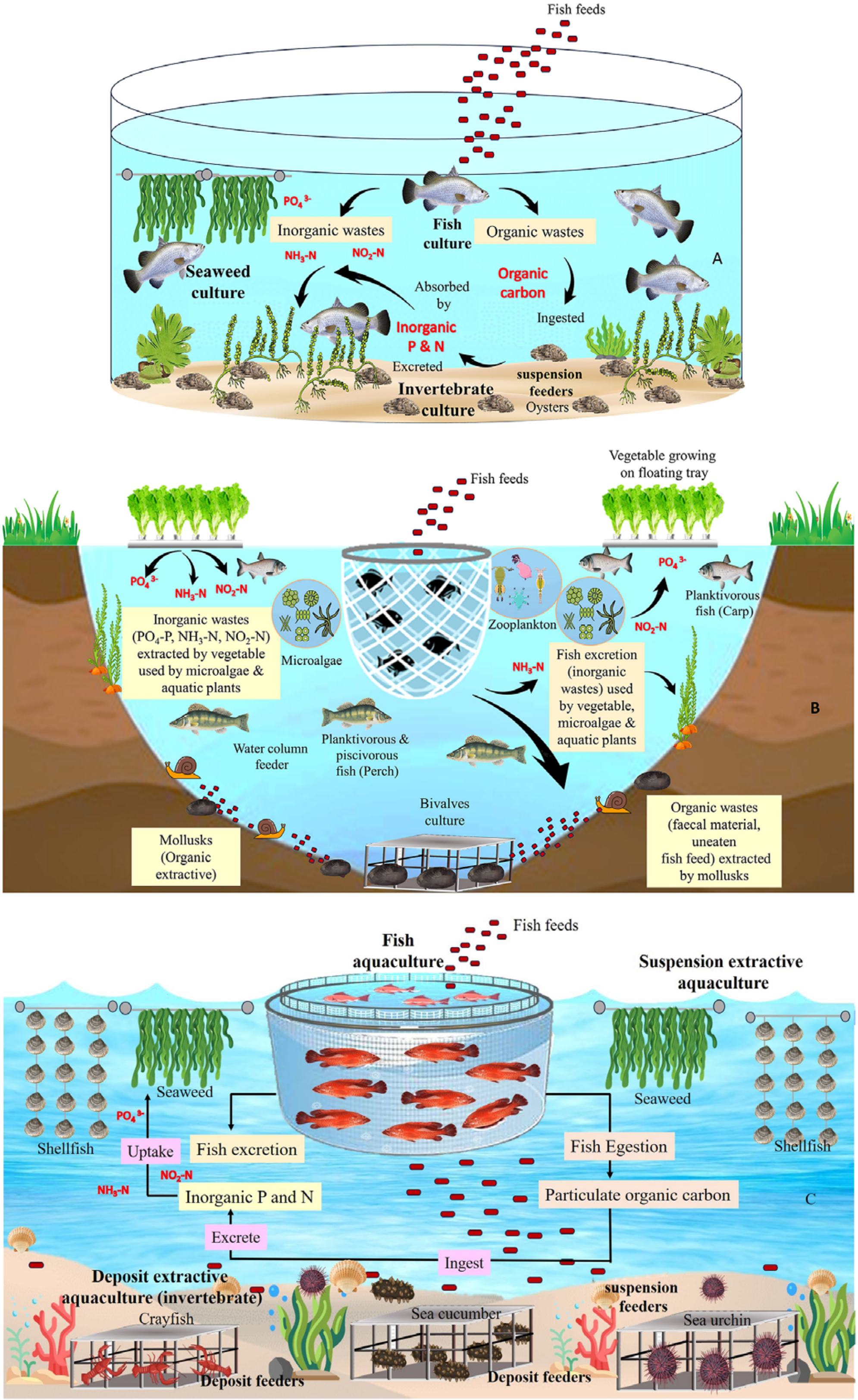

Figure 3. Integrated multitrophic aquaculture (IMTA) systems; in tanks (A), in ponds (B) and in coastal waters (C).

low efficiency and high energy costs (Díaz et al., 2012; Gendel and Lahav, 2013). Yogev et al. (2020) showed that P from RAS can be efficiently (>99%) removed through biomineralization in an anaerobic reactor and reused as fertilizer. For other toxic compounds, Bergstedt et al. (2022) proposed the use of hydrogen peroxide to remove H_2S from a saltwater RAS. RAS is advantageous in areas with limited land and water. In countries with severe water shortages, such as Gulf Cooperation Council countries, RAS is useful for

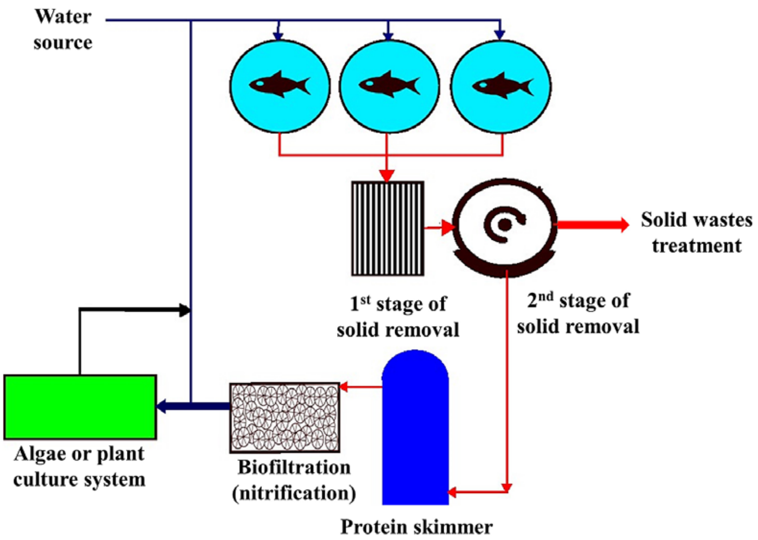

Figure 4. A recycling aquaculture system with an additional algae/plant culture compartment.

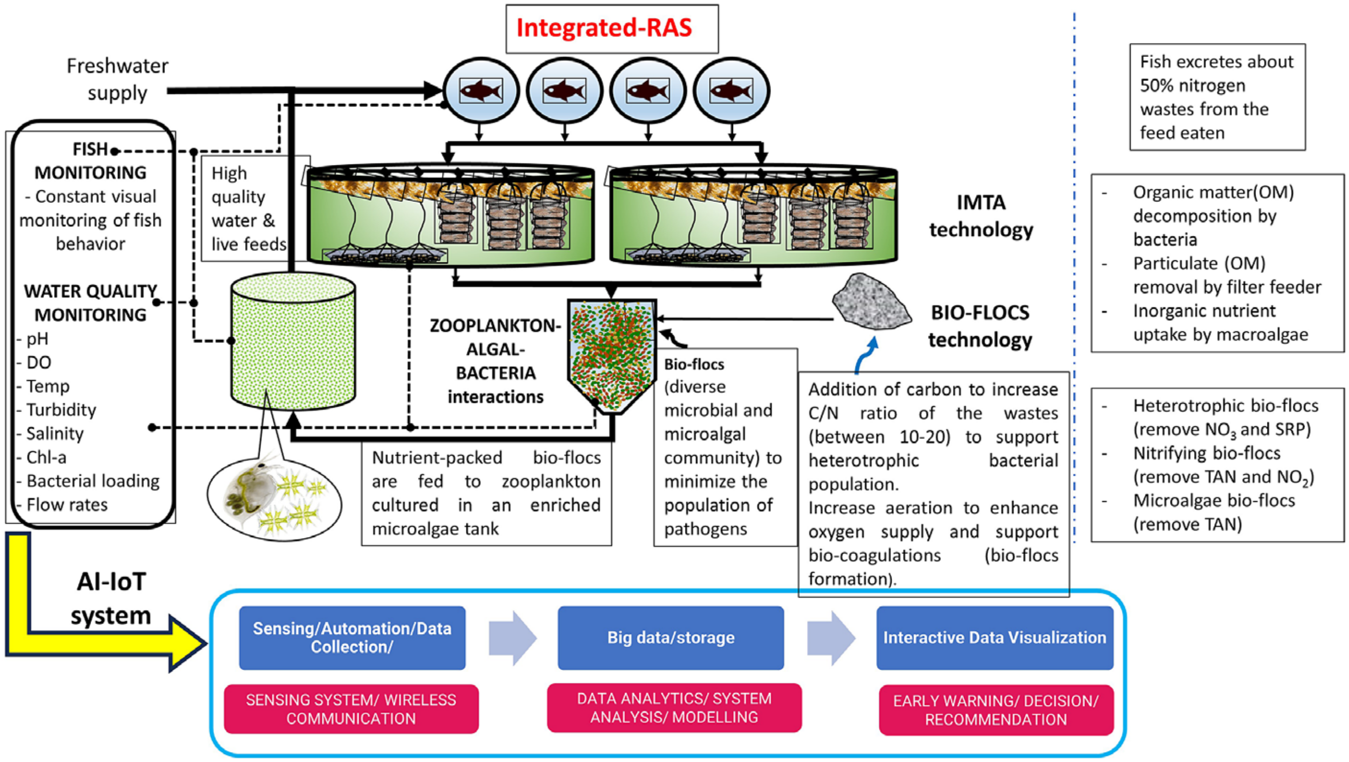

Figure 5. Integrated recycling aquaculture system (I-RAS) combining different systems and technologies (integrated multitrophic aquaculture (IMTA), biofloc, bioremediation, bacteria-microalgae consortium, water quality monitoring, and artificial intelligence-internet-of-things (AI-IoT)), to make the I-RAS more efficient and effective in recycling the waste, while enhancing water quality and aquaculture production.

recycling wastewater to overcome water scarcity for aquaculture (Qureshi, 2022).

Integration of production systems using ecosystem-based approaches for water quality improvement

In most aquaculture systems, toxic compounds such as ammonia, nitrite and H_2S can deteriorate water quality, increase mortality and reduce yields. Although Aquaponics, IMTA and RAS have been designed individually to improve water quality and increase yields, integration of these production system could increase the efficiencies and performances of aquaculture systems. Integration of A-RAS (Aquaponics and RAS), and I-RAS (IMTA and RAS), supported by a variety of functional biological components such as bacteria and microalgae can make aquaculture production systems more productive, cost-effective and efficient with less water consumption and lower disease risks (Figure 5).

Essentially aquaponics, IMTA, RAS and their combinations (A-RAS, I-RAS) are conceptually based on ecosystem-based approaches, where holistic integration and management of different ecosystem components are essential to maintain its ecological resilience and stability to ensure optimum production in closed aquaculture systems. However, ecosystem-based aquaculture system can also be carried out in the open system such as the integration of aquaculture and mangrove forest management in eco-green approach (Racine et al., 2021; Musa et al., 2023). Ecosystem model with the co-culture of bivalves (as the grazers) and seaweeds (as nutrient consumers) would drive the nutrient-phytoplankton-zooplankton-detrital food web, increase the efficiency of waste recycling, improve water quality and enhance aquaculture yields (Cabral et al., 2016; Park et al., 2018). Fan et al. (2020) reported increased production of kelp (*Saccharina japonica* – seaweed) and oysters (*Crassostrea gigas* – a mollusk) with improved water quality, making the ecosystem resilient and stable (Table 3).

Methods for water quality enhancement

Different technologies (such as bioremediation, bio-floc and internet-of-things [IoT]) and processes (chemical reactions, filtrations, coagulations and flocculations) can be imbedded in closed aquaculture systems such as aquaponics and RAS, or open systems such as coastal waters to make the wastewater treatment and recycling more efficient, which in turns, improve water quality and enhance aquaculture yields (Table 4, Figure 5). Liu et al. (2021b) integrated heterotrophic biofloc and nitrifying biofloc filters to simultaneously control ammonia, nitrite, nitrate, soluble reactive phosphorus and alkalinity with relevant functional microbes such as ammonia and nitrite-oxidizing bacteria, denitrifying bacteria, phosphorus accumulating organisms (PAOs), denitrifying PAOs and glycogen accumulating bacteria.

Bioremediation

Bioremediation involves the use of environmentally friendly microorganisms to mitigate pollution, improve water quality and maintain ecological health in aquaculture systems (Devaraja et al., 2002; Sun et al., 2022). These bioremediation bacteria function to decompose organic wastes into useful inorganic compounds that are recycled to maintain a healthy nutrient cycle in various culture systems (Table 4). Bioremediation minimizes the use of antibiotics and drugs and thus, decreases the detrimental consequences of routinely used chemotherapeutic agents and produces safe aquatic products for human consumption (Sha et al., 2022). In addition, these environmentally friendly bacteria help to improve the health conditions of cultured organisms by protecting them against infectious diseases, delivering antigens and providing several other health benefits in aquaculture.

Several bioremediation bacteria have been used in aquaculture and the most common and popular ones are *Bacillus* species. Geng et al. (2022) used bacteria (*Bacillus subtilis* and *Bacillus licheniformis*) and microalgae (*Chlorella vulgaris*) to bioremediate aquaculture wastes, and these organisms, in turn, became foods for the filtering triangle sail mussel (*Hyriopsis cumingii*). In addition, *Bacillus* species enhanced the digestive enzymes activities of the mussel. Gao et al. (2018) reported that an efficient aerobic denitrifier *Bacillus megaterium* has a high capacity to remove toxic nitrite and improve water quality. John et al. (2020) reported that ammonia, nitrite and nitrate concentrations in tilapia culture wastewater microbial consortium were significantly reduced by using microbial consortium of *Bacillus cereus*, *Bacillus amyloliquefaciens and Pseudomonas stutzeri* as bioremediators.

Phytoremediation using plants such as macrophytes and microalgae, for sequestering nutrients, is another form of bioremediation that is useful treatment to improve water quality aquaculture systems (Table 4). Tejido-Nuñez et al. (2019) showed improved water quality when the aquaculture effluent was treated with *C. vulgaris* and *Tetraselmis obliquus*, indicating that the microalgae were effective in nutrient removal. Nie et al. (2020) suggested a few options for the integration of microalgae culture with the aquaculture system such as permeable floating photobioreactors, bacteria–microalgae consortia, mixotrophic microalgae cultivation and biofilm production. Bioflocculation of microalgae and bacteria can enhance nutrient removal and facilitate microalgae harvesting (Nguyen et al., 2019a). Kumar et al. (2016) showed that agar–alginate algal blocks, known as immobilized marine microalgae biofilter systems, were effective for nutrient removal from aquaculture wastewater. Microalgae can be introduced not only in the biofiltration system but also as a component to utilize inorganic N and P for their enhanced growth, and the resulting biomass can be valorized as feed for other aquatic organisms (Milhazes-Cunha and Otero, 2017). Li et al. (2019) and Nguyen et al. (2019b) reported that *C. vulgaris* produced higher biomass with a significant decrease in total N, total P, BOD and COD when recycled aquaculture wastewater was used as the culture medium. Wang et al. (2021) showed that microalgae produced higher biomass and nutritional contents when cultured in fishery wastes. When cultured with bioremediation bacteria (binary microalgae culture), microalgae exhibited a high growth rate, enhanced bio-flocculation, high-value metabolites and high removal efficiencies of total organic carbon, ammonium nitrogen and total phosphorus (Rashid et al., 2018; Luo et al., 2019). An increased number of degrading bacteria causes the integration of microalgae bacteria more effective in the degradation of organic pollutants in aquaculture wastewater, which promotes fish health (Zhang et al., 2022b).

Biofloc technology

Bioflocs are aggregates of mixed biological communities consisting of bacteria, algae, fungi and zooplankton that function not only to degrade the organic matter, reduce contaminants and improve water quality, but also to form an important source of food and immunostimulants to the cultured organisms (Table 4). The microbial community enhances the nutrient recycling of metabolites through in situ bioremediation, generating nutrients for the development of microalgae and zooplankton which serve as natural foods, and maintains the water quality in the system (Chen et al., 2023). In the biofloc technology (BFT), bacterial communities dominated by heterotrophic bacteria can be developed in aquaculture systems using appropriate carbon sources in suitable C:N ratios (Gaona et al., 2016). Ríos et al. (2023) reported that C:N ratio of 10 significantly enhanced the immune stimulation in shrimp. Heterotrophic bacteria use organic carbon such as starch and sugar to generate energy and to grow into micro-biomass. Putra et al. (2020) observed that molasses was the best biofloc starter for a tilapia culture system. Luo et al. (2017) suggested the use of external carbohydrates (poly-β-hydroxybutyric and polycaprolactone) to improve the bacterial community, nitrogen dynamic and biofloc quality in tilapia (*O. niloticus*) culture system. Kim et al. (2022b) reported that environmentally friendly microbial groups in a biofloc system of Pacific white shrimp, *Litopenaeus vannamei*, include Rhodobacteraceae, Flavobacteriaceae and Actinobacteria. In general, in BFT, heterotrophs were better compared to autotrophic bacteria for the treatment of the wastewater (Kim et al. 2020).

Physical–chemical methods

Physical and chemical methods such as filtrations, coagulation, flocculation and adsorption function to remove contaminants from the aquaculture wastewater, while electrochemical oxidation breakdown persistent organic compounds and aeration increased the dissolved oxygen in the water (Santos et al., 2022). These methods can be applied singly or in combination in various aquaculture systems to further increase the efficiency of water quality improvement and enhance aquaculture production (Table 4). Biofilters (media with attached microorganisms such as bacteria, fungi, algae and protozoans) and membrane filters remove contaminants as the wastewater flows through them (Ng et al., 2018; Hassan et al., 2022; Jin et al., 2023). Coagulation (clumping of particles), flocculation (settling of coagulated materials) and adsorption (adhering of substances) can effectively remove suspended and dissolved solids from the aquaculture wastewater (Letelier-Gordo and Fernandes, 2021; Igwegbe et al., 2022). Yanuhar et al. (2022) reported that water quality in concrete ponds can be improved by aeration, filtration and reduction of organic matter by optimizing the feed. Different types of biofiltration, biocoagulation, bioflocculation and biological interactions can be selected to enhance wastewater treatment and performance in aquaculture systems depending on their functionality and costs (Table 4).

Santos et al. (2022) introduced electrochemical oxidation as an alternative to biofiltration in RAS and reported several advantages including the decrease of toxic compounds and harmful by-products, water disinfection, reduced water use, easy adaptation to different production scales and an increase in fish health and yields. In addition, aquaculture effluents can be treated by coagulation of phosphorus and organic matter using $FeCl_3$ and $AlSO_4$ (Letelier-Gordo and Fernandes, 2021). Kujala et al. (2020) and Lindholm-Lehto et al. (2020) used a woodchip reactor, organic flocculants and slow sand filtration to efficiently remove nitrogen, phosphorus, geosmin and heavy metal, from rainbow trout (*Oncorhynchus mykiss*) culture.

IoT technologies and models

Traditionally, water quality monitoring in aquaculture systems needs manual sampling that requires a lot of time and cost. With the advent of technologies, real-time monitoring and early warning systems based on the IoT and intelligent monitoring system (IMS) can be designed and developed to make water quality monitoring and management more efficient and effective. IoT, consisting of collective network of communication devices integrated with artificial intelligence (AI) and modeling, can improve the monitoring and management of essential water quality parameters such as dissolved oxygen, pH values, turbidity and temperature in an aquaculture system (Figure 5). Wireless sensor network has been used widely for water quality monitoring (Shi et al., 2018; Wei et al., 2023). Rana et al. (2021) used the machine learning approach to assess the influence of water quality parameters on the growth performance of freshwater aquaculture. Rahman et al. (2021) developed an integrated framework for aquaculture prawn farm management using sensors, machine learning and augmented reality-based visualization methods through real-time interactive interfaces. Thus, models for accurate predictions of water quality parameters, such as the hybrid prediction model (Eze et al., 2021; Ranjan et al., 2023) and fuzzy comprehensive evaluation method (You et al., 2021), can be developed for improved water quality management. Caballero and Navarro (2021) and Oiry and Barillé (2021) used the sentinel-2 satellite to monitor water quality, cyanoHAB and microphytobenthos. Xiang et al. (2023) used satellite remote sensing to monitor water color and water transparency, in relation to land-based activities that cause water turbidity and an increase of pollutants in aquatic ecosystems.

Precision feeding with minimal food waste is essential to maintain good water quality in aquaculture systems since excess feed is one of the major reasons for water quality deterioration in aquaculture systems. Fiordelmondo et al. (2020) reported that feeding type and management could improve water quality in rainbow trout farming. Liu et al. (2023b) developed a precision feeding system on a software platform by integrating feeding management, a water quality monitoring system, a fish feeding activity sensor and an automatic feeding machine on a software platform. For convenience, efficiency and precision, Wu et al. (2022) applied intelligent and unmanned equipment for water quality management, underwater inspection, precision feeding and biomass estimation in deep-sea aquaculture. Ubina and Cheng (2022) noted unmanned systems are necessary for locations that are difficult to access due to risks associated with extreme climate and long distances from the shore.

The IoT can be used to develop automatic fish feeding with precise amounts and timing. Gao et al. (2019) developed IoT-based intelligent fish farming system that includes a forecasting method for water quality management. The overall framework and constructs of the IoT and IMS-based aquaculture environment should integrate the control circuit, information collection, culture observation, data transmission and early warning system. IoT in aquaculture water quality monitoring involved the development of a cloud-based dashboard for data acquisition. Several cameras installed in the aquaculture farm are used to upload information wirelessly to the dashboard. Water quality parameters such as temperature, pH, conductivity, salinity, turbidity, dissolved oxygen and light intensity can be downloaded from a wireless sensing module. Islam et al. (2021) proposed a cost-effective long-range multistep predictor to improve the forecasting for water quality monitoring. Sampaio et al. (2021) used low-to-high frequency data for water quality monitoring and fish production.

Bai et al. (2021) proposed a risk assessment approach using bioreaction kinetic models to evaluate pollutant accumulation in fish tissue as the index for environmental quality and safety in aquaculture. Various models for predicting and managing HABs have been established to reduce the impacts of algal toxins and water quality deterioration associated with eutrophication in aquaculture (Derot et al., 2020). Water quality modeling can also be based on disease agents. Jampani et al. (2022) suggested a water quality modeling framework to model and evaluate AR bacteria and AR genes in aquaculture systems.

AI techniques are useful and convenient for water quality management in aquaculture operations that are subjected to harsh environments and extreme climate such as offshore cage aquaculture. Chang et al. (2021) developed an AI-IoT smart cage culture management system to solve problems related to physical inaccessibility to large coastal and off-shore aquaculture operations. In fact, intelligent and unmanned equipment provide convenient and efficient applications for water quality management, precision feeding and biomass estimation in aquaculture (Wu et al., 2022). AI-IoT methods supported by sensors, wireless networks, automation and cloud data approaches are also applied for water quality monitoring in coastal waters, estuaries and land-based aquaculture systems (Danh et al., 2020; Huan et al., 2020; Pasika and Gandla, 2020).

Policy and regulation

Policies and regulations are important in ensuring the implementation of aquaculture effluent management strategies as rapid expansion in the aquaculture industry not only provides economic opportunities but also presents risks to the environment and human society. In their assessment of sustainable global aquaculture Davies et al. (2019) noted that many countries with active aquaculture sectors have some level of governance but lack clear frameworks for sustainable aquaculture development. Bohnes et al. (2022) proposed a stepwise framework to assess the environmental impacts of aquaculture industries taking into account the existing national policy coupled with economic equilibrium models and life cycle assessment of aquaculture activities, especially those related to aquaculture feed production and usage.

Aquaculture farmers in many countries in Asia, where 90% of aquaculture activities are located, have difficulties in adopting environmental governance due to their small farms with limited physical and financial resources. For large farms, access to global markets via certification could be the major driver for adopting environmental governance. Quyen et al. (2020) reported that Vietnamese shrimp farmers followed specific certification guidelines and conducted good aquaculture practices to produce quality and safe products as required by the importing countries, avoiding rejections and economic losses. However, most aquaculture smallholders are experiencing environmental and water quality problems that extend beyond the boundary of their farms. To mitigate environmental risk due to non-sustainable aquaculture practices, Bush et al. (2019) suggested implementing environmental governance for water quality management such as certification, finance and insurance on a wider landscape instead of focusing on each farm. Bohnes et al. (2022) proposed a stepwise framework to assess the environmental impacts of aquaculture industries taking into account the existing national policy coupled with economic equilibrium models and life cycle assessment of aquaculture activities, especially those related to aquaculture feed production and usage. Wood et al. (2017) also showed that a small farm on its own is unlikely to have a significant effect on water quality and environmental conservation compared to a very large farm or a conglomerate of small farms. Thus, environmental policies and regulations that consider all elements of farm-to-market operation including production systems (cost-effectiveness and sustainable supply); water quality (sources and effluents); ecosystem health (ecosystem services) and socioeconomics (human health, economy and livelihoods) are needed to make the aquaculture industry a viable food producer.

Conclusions

Water quality is one of the critical factors to be considered in aquaculture as it has significant effects on fish growth, health and yields. A lack of knowledge and practices in water quality management could severely impede the growth of the aquaculture sector and jeopardize the utilization of the available water resources for a sustainable aquaculture industry.

Aquaculture requires a significant understanding of the factors and problems affecting production systems, in addition to improvements of approaches and technologies in water quality management. Water quality enhancement in production systems such as RAS, IMTA and aquaponics through efficient integration with physical, chemical and biological factors would boost the FCR and improve the health of cultured animals. The recycling of nutrients using different organisms along the aquatic food chain, such as bacteria, microalgae, seaweeds and fish, can enhance the growth, survival and production of the cultured species as well as accumulate the biomass of the supporting organisms. In addition, microalgae-based technologies are a promising solution for aquaculture wastewater treatment and the resulting microalgal biomass can be valorized. The use of these technologies in the forms of biofloc, bioremediation, coagulation-flocculation-biofiltration technologies and various ecosystem-based approaches provide options for aquaculture best practices that could improve water quality, resulting in improved aquaculture production.

The application of AI and IoT in aquaculture production systems supported by sensors, wireless transmission systems, unmanned equipment, automation and big data would enable intelligent water quality monitoring, precision feeding systems, fish activity monitoring and early problem detection. The integration of smart production systems and advanced processes would result in precision feeding, improved water quality, increased survival rates and increased growth of the cultured species. Overall, the use of these technologies in water quality management supported by relevant policy and regulation would facilitate the approach to sustainable aquaculture production via effective management of the environment and fish health.

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