Water Quality Management in Aquaculture

Fatimah M. Yusoff [1,2], Wahidah A.D. Umi[1], Norulhuda M. Ramli[2,3] and Razif Harun[2,4]

[1]Department of Aquaculture, Faculty of Agriculture, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia; [2]International Institute of Aquaculture and Aquatic Sciences, 71050 Port Dickson, Negeri Sembilan, Malaysia; [3]Department of Biological and Agricultural Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia; [4]Department of Chemical Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia.

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 (HABs) 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 RAS (recycling aquaculture system), IMTA (integrated multi-trophic aquaculture), and aquaponics including features of waste recycling are viable

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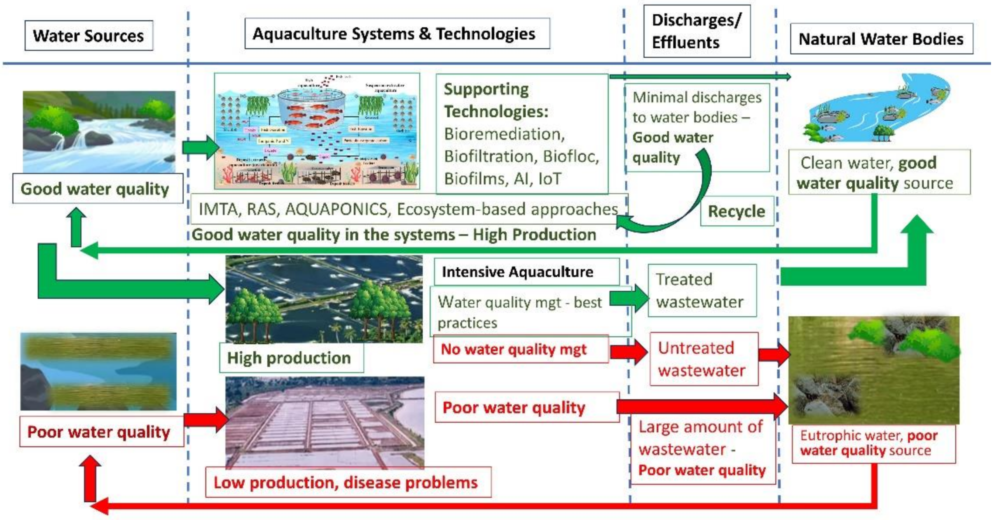
options in aquaculture schemes. Best aquaculture practices integrating advanced water quality treatment processes and technologies, supported by automation and sensors, modelling, and AI-IoT (artificial intelligence-internet of things) are necessary for a sustainable aquaculture environment, production, 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.

Graphical Abstract



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 environment and the human community. This review provides assessments on the 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 cost 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 and 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.

Keywords: Aquaculture wastewater, eutrophication, harmful algal blooms, aquaculture production systems, integrated recycling systems.

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 socio-economic 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, intensive), types of systems (closed, semi-open, open), different cultured species, and stocking densities can generate different 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 the intensified cultural system involves increased waste that requires proper treatment to avoid pollution and deleterious impacts on the environment (da Silva Morales 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 sulphide, together with low dissolved oxygen, hypoxic conditions, harmful algal blooms, 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 harmful algal blooms in adjacent water bodies (Zhang et al., 2018; Purnomo et al., 2022). Harmful algal blooms (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-flavour 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 Morales at 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 RAS (recirculating aquaculture system), IMTA (integrated multi-trophic aquaculture), and aquaponics (aquaculture and hydroponics). In these circular economic activities, aquaculture wastes can generate additional products such as seaweeds, herbs, vegetables, mollusks, 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%), harmful algal blooms (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 harmful algal blooms (HAB), such as cyanobacteria and dinoflagellates, and high mortality of cultured organisms in cultured systems (Table 1). Cyanobacterial blooms are also commonly associated with toxic-odour compounds such as geosmin and 2-MIB (2-methylisoborneol) 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 which 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 socio-economic 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 health and growth of the culture species 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 are 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 non-point 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).

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 molluscs and seaweeds. Water treatment plants; removal of soluble reactive P (SRP) by adsorption to	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

		particulate organic matter		
		Installation of seaweed farms	Extract pollutants and improve water quality. Improved ecosystem services	Cabral et al., 2016
Harmful algal blooms (HABs) – taste and odour (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-flavour compounds, and improve fish quality	Lukasssen et al., 2019a
	RAS – off flavour compounds	Optimization of the depuration method with improved water treatment	Reduce the off-flavour 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

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, micro-organisms, 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 physico-chemical 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 characterised 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 (NH_4^+) 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 sulphide (H_2S), and nitrous oxide (N_2O), which could adversely affect water quality (Table 2). Toxic hydrogen sulphide (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 methane and carbon dioxide were released from mariculture ponds. In freshwater aquaculture ponds, Zhao et al. (2021) reported that high concentrations of methane were released and showed that dredging of the pond bottom as part of pond preparation was more effective in reducing methane compared to aeration. Thus, there is a need for immediate and continuous removal of toxic compounds such as ammonia, nitrite, H_2S, and methane in aquaculture systems.

Nutrient-rich waters are also associated with cyanobacterial blooms that could produce toxic-odour compounds such as geosmin and 2-MIB (2-methylisoborneol), 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-flavour in a wide range of environments including recirculating aquaculture systems (RAS) (Azaria and 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 (*Oreochromis 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 harmful algal blooms. 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 (PCR) 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 (UV) 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 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.

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

Factors	Types of Stressors/Impacts	Mitigating Measures	References
Physico-chemical 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 sulphide (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	Yñigues 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	Lou et al., 2022

		surface optimization, degradation kinetics and degradation pathways	
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

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

Water quality in aquaculture production systems

Aquaculture production systems including RAS (recirculating aquaculture system), IMTA (integrated multi-trophic aquaculture), aquaponics (aquaculture and hydroponics), and ecosystem-based approaches were designed and constantly improved to enhance water quality and production (Table 3). These integrated 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 systema and sustainable aquaculture development (Yep and Zheng, 2019; Chiquito-Contrera 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 (BFAS) 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 A-RAS (aquaponic-RAS), which proved to be effective in improving water quality, survival rate, feed conversion ratio, 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 CRIS (cray fish integrated system) for efficient use of waste for rice production. There are different combinations of fed and extractive species in different systems to improve water quality, such as catfish, plants, and bacteria in hydroponic-biofilm and NFT (nutrient film technique (NFT) systems (Mohapatra et al., 2020; Li et al., 2022b) to improve biofilter and ammonia removal efficiencies. Addy et al. (2017) showed that microalgae was 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 (IMTA)

The concept of integrated multi-trophic aquaculture (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 molluscs 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 culture to minimize 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 (RAS)

The recirculating aquaculture system (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 feed conversion ratio (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-flavour, microalgae system to enhance nutrient removal, and bacterial communities as in SNAD (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 low efficiency and high energy costs (Diaz 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 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 hydrogen sulphide 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 aquaponics and RAS (A-RAS), IMTA, and RAS (I-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 (EBAS) 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) 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 glucogen 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 which 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.

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.) was 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 (*Oncorhynchus 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
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 (*Clarias 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 (*Litopenaeus 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

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 *B. 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 *B. 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*, *B. amyloliquefaciens*, and *Pseudomonas stutzeri* as bioremediators.

Phytoremediation using plants such as macrophytes and microalgae, for sequestering nutrients, is another form of bioremediation which is useful treatment to improve water quality aquaculture systems (Table 4). Tejido-Nunez et al. (2019) showed improved water quality when the aquaculture effluent was treated with *Chlorella 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 (AAAB) known as immobilized marine microalgae biofilter system, 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 *Chlorella 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 degradation of organic pollutants in aquaculture wastewater which promotes fish health (Zhang et al., 2022b).

Biofloc Technology (BFT)

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, 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 (*Oreochromis 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 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.

Internet-of-things technologies (IoT) and models

Traditionally, water quality monitoring in aquaculture systems needs manual sampling which requires a lot of time and cost. With the advent of technologies, real-time monitoring and early warning systems based on the internet-of-things (IoT) and intelligent-monitoring-system (IMS) can be designed and developed to make water quality monitoring and management more efficient and effective. Internet-of things, consisting of collective network of communication devices, integrated with artificial intelligence 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 sentinel-2 satellite to monitor water quality, cyanoHAB, and microphytobenthos. Xiang et al. (2023) used satellite remote sensing to monitor water colour and water transparency, in relation to land-based activities which 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. Ubani 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 internet-of-things (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 multi-step 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 bio-reaction 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 antibiotic-resistant (AR) bacteria and AR genes in aquaculture systems.

Artificial intelligence (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).

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*, *B. licheniformis* and microalga, *Chlorellavulgaris*/bioremediate aquaculture wastes, provide foods for the mussels (*Hyriopsis 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*, *B. 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 waste water) 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 Özcimen, 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 psedonana* and *Isochrysis galbana*. Microalgae – improved water quality and enhanced algal growth	Wang et al., 2021

	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 incommon 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
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 electro-coagulation filtration method	Wastewater of aquaculture system-electro-coagulation (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 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, 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 multi-step 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
	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

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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. (2023) 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 socio-economics (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 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 such as RAS, IMTA, and aquaponics through efficient integration with physical, chemical, and biological factors would boost the feed conversion ratio 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 artificial intelligence and IoT (AI-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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The authors declare no competing interest exists.

References

Abisha R, Krishnani KK, Sukhdhane K, Verma AK, Brahmane M and Chadha NK (2022) Sustainable development of climate-resilient aquaculture and culture-based fisheries through adaptation of abiotic stresses: A review. *Journal of Water and Climate Change* **13**, 2671-2689. https://doi.org/10.2166/wcc.2022.045

Addy MM, Kabir F, Zhang R, Lu Q, Deng X, Current D, Griffith R, Ma Y, Zhou W, Chen P and Ruan R (2017) Co-cultivation of microalgae in aquaponic systems. *Bioresource Technology* **245**, 27-34. http://dx.doi.org/10.1016/j.biortech.2017.08.151

Alam SMA, Sarkar SI, Miah, MA and Rashid H (2021) Management strategies for Nile Tilapia (*Oreochromis niloticus*) hatchery in the face of climate change induced rising temperature. *Aquaculture Studies* **21**, 55-62. http://doi.org/10.4194/2618-6381-v21_2_02

Arega F, Lee JH and Choi DK (2022) Uncertainty evaluation and performance assessment of water quality model for mariculture management. *Marine Pollution Bulletin* **184**, 114172. https://doi.org/10.1016/j.marpolbul.2022.114172

Ashkanani A, Almomani F, Khraisheh M, Bhosale R, Tawalbeh M and AlJaml K (2019) Bio-carrier and operating temperature effect on ammonia removal from secondary wastewater effluents using moving bed biofilm reactor (MBBR). *Science of The Total Environment* **693**, 133425. https://doi.org/10.1016/j.scitotenv.2019.07.231

Azaria S and van Rijn J (2018) Off-flavor compounds in recirculating aquaculture systems (RAS): Production and removal processes. *Aquacultural Engineering* **83**, 57-64. https://doi.org/10.1016/j.aquaeng.2018.09.004

Bai X, Fu Z, Li N, Stankovski S, Zhang X and Li X (2021) Water environmental nexus-based quality and safety risk assessment for fish (*Carassius auratus*) in aquaculture. *Journal of Cleaner Production* **288**, 125633. https://doi.org/10.1016/j.jclepro.2020.125633

Bergstedt JH, Skov PV and Letelier-Gordo CO (2022) Efficacy of H_2O_2 on the removal kinetics of H_2S in saltwater aquaculture systems, and the role of O_2 and NO_3^-. *Water Research* **222**, 118892. https://doi.org/10.1016/j.watres.2022.118892

Bhatia SK, Ahuja V, Chandel N, Mehariya S, Kumar P, Vinayak V, Saratale GD, Raj T and Yang YH (2022) An overview on microalgal-bacterial granular consortia for resource recovery and wastewater treatment. *Bioresource technology* **351**, 127028. https://doi.org/10.1016/j.biortech.2022.127028

Bohnes FA, Hauschild MZ, Schlundt J, Nielsen M and Laurent A (2022) Environmental sustainability of future aquaculture production: Analysis of Singaporean and Norwegian policies. *Aquaculture* **549**, 737717. https://doi.org/10.1016/j.aquaculture.2021.737717

Boyd CE, McNevin AA and Davis RP (2022) The contribution of fisheries and aquaculture to the global protein supply. *Food security* **14**, 805-827. https://doi.org/10.1007/s12571-021-01246-9

Brigolin D, Lourguioui H, Taji MA, Venier C, Mangin A and Pastres R (2015) Space allocation for coastal aquaculture in North Africa: data constraints, industry requirements and conservation issues. *Ocean and Coastal Management* **116**, 89-97. http://dx.doi.org/10.1016/j.ocecoaman.2015.07.010

Bull EG, Cunha CDLDN and Scudelari AC (2021) Water quality impact from shrimp farming effluents in a tropical estuary. *Water Science and Technology* **83**, 123-136. https://doi.org/10.2166/wst.2020.559

Bush SR, Oosterveer P, Bottema M, Meuwissen M, de Mey Y, Chamsai S, Ho LH and Chadag M (2019) Inclusive environmental performance through 'beyond-farm'aquaculture governance. *Current Opinion in Environmental Sustainability* **41**, 49-55. https://doi.org/10.1016/j.cosust.2019.09.013

Caballero I and Navarro G (2021) Monitoring cyanoHABs and water quality in Laguna Lake (Philippines) with Sentinel-2 satellites during the 2020 Pacific typhoon season. *Science of The Total Environment* **788**, 147700. https://doi.org/10.1016/j.scitotenv.2021.147700

Cabral P, Levrel H, Viard F, Frangoudes K, Girard S and Scemama P (2016) Ecosystem services assessment and compensation costs for installing seaweed farms. *Marine Policy* **71**, 157-165. http://dx.doi.org/10.1016/j.marpol.2016.05.031

Calone R, Pennisi G, Morgenstern R, Sanyé-Mengual E, Lorleberg W, Dapprich P, Winkler P, Orsini F and Gianquinto G (2019) Improving water management in European catfish recirculating aquaculture systems through catfish-lettuce aquaponics. *Science of the total environment* **687**, 759-767. https://doi.org/10.1016/j.scitotenv.2019.06.167

Cardoso-Mohedano J, Lima-Rego J, Sánchez-Cabeza J, Ruiz-Fernández A, Canales-Delgadillo J, Sánchez-Flores E and Paez-Osuna F (2018) Sub-tropical coastal lagoon salinization associated to shrimp ponds effluents. *Estuarine, Coastal and Shelf Science* **203**, 72–79. https://doi.org/10.1016/j.ecss.2018.01.022

Chang CC, Wang JH, Wu JL, Hsieh YZ, Wu TD, Cheng SC, Chang CC, Juang JG, Liou CH, Hsu TH, Huang YS, Huang CT, Lin CC, Peng YT, Huang RJ, Jhang JY, Liou YH and Lin CY (2021) Applying artificial intelligence (AI) techniques to implement a practical smart cage aquaculture management system. *Journal of Medical and Biological Engineering* **41**, 652-658. https://doi.org/10.1007/s40846-021-00621-3

Chen M, Jin M, Tao P, Wang Z, Xie W, Yu X and Wang K (2018) Assessment of microplastics derived from mariculture in Xiangshan Bay, China. *Environmental Pollution*, *242*, 1146-1156. https://doi.org/10.1016/j.envpol.2018.07.133

Chen H, Wu X, Li L, Wang M, Song C, Wang S and Yan Z (2022) In vitro and in vivo roles of cyanobacterial carbonic anhydrase as a biomarker for monitoring antibiotics. *Journal of Hazardous Materials Letters* **3**, 100055. https://doi.org/10.1016/j.hazl.2022.100055

Chen P, Kim HJ, Thatcher LR, Hamilton JM, Alva ML, Zhou (George) Z and Brown PB (2023) Maximizing nutrient recovery from aquaponics wastewater with autotrophic or heterotrophic management strategies. *Bioresource Technology Reports* **21**, 101360. https://doi.org/10.1016/j.biteb.2023.101360

Chen S, Yu J, Wang H, Yu H and Quan X (2015) A pilot-scale coupling catalytic ozonation–membrane filtration system for recirculating aquaculture wastewater treatment. *Desalination* **363**, 37-43. http://dx.doi.org/10.1016/j.desal.2014.09.006

Chen Y, Dong S, Wang F, Gao Q and Tian X (2016) Carbon dioxide and methane fluxes from feeding and no-feeding mariculture ponds. *Environmental Pollution* **212**, 489-497. http://dx.doi.org/10.1016/j.envpol.2016.02.039

Chen Z, Chang Z, Zhang L, Jiang Y, Ge H, Song X, Chen S, Zhao F and Li J (2019) Effects of water recirculation rate on the microbial community and water quality in relation to the growth and survival of white shrimp (*Litopenaeus* *vannamei*). *BMC microbiology* **19**, 1-15. https://doi.org/10.1186/s12866-019-1564-x

Chen Z, Chang Z, Zhang L, Wang J, Qiao L, Song X and Li J (2020) Effects of carbon source addition on microbial community and water quality in recirculating aquaculture systems for *Litopenaeus vannamei*. *Fisheries science* **86**, 507-517. https://doi.org/10.1007/s12562-020-01423-3

Chiquito-Contreras RG, Hernandez-Adame L, Alvarado-Castillo G, Martínez-Hernández MD J, Sánchez-Viveros G, Chiquito-Contreras CJ and Hernandez-Montiel LG (2022) Aquaculture—Production System and Waste Management for Agriculture Fertilization—A Review. *Sustainability* **14**, 7257. https://doi.org/10.3390/su14127257

Cholewińska P, Moniuszko H, Wojnarowski K, Pokorny P, Szeligowska N, Dobicki W, Polechonski R and Górniak W (2022) The occurrence of microplastics and the formation of biofilms by pathogenic and opportunistic bacteria as threats in aquaculture. *International Journal of Environmental Research and Public Health* **19**, 8137. https://doi.org/10.3390/ijerph19138137

Chun SJ, Cui Y, Ahn CY and Oh HM (2018) Improving water quality using settleable microalga *Ettlia* sp. and the bacterial community in freshwater recirculating aquaculture system of Danio rerio. *Water research* **135**, 112-121. https://doi.org/10.1016/j.watres.2018.02.007

da Silva Morales U, Rotta MA, Fornari DC and Streit Jr DP (2022) Aquaculture sustainability assessed by emergy synthesis: The importance of water accounting. *Agriculture* **12**, 1947. https://doi.org/10.3390/agriculture12111947

Danh LVQ, Dung DVM, Danh TH and Ngon NC (2020) Design and deployment of an IoT-based water quality monitoring system for aquaculture in Mekong Delta. *International Journal of Mechanical Engineering and Robotics Research* **9**, 1170-1175. https://doi.org/10.18178/ijmerr.9.8.1170-1175

Davidson J, Redman N, Crouse C and Vinci B (2022) Water quality, waste production, and off-flavor characterization in a depuration system stocked with market-size Atlantic salmon *Salmo salar*. *Journal of the World Aquaculture Society* **54**, 96-112. https://doi.org/10.1111/jwas.12920

Davies IP, Carranza V, Froehlich HE, Gentry RR, Kareiva P and Halpern BS (2019) Governance of marine aquaculture: pitfalls, potential, and pathways forward. *Marine Policy* **104**, 29-36. https://doi.org/10.1016/j.marpol.2019.02.054

Dayıoğlu MA (2022) Experimental study on design and operational performance of solar-powered venturi aeration system developed for aquaculture–A semi-floating prototype. *Aquacultural Engineering* **98**, 102255. https://doi.org/10.1016/j.aquaeng.2022.102255

de Alva MS and Pabello VML (2021) Phycoremediation by simulating marine aquaculture effluent using *Tetraselmis* sp. and the potential use of the resulting biomass. *Journal of Water Process Engineering* **41**, 102071. https://doi.org/10.1016/j.jwpe.2021.102071

Derot J, Yajima H and Jacquet S (2020) Advances in forecasting harmful algal blooms using machine learning models: A case study with Planktothrix rubescens in Lake Geneva. *Harmful Algae* **99**, 101906. https://doi.org/10.1016/j.hal.2020.101906

Devaraja TN, Yusoff FM and Shariff M (2002) Changes in bacterial populations and shrimp production in ponds treated with commercial microbial products. *Aquaculture* 206, 245-256. https://doi.org/10.1016/S0044-8486(01)00721-9

Díaz V, Ibáñez R, Gómez P, Urtiaga AM and Ortiz I (2012) Kinetics of nitrogen compounds in a commercial marine recirculating aquaculture system. *Aquacultural Engineering*. **50**, 20–27. https://doi.org/10.1016/j.aquaeng.2012.03.004.

Ekawati AW, Ulfa SM, Dewi CSU, Amin AA, Salamah LNM, Yanuar AT and Kurniawan A (2021) Analysis of aquaponic-recirculation aquaculture system (A-Ras) application in the catfish (*Clarias gariepinus*) aquaculture in Indonesia. *Aquaculture Studies* **21**, 93-100. http://doi.org/10.4194/2618-6381-v21_3_01

Elizondo-González R, Quiroz-Guzmán E, Escobedo-Fregoso C, Magallón-Servín P and Peña-Rodríguez A (2018) Use of seaweed *Ulva lactuca* for water bioremediation and as feed additive for white shrimp *Litopenaeus vannamei*. *PeerJ* **6**, e4459. https://doi.org/10.7717/peerj.4459

Emparan Q, Jye YS, Danquah MK and Harun R (2020) Cultivation of *Nannochloropsis* sp. microalgae in palm oil mill effluent (POME) media for phycoremediation and biomass production: Effect of microalgae cells with and without beads. *Journal of Water Process Engineering* **33**, 101043. https://doi.org/10.1016/j.jwpe.2019.101043

Eze E and Ajmal T (2020) Dissolved oxygen forecasting in aquaculture: a hybrid model approach. *Applied Sciences* **10**, 7079. https://doi.org/10.3390/app10207079

Eze E, Halse S and Ajmal T (2021) Developing a novel water quality prediction model for a South African aquaculture farm. *Water* **13**, 1782. https://doi.org/10.3390/w13131782

Falconer L, Telfer TC and Ross LG (2018) Modelling seasonal nutrient inputs from non-point sources across large catchments of importance to aquaculture. *Aquaculture* **495**, 682-692. https://doi.org/10.1016/j.aquaculture.2018.06.054

Fan LIN, Meirong DU, Hui LIU, Jianguang FANG, Lars A and Zengjie JIANG (2020) A physical-biological coupled ecosystem model for integrated aquaculture of bivalve and seaweed in Sanggou Bay. *Ecological Modelling* **431**, 109181. https://doi.org/10.1016/j.ecolmodel.2020.109181

Farradia Y, Sunarno MTD and Syamsunarno MB (2022) Developing green feed toward environment sustainability in freshwater aquaculture in Indonesia. WSEAS Transactions on Systems and Control **17**, 177-185. https://doi.org/10.37394/23203.2022.17.20

Fernanda PA, Liu S, Yuan T, Ramalingam B, Lu J and Sekar R (2022) Diversity and abundance of antibiotic resistance genes and their relationship with nutrients and land use of the inflow rivers of Taihu Lake. *Frontiers in microbiology* **13**, 1009297. https://doi.org/10.3389/fmicb.2022.1009297

Fiordelmondo E, Magi GE, Mariotti F, Bakiu R and Roncarati A (2020) Improvement of the water quality in rainbow trout farming by means of the feeding type and management over 10 years (2009–2019). *Animals* **10**, 1541. https://doi.org/10.3390/ani10091541

Flickinger DL, Costa GA, Dantas DP, Proença DC, David FS, Durborow RM, Moraes-Valenti P and Valenti WC (2020) The budget of carbon in the farming of the Amazon river prawn and tambaqui fish in earthen pond monoculture and integrated multitrophic systems. *Aquaculture Reports* **17**, 100340. https://doi.org/10.1016/j.aqrep.2020.100340

Gamperl AK, Ajiboye OO, Zanuzzo FS, Sandrelli RM, Ellen de Fátima CP and Beemelmanns, A (2020) The impacts of increasing temperature and moderate hypoxia on the production characteristics, cardiac morphology and haematology of Atlantic Salmon (*Salmo salar*). *Aquaculture* **519**, 734874. https://doi.org/10.1016/j.aquaculture.2019.734874

Gao G, Xiao K and Chen M (2019) An intelligent IoT-based control and traceability system to forecast and maintain water quality in freshwater fish farms. *Computers and Electronics in Agriculture* **166**, 105013. https://doi.org/10.1016/j.compag.2019.105013

Gao J, Gao D, Liu H, Cai J, Zhang J and Qi Z (2018) Biopotentiality of high efficient aerobic denitrifier *Bacillus megaterium* S379 for intensive aquaculture water quality management. *Journal of environmental management* **222**, 104-111. https://doi.org/10.1016/j.jenvman.2018.05.073

Gaona CAP, da Paz Serra F, Furtado PS, Poersch LH and Wasielesky Jr W (2016) Effect of different total suspended solids concentrations on the growth performance of *Litopenaeus vannamei* in a BFT system. *Aquacultural Engineering* **72**, 65-69. http://dx.doi.org/10.1016/j.aquaeng.2016.03.004

Gendel Y and Lahav O (2013). A novel approach for ammonia removal from fresh-water recirculated aquaculture systems, comprising ion exchange and electrochemical regeneration. *Aquacultural Engineering* **52**, 27–38. https://doi.org/10.1016/j.aquaeng.2012.07.005.

Geng B, Li Y, Liu X, Ye J and Guo W (2022) Effective treatment of aquaculture wastewater with mussel/microalgae/bacteria complex ecosystem: a pilot study. *Scientific Reports* **12**, 2263. https://doi.org/10.1038/s41598-021-04499-8

Goddek S and Körner O (2019) A fully integrated simulation model of multi-loop aquaponics: a case study for system sizing in different environments. *Agricultural systems* **171**, 143-154. https://doi.org/10.1016/j.agsy.2019.01.010

Gopaiah M, Chandra DI and Vazeer M (2023) Modelling the spatial distribution and future trends of seawater intrusion due to aquaculture activities in coastal aquifers of Nizampatnam, Andhra Pradesh. *Disaster Advances* **16**, 1-10. https://doi.org/10.25303/1610da01010

Guo X, Huang M, Luo X, You W and Ke C (2023) Impact of ocean acidification on shells of the abalone species *Haliotis diversicolor* and *Haliotis discus hannai*. *Marine Environmental Research* **192**, 106183. https://doi.org/10.1016/j.marenvres.2023.106183

Hadley S, Wild-Allen K, Johnson C and Macleod C (2018) Investigation of broad scale implementation of integrated multitrophic aquaculture using a 3D model of an estuary. *Marine pollution bulletin* **133**, 448-459. https://doi.org/10.1016/j.marpolbul.2018.05.045

Han QF, Zhao S, Zhang XR, Wang XL, Song C and Wang SG (2020) Distribution, combined pollution and risk assessment of antibiotics in typical marine aquaculture farms surrounding the Yellow Sea, North China. *Environment International* **138**, 105551. https://doi.org/10.1016/j.envint.2020.105551

Hasibuan S, Syafriadiman S, Aryani N, Fadhli M and Hasibuan M (2023) The age and quality of pond bottom soil affect water quality and production of *Pangasius hypophthalmus* in the tropical environment. *Aquaculture and Fisheries* **8**, 296-304. https://doi.org/10.1016/j.aaf.2021.11.006

Hassan SM, Rashid MS, Muhaimeed AR, Madlul NS, Al-Katib MU and Sulaiman MA (2022) Effect of new filtration medias on water quality, biomass, blood parameters and plasma biochemistry of common carp (*Cyprinus Carpio*) in

RAS. *Aquaculture* **548**, 737630. https://doi.org/10.1016/j.aquaculture.2021.737630

Heddam S and Kisi O (2018) Modelling daily dissolved oxygen concentration using least square support vector machine, multivariate adaptive regression splines and M5 model tree. *Journal of Hydrology* **559**, 499-509. https://doi.org/10.1016/j.jhydrol.2018.02.061

Herbeck L, Unger D, Wu Y and Jennerjahn TC (2013) Effluent, nutrient and organic matter export from shrimp and fish ponds causing eutrophication in coastal and back-reef waters of NE Hainan, tropical China. *Continental Shelf Research* **57**, 92–104. https://doi.org/10.1016/j.csr.2012.05.006

Hu W, Li CH, Ye C, Chen HS, Xu J, Dong XH, Liu XS and Li D (2022) Effects of aquaculture on the shallow lake aquatic ecological environment of Lake Datong, China. *Environmental Sciences Europe* **34**, 19. https://doi.org/10.1186/s12302-022-00595-2

Huan J, Li H, Wu F and Cao W (2020) Design of water quality monitoring system for aquaculture ponds based on NB-IoT. *Aquacultural Engineering* **90**, 102088. https://doi.org/10.1016/j.aquaeng.2020.102088

Igwegbe CA, Ovuoraye PE, Białowiec A, Okpala COR, Onukwuli OD and Dehghani MH (2022) Purification of aquaculture effluent using *Picralima nitida* seeds. *Scientific Reports* **12**, 21594. https://doi.org/10.1038/s41598-022-26044-x

Islam ARMT, Pal SC, Chowdhuri I, Salam R, Islam MS, Rahman MM, Zahid A and Idris AM (2021) Application of novel framework approach for prediction of nitrate concentration susceptibility in coastal multi-aquifers, Bangladesh. *Science of The Total Environment* **801**, 149811. https://doi.org/10.1016/j.scitotenv.2021.149811

Jampani M, Gothwal R, Mateo-Sagasta J and Langan S (2022) Water quality modelling framework for evaluating antibiotic resistance in aquatic environments. *Journal of Hazardous Materials Letters* **3**, 100056. https://doi.org/10.1016/j.hazl.2022.100056

Jayanthi M, Thirumurthy S, Samynathan M, Kumararaja P, Muralidhar M and Vijayan KK (2021) Multi-criteria based geospatial assessment to utilize brackishwater resources to enhance fish production. *Aquaculture* **537**, 736528. https://doi.org/10.1016/j.aquaculture.2021.736528

Jiang W, Tian X, Li L, Dong S, Zhao K, Li H and Cai Y (2019) Temporal bacterial community succession during the start-up process of biofilters in a cold-freshwater recirculating aquaculture system. *Bioresource technology* **287**, 121441. https://doi.org/10.1016/j.biortech.2019.121441

Jin L, Sun X, Ren H and Huang H (2023) Biological filtration for wastewater treatment in the 21st century: A data-driven analysis of hotspots, challenges and prospects. *Science of the Total Environment* **855**, 158951. http://dx.doi.org/10.1016/j.scitotenv.2022.158951

John EM, Krishnapriya K and Sankar TV (2020) Treatment of ammonia and nitrite in aquaculture wastewater by an assembled bacterial consortium. *Aquaculture* **526**, 735390. https://doi.org/10.1016/j.aquaculture.2020.735390

John N, Koehler AV, Ansell BR, Baker L, Crosbie ND and Jex AR (2018) An improved method for PCR-based detection and routine monitoring of geosmin-producing cyanobacterial blooms. *Water research* **136**, 34-40. https://doi.org/10.1016/j.watres.2018.02.041

Kamali S, Ward VC and Ricardez-Sandoval L (2022) Dynamic modeling of recirculating aquaculture systems: Effect of management strategies and water quality parameters on fish performance. *Aquacultural Engineering* **99**, 102294. https://doi.org/10.1016/j.aquaeng.2022.102294

Kalayci Kara A, Fakıoğlu O, Kotan R, Atamanal P and Alak G (2021) The investigation of bioremediation potential of *Bacillus subtilis* and *B. thuringiensis* isolates under controlled conditions in freshwater. *Archives of microbiology* **203**, 2075-2085. https://doi.org/10.1007/s00203-021-02187-9

Kawasaki N, Kushairi MRM, Nagao N, Yusoff F, Imai A and Kohzu A (2016) Release of nitrogen and phosphorus from aquaculture farms to Selangor River, Malaysia. International *Journal of Environmental Science and Development*, **7**, 113. https://doi.org/10.7763/IJESD.2016.V7.751

Khatoon H, Penz KP, Banerjee S, Rahman MR, Minhaz TM, Islam Z, Mukta FA, Nayma Z, Sultana R and Amira KI (2021) Immobilized *Tetraselmis* sp. for reducing nitrogenous and phosphorous compounds from aquaculture wastewater. *Bioresource technology* **338**, 125529. https://doi.org/10.1016/j.biortech.2021.125529

Kibuye FA, Zamyadi A and Wert EC (2021) A critical review on operation and performance of source water control strategies for cyanobacterial blooms: Part I-chemical control methods. *Harmful Algae* **109**, 102099. https://doi.org/10.1016/j.hal.2021.102099

Kim CS, Kim SH, Lee WC and Lee DH (2022a) Spatial variability of water quality and sedimentary organic matter during winter season in coastal aquaculture zone of Korea. *Marine Pollution Bulletin* **182**, 113991. https://doi.org/10.1016/j.marpolbul.2022.113991

Kim K, Hur JW, Kim S, Jung JY and Han HS (2020) Biological wastewater treatment: Comparison of heterotrophs (BFT) with autotrophs (ABFT) in aquaculture systems. *Bioresource technology* **296**, 122293. https://doi.org/10.1016/j.biortech.2019.122293

Kim SK, Song J, Rajeev M, Kim SK, Kang I, Jang IK and Cho JC (2022b) Exploring bacterioplankton communities and their temporal dynamics in the rearing water of a biofloc-based shrimp (*Litopenaeus vannamei*) aquaculture system. *Frontiers in Microbiology* **13**, 995699. https://doi.org/10.3389/fmicb.2022.995699

Klootwijk AT, Alve E, Hess S, Renaud PE, Sørlie C and Dolven JK (2021) Monitoring environmental impacts of fish farms: Comparing reference conditions of sediment geochemistry and benthic foraminifera with the present. *Ecological Indicators* **120**, 106818. https://doi.org/10.1016/j.ecolind.2020.106818

Krüger L, Casado-Coy N, Valle C, Ramos M, Sánchez-Jerez P, Gago J, Carretero O, Beltran-Sanahuja A and Sanz-Lazaro C (2020) Plastic debris accumulation in the seabed derived from coastal fish farming. *Environmental Pollution* **257**, 113336. https://doi.org/10.1016/j.envpol.2019.113336

Kujala K, Pulkkinen J and Vielma J (2020) Discharge management in fresh and brackish water RAS: Combined phosphorus removal by organic flocculants and nitrogen removal in woodchip reactors. *Aquacultural Engineering* **90**, 102095. https://doi.org/10.1016/j.aquaeng.2020.102095

Kumar SD, Santhanam P, Park MS and Kim MK (2016) Development and application of a novel immobilized marine microalgae biofilter system for the treatment of shrimp culture effluent. *Journal of Water Process Engineering* **13**, 137-142. http://dx.doi.org/10.1016/j.jwpe.2016.08.014

Largo DB, Diola AG and Marababol MS (2016) Development of an integrated multi-trophic aquaculture (IMTA) system for tropical marine species in southern Cebu, Central Philippines. *Aquaculture Reports* **3**, 67-76. http://dx.doi.org/10.1016/j.aqrep.2015.12.006

Le ND, Hoang TTH, Phung VP, Nguyen TL, Rochelle-Newall E, Duong TT, Pham TMH, Phung TXB, Nguyen TD, Le PT, Pham LA, Nguyen TAH and Le TPQ (2022) Evaluation of heavy metal contamination in the coastal aquaculture zone of the Red River Delta (Vietnam). *Chemosphere* **303**, 134952. https://doi.org/10.1016/j.chemosphere.2022.134952

Lee C and Wang YJ (2020) Development of a cloud-based IoT monitoring system for Fish metabolism and activity in aquaponics. *Aquacultural Engineering* **90**, 102067. https://doi.org/10.1016/j.aquaeng.2020.102067

Letelier-Gordo CO and Fernandes PM (2021) Coagulation of phosphorous and organic matter from marine, land-based recirculating aquaculture system effluents. *Aquacultural Engineering* **92**, 102144. https://doi.org/10.1016/j.aquaeng.2020.102144

Li F, Wen D, Bao Y, Huang B, Mu Q and Chen L (2022a) Insights into the distribution, partitioning and influencing factors of antibiotics concentration and ecological risk in typical bays of the East China Sea. *Chemosphere* **288**, 132566. https://doi.org/10.1016/j.chemosphere.2021.132566

Li P, Wang C, Liu G, Luo X, Rauan A, Zhang C, Li T, Yu H, Dong S and Gao Q (2022b) A hydroponic plants and biofilm combined treatment system efficiently purified wastewater from cold flowing water aquaculture. *Science of The Total Environment* **821**, 153534. http://dx.doi.org/10.1016/j.scitotenv.2022.153534

Li Y, Zhang Z, Duan Y and Wang H (2019) The effect of recycling culture medium after harvesting of *Chlorella vulgaris* biomass by flocculating bacteria on microalgal growth and the functionary mechanism. *Bioresource technology* **280**, 188-198. https://doi.org/10.1016/j.biortech.2019.01.149

Lindholm-Lehto P, Pulkkinen J, Kiuru T, Koskela J and Vielma J (2020) Water quality in recirculating aquaculture system using woodchip denitrification and slow sand filtration. *Environmental Science and Pollution Research* **27**, 17314-17328. https://doi.org/10.1007/s11356-020-08196-3

Liu C, Hu N, Song W, Chen Q and Zhu L (2019) Aquaculture feeds can be outlaws for eutrophication when hidden in rice fields? A case study in Qianjiang, China. *International Journal of Environmental Research and Public Health* **16**, 4471. https://doi.org/10.3390/ijerph16224471

Liu G, Chen L, Wang W, Wang M, Zhang Y, Li J, Lin C, Xiong J, Zhu Q, Liu Y, Zhu H and Shen Z (2023a) Balancing water quality impacts and cost-effectiveness for sustainable watershed management. *Journal of Hydrology* **621**, 129645. https://doi.org/10.1016/j.jhydrol.2023.129645

Liu H, Yang R, Duan Z and Wu H (2021a) A hybrid neural network model for marine dissolved oxygen concentrations time-series forecasting based on multi-factor analysis and a multi-model ensemble. *Engineering* **7**, 1751-1765. https://doi.org/10.1016/j.eng.2020.10.023

Liu W, Du X, Tan H, Xie J, Luo G and Sun D (2021b) Performance of a recirculating aquaculture system using biofloc biofilters with convertible water-treatment efficiencies. *Science of the Total Environment* **754**, 141918. https://doi.org/10.1016/j.scitotenv.2020.141918

Liu X, Du K, Zhang C, Luo Y, Sha Z and Wang C (2023b) Precision feeding system for largemouth bass (*Micropterus salmoides*) based on multi-factor comprehensive control. *Biosystems Engineering* **227**, 195-216. https://doi.org/10.1016/j.biosystemseng.2023.02.005

Lou Q, Wu Y, Ding H, Zhang B, Zhang W, Zhang Y, Han L, Liu M, He T and Zhong J (2022) Degradation of sulfonamides in aquaculture wastewater by laccase–syringaldehyde mediator system: Response surface optimization, degradation kinetics, and degradation pathway. *Journal of Hazardous Materials* **432**, 128647. https://doi.org/10.1016/j.jhazmat.2022.128647

Lu J, Zhang Y, Wu J and Wang J (2020) Nitrogen removal in recirculating aquaculture water with high dissolved oxygen conditions using the simultaneous partial nitrification, anammox and denitrification system. *Bioresource Technology* **305**, 123037. https://doi.org/10.1016/j.biortech.2020.123037

Lukassen MB, de Jonge N, Bjerregaard SM, Podduturi R, Jørgensen NO, Petersen MA, David GS, da Silva RJ and Nielsen JL (2019a) Microbial production of the off-flavor geosmin in tilapia production in Brazilian water reservoirs: importance of bacteria in the intestine and other fish-associated environments. *Frontiers in microbiology* **10**, 2447. https://doi.org/10.3389/fmicb.2019.02447

Lukassen MB, Podduturi R, Rohaan B, Jørgensen NO and Nielsen JL (2019b) Dynamics of geosmin-producing bacteria in a full-scale saltwater recirculated aquaculture system. *Aquaculture* **500**, 170-177. https://doi.org/10.1016/j.aquaculture.2018.10.008

Luo G, Zhang N, Cai S, Tan H and Liu Z (2017) Nitrogen dynamics, bacterial community composition and biofloc quality in biofloc-based systems cultured *Oreochromis niloticus* with poly-β-hydroxybutyric and polycaprolactone as external carbohydrates. *Aquaculture* **479**, 732-741. http://dx.doi.org/10.1016/j.aquaculture.2017.07.017

Luo S, Wu X, Jiang H, Yu M, Liu Y, Min A, Li W and Ruan R (2019) Edible fungi-assisted harvesting system for efficient microalgae bio-flocculation. *Bioresource technology* **282**, 325-330. https://doi.org/10.1016/j.biortech.2019.03.033

Lusiastuti AM, Prayitno SB, Sugiani D and Caruso D (2020) Building and improving the capacity of fish and environmental health management strategy in Indonesia. *IOP Conference Series: Earth and Environmental Science* **521**, 012016. https://doi.org/10.1088/1755-1315/521/1/012016

Ma L, Wang C, Li H, Peng F and Yang Z (2018) Degradation of geosmin and 2-methylisoborneol in water with UV/chlorine: influencing factors, reactive species, and possible pathways. *Chemosphere* **211**, 1166-1175. https://doi.org/10.1016/j.chemosphere.2018.08.029

Mallik A, Xavier KM, Naidu BC and Nayak BB (2021) Ecotoxicological and physiological risks of microplastics on fish and their possible mitigation measures. *Science of the Total Environment* **779**, 146433. https://doi.org/10.1016/j.scitotenv.2021.146433

Marques ÉAT, da Silva GMN, de Oliveira CR, Cunha MCC and Sobral MDC (2018) Assessing the negative impact of an aquaculture farm on effluent water quality in Itacuruba, Pernambuco, Brazilian semiarid region. *Water Science and Technology* **78**, 1438-1447. https://doi.org/10.2166/wst.2018.417

Mayrand E and Benhafid Z (2023) Spatiotemporal variability of pH in coastal waters of New Brunswick (Canada) and potential consequences for oyster aquaculture. *Anthropocene Coasts* **6**, 14. https://doi.org/10.1007/s44218-023-00029-3

Menon A, Arunkumar AS, Nithya K and Shakila H (2023). Salinizing livelihoods: the political ecology of brackish water shrimp aquaculture in South India. *Maritime Studies* **22**, 6. https://doi.org/10.1007/s40152-023-00294-5

Milhazes-Cunha H and Otero A (2017) Valorisation of aquaculture effluents with microalgae: the integrated multi-trophic aquaculture concept. *Algal research* **24**, 416-424. http://dx.doi.org/10.1016/j.algal.2016.12.011

Mohapatra BC, Chandan NK, Panda SK, Majhi D and Pillai BR (2020) Design and development of a portable and streamlined nutrient film technique (NFT) aquaponic system. *Aquacultural Engineering* **90**, 102100. https://doi.org/10.1016/j.aquaeng.2020.102100

Mopoung S, Udeye V, Viruhpintu S, Yimtragool N and Unhong V (2020) Water treatment for fish aquaculture system by biochar-supplemented planting panel system. *The Scientific World Journal* **2020**, 7901362. https://doi.org/10.1155/2020/7901362

Musa M, Mahmudi M, Arsad S, Lusiana ED, Wardana WA, Ompusunggu MF and Damayanti DN (2023) Interrelationship and determining factors of water quality dynamics in whiteleg shrimp ponds in Tropical Eco-Green Aquaculture System. *Journal of Ecological Engineering* **24**. 19-27. https://doi.org/10.12911/22998993/156003

Nagaraju TV, Malegole SB, Chaudhary B and Ravindran G (2022) Assessment of environmental impact of aquaculture ponds in the western delta region of Andhra Pradesh. *Sustainability* **14**, 13035. https://doi.org/10.3390/su142013035

Ng LY, Ng CY, Mahmoudi E, Ong CB and Mohammad AW (2018) A review of the management of inflow water, wastewater and water reuse by membrane technology for a sustainable production in shrimp farming. *Journal of Water Process Engineering* **23**, 27-44. https://doi.org/10.1016/j.jwpe.2018.02.020

Nguyen TDP, Le TVA, Show PL, Nguyen TT, Tran MH, Tran TNT and Lee SY (2019a) Bioflocculation formation of microalgae-bacteria in enhancing microalgae harvesting and nutrient removal from wastewater effluent. *Bioresource Technology* **272**, 34-39. https://doi.org/10.1016/j.biortech.2018.09.146

Nguyen TDP, Tran TNT, Le TVA, Phan TXN, Show PL and Chia SR (2019b) Auto-flocculation through cultivation of *Chlorella vulgaris* in seafood wastewater discharge: Influence of culture conditions on microalgae growth and nutrient removal. *Journal of Bioscience and Bioengineering* **127**, 492-498. https://doi.org/10.1016/j.jbiosc.2018.09.004

Nie X, Mubashar M, Zhang S, Qin Y and Zhang X (2020) Current progress, challenges and perspectives in microalgae-based nutrient removal for aquaculture waste: A comprehensive review. *Journal of Cleaner Production* **277**, 124209. https://doi.org/10.1016/j.jclepro.2020.124209

Oiry S and Barillé L (2021) Using sentinel-2 satellite imagery to develop microphytobenthos-based water quality indices in estuaries. *Ecological Indicators* **121**, 107184. https://doi.org/10.1016/j.ecolind.2020.107184

Okomoda VT, Oladimeji SA, Solomon SG, Olufeagba SO, Ogah SI and Ikhwanuddin M (2023) Aquaponics production system: A review of historical perspective, opportunities, and challenges of its adoption. *Food science & nutrition* **11**, 1157-1165. https://doi.org/10.1002/fsn3.3154

O'Neill EA and Rowan NJ (2022) Microalgae as a natural ecological bioindicator for the simple real-time monitoring of aquaculture wastewater quality including provision for assessing impact of extremes in climate variance–a comparative case study from the Republic of Ireland. *Science of the Total Environment* **802**, 149800. https://doi.org/10.1016/j.scitotenv.2021.149800

Obirikorang KA, Sekey W, Gyampoh BA, Ashiagbor G and Asante W (2021) Aquaponics for improved food security in Africa: A review. *Frontiers in Sustainable Food Systems* **5**, 705549. https://doi.org/10.3389/fsufs.2021.705549

Ouyang W, Song K, Wang X and Hao F (2014) Non-point source pollution dynamics under long-term agricultural development and relationship with landscape dynamics. *Ecological indicators* **45**, 579-589. http://dx.doi.org/10.1016/j.ecolind.2014.05.025

Pandey D, Daverey A, Dutta K and Arunachalam K (2022) Bioremoval of toxic malachite green from water through simultaneous decolorization and degradation using laccase immobilized biochar. *Chemosphere* **297**, 134126. https://doi.org/10.1016/j.chemosphere.2022.134126

Pal M, Yesankar PJ, Dwivedi A and Qureshi A (2020) Biotic control of harmful algal blooms (HABs): A brief review. *Journal of environmental management* **268**, 110687. https://doi.org/10.1016/j.jenvman.2020.110687

Palm HW, Knaus U, Appelbaum S, Goddek S, Strauch SM, Vermeulen T, Jijakli MH and Kotzen B (2018) Towards commercial aquaponics: A review of systems, designs, scales and nomenclature. *Aquaculture international* **26**, 813-842. https://doi.org/10.1007/s10499-018-0249-z

Paolacci S, Stejskal V, Toner D and Jansen MA (2022) Wastewater valorisation in an integrated multitrophic aquaculture system; assessing nutrient removal and biomass production by duckweed species. *Environmental Pollution* **302,** 119059. https://doi.org/10.1016/j.envpol.2022.119059

Park M, Shin SK, Do YH, Yarish C and Kim JK (2018) Application of open water integrated multi-trophic aquaculture to intensive monoculture: a review of the current status and challenges in Korea. *Aquaculture* **497**, 174-183. https://doi.org/10.1016/j.aquaculture.2018.07.051

Pasika S and Gandla ST (2020) Smart water quality monitoring system with cost-effective using IoT. *Heliyon* **6**. e04096. https://doi.org/10.1016/j.heliyon.2020.e04096

Patil PK, Geetha R, Bhuvaneswari T, Saraswathi R, Raja RA, Avunje S, Solanki HG, Alavandi SV and Vijayan KK (2022) Use of chemicals and veterinary medicinal products (VMPs) in Pacific whiteleg shrimp, *P. vannamei* farming in India. *Aquaculture* **546**, 737285. https://doi.org/10.1016/j.aquaculture.2021.737285

Polidoro BA, Carpenter KE, Collins L, Duke NC, Ellison AM, Ellison JC, Farnsworth EJ, Fernando ES, Kathiresan K, Koedam NE, Livingstone SR, Miyagi T, Moore GE, Nam VN, Ong JE, Primavera JH, Salmo III S.G, Sanciangco JC, Sukardjo, S, Wang Y and Yong JWH (2010) The loss of species: mangrove extinction risk and geographic areas of global concern. *PLoS One* **5**, 10095. https://doi.org/10.1371/journal.pone.0010095

Pu J, Wang S, Ni Z, Wu Y, Liu X, Wu T and Wu H (2021) Implications of phosphorus partitioning at the suspended particle-water interface for lake eutrophication in China’s largest freshwater lake, Poyang Lake. *Chemosphere* **263**, 128334. https://doi.org/10.1016/j.chemosphere.2020.128334

Pulkkinen JT, Kiuru T, Aalto SL, Koskela J and 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**, 38-45. https://doi.org/10.1016/j.aquaeng.2018.06.003

Purnomo AR, Patria MP, Takarina ND and Karuniasa M (2022) Environmental impact of the intensive system of *Vannamei* Shrimp (*Litopenaeus vannamei*) farming on the Karimunjawa-Jepara-Muria Biosphere Reserve, Indonesia. *International Journal on Advanced Science, Engineering and Information Technology* **12**, 873-880.

Putra I, Effendi I, Lukistyowati I, Tang UM, Fauzi M, Suharman I and Muchlisin ZA (2020) Effect of different biofloc starters on ammonia, nitrate, and nitrite concentrations in the cultured tilapia *Oreochromis niloticus* system. *F1000Research* **9**. 293 https://doi.org/10.12688/f1000research.22977.3

Qureshi AS (2022) Challenges and prospects of using treated wastewater to manage water scarcity crises in the Gulf Cooperation Council countries. *Desalination and Water Treatment* **263**, 125-126. https://doi.org/10.3390/w12071971

Quyen NTK, Hien HV, Khoi LND, Yagi N and Karia Lerøy Riple A (2020) Quality management practices of intensive whiteleg shrimp (*Litopenaeus vannamei*) farming: A study of the Mekong Delta, Vietnam. *Sustainability* **12**, 4520. https://doi.org/10.3390/su12114520

Racine P, Marley A, Froehlich HE, Gaines SD, Ladner I, MacAdam-Somer I and Bradley D (2021) A case for seaweed aquaculture inclusion in US nutrient pollution management. *Marine Policy* **129**, 104506. https://doi.org/10.1016/j.marpol.2021.104506

Rahman A, Xi M, Dabrowski JJ, McCulloch J, Arnold S, Rana M, George A and Adcock M (2021) An integrated framework of sensing, machine learning, and augmented reality for aquaculture prawn farm management. *Aquacultural Engineering* **95**, 102192. https://doi.org/10.1016/j.aquaeng.2021.102192

Ramli NM, Verdegem MCJ, Yusoff FM, Zulkifely MK and Verreth JAJ (2017) Removal of ammonium and nitrate in recirculating aquaculture systems by the epiphyte *Stigeoclonium nanum* immobilized in alginate beads. *Aquaculture Environment Interactions* **9**, 213-222. https://doi.org/10.3354/aei00225

Rana M, Rahman A, Dabrowski J, Arnold S, McCulloch J and Pais B (2021) Machine learning approach to investigate the influence of water quality on aquatic livestock in freshwater ponds. *Biosystems Engineering* **208**, 164-175. https://doi.org/10.1016/j.biosystemseng.2021.05.017

Ranjan R, Tsukuda S and Good C (2023) Effects of image data quality on a convolutional neural network trained in-tank fish detection model for recirculating aquaculture systems. *Computers and Electronics in Agriculture* **205**, 107644. https://doi.org/10.1016/j.compag.2023.107644

Rashid N, Park WK and Selvaratnam T (2018) Binary culture of microalgae as an integrated approach for enhanced biomass and metabolites productivity, wastewater treatment, and bioflocculation. *Chemosphere* **194**, 67-75. https://doi.org/10.1016/j.chemosphere.2017.11.108

Ren Q, Wang X, Li W, Wei Y and An D (2020) Research of dissolved oxygen prediction in recirculating aquaculture systems based on deep belief network. *Aquacultural Engineering* **90**, 102085. https://doi.org/10.1016/j.aquaeng.2020.102085

Reyimu Z and Özçimen D (2017) Batch cultivation of marine microalgae *Nannochloropsis oculata* and *Tetraselmis suecica* in treated municipal wastewater toward bioethanol production. *Journal of Cleaner Production* **150**, 40-46. http://dx.doi.org/10.1016/j.jclepro.2017.02.189

Ríos LDM, Monteagudo EB, Barrios YC, González LL, Vaillant YDLCV, Bossier P and Arenal A (2023) Biofloc technology and immune response of penaeid shrimp: A meta-analysis and meta-regression. *Fish & Shellfish Immunology* **138**, 108805. https://doi.org/10.1016/j.fsi.2023.108805

Rong Q, Zeng J, Su M, Yue W, Xu C and Cai Y (2021) Management optimization of nonpoint source pollution considering the risk of exceeding criteria under uncertainty. *Science of the Total Environment* **758**, 143659. https://doi.org/10.1016/j.scitotenv.2020.143659

Ryan KA, Palacios LC, Encina F, Graeber D, Osorio S, Stubbins A, Woelfl S and Nimptsch J (2022) Assessing inputs of aquaculture-derived nutrients to streams using dissolved organic matter fluorescence. *Science of The Total Environment* **807**, 150785. https://doi.org/10.1016/j.scitotenv.2021.150785

Sampaio FG, Araújo CA, Dallago BSL, Stech JL, Lorenzzetti JA, Alcântara E, Losekann ME, Marin DB, Leao JAD and Bueno GW (2021) Unveiling low-to-high-frequency data sampling caveats for aquaculture environmental monitoring and management. *Aquaculture Reports* **20**, 100764. https://doi.org/10.1016/j.aqrep.2021.100764

Santos G, Ortiz-Gándara I, Del Castillo A, Arruti A, Gómez P, Ibáñez R, Urtiaga A and Ortiz I (2022) Intensified fish farming. Performance of electrochemical remediation of marine RAS waters. *Science of the Total Environment* **847,** 157368. http://dx.doi.org/10.1016/j.scitotenv.2022.157368

Sha S, Dong Z, Gao Y, Hashim H, Lee CT and Li C (2022) In-situ removal of residual antibiotics (enrofloxacin) in recirculating aquaculture system: Effect of ultraviolet photolysis plus biodegradation using immobilized microbial granules. *Journal of Cleaner Production* **333**, 130190. https://doi.org/10.1016/j.jclepro.2021.130190

Shen M, Lin J, Ye Y, Ren Y, Zhao J and Duan H (2023) Increasing global oceanic wind speed partly counteracted water clarity management effectiveness: A case study of Hainan Island coastal waters. *Journal of Environmental Management* **339**, 117865. https://doi.org/10.1016/j.jenvman.2023.117865

Shi B, Sreeram V, Zhao D, Duan S and Jiang J (2018) A wireless sensor network-based monitoring system for freshwater fishpond aquaculture. *Biosystems Engineering* **172**, 57-66. https://doi.org/10.1016/j.biosystemseng.2018.05.016

Sopawong A, Yusoff FM, Zakaria MH, Khaw YS, Monir MS and Amalia MH (2023) Development of a bio-green floating system (BFAS) for the improvement of water quality, fish health, and aquaculture production. *Aquaculture International.* 1-18. https://doi.org/10.1007/s10499-023-01207-3

Ssekyanzi A, Nevejan N, Kabbiri R, Wesana J and Stappen GV (2022) Knowledge, attitudes, and practices of fish farmers regarding water quality and its management in the Rwenzori region of Uganda. *Water* **15**, 42. https://doi.org/10.3390/w15010042

Suhr KI, Pedersen LF and Nielsen JL (2014) End-of-pipe single-sludge denitrification in pilot-scale recirculating aquaculture systems. *Aquacultural Engineering* **62**, 28-35. http://dx.doi.org/10.1016/j.aquaeng.2014.06.002

Sun X, Li X, Tang S, Lin K, Zhao T and Chen X (2022) A review on algal-bacterial symbiosis system for aquaculture tail water treatment. *Science of The Total Environment* **847**, 157620. http://dx.doi.org/10.1016/j.scitotenv.2022.157620

Swathi A, Shekhar MS and Karthic K (2021) Variation in biotic and abiotic factors associated with white spot syndrome virus (WSSV) outbreak in shrimp culture ponds. *Indian Journal of Fisheries* **68**, 127-136. https://doi.org/10.21077/ijf.2021.68.1.89356-18

Taha MF, ElMasry G, Gouda M, Zhou L, Liang N, Abdalla A, Rousseau D and Qiu Z (2022) Recent advances of smart systems and Internet of Things (IoT) for aquaponics automation: A comprehensive overview. *Chemosensors* **10**, 303. https://doi.org/10.3390/chemosensors10080303

Tejido-Nuñez Y, Aymerich E, Sancho L and Refardt D (2019) Treatment of aquaculture effluent with *Chlorella vulgaris* and *Tetradesmus obliquus*: The effect of pretreatment on microalgae growth and nutrient removal efficiency. *Ecological Engineering* **136**, 1-9. https://doi.org/10.1016/j.ecoleng.2019.05.021

Theuerkauf SJ, Morris Jr JA, Waters TJ, Wickliffe LC, Alleway HK and Jones RC (2019) A global spatial analysis reveals where marine aquaculture can benefit nature and people. *PLoS One* **14**, e0222282. https://doi.org/10.1371/journal.pone.0222282

Troell M, Costa-Pierce B, Stead S, Cottrell RS, Brugere C, Farmery AK, Little DC, Strand A, Pullin R, Soto D, Beveridge M, Salie K, Dresdner J, Moraes-Valenti P, Blanchard J, James P, Yossa R, Allison E, Devaney C, Barg U (2023) Perspectives on aquaculture's contribution to the Sustainable Development Goals for improved human and planetary health. *Journal of the World Aquaculture Society* **54**, 251-342. https://doi.org/10.1111/jwas.12946

Ubina NA and Cheng SC (2022) A review of unmanned system technologies with its application to aquaculture farm monitoring and management. *Drones* **6,** 12. https://doi.org/10.3390/drones6010012

Vaz L, Sousa MC, Gómez-Gesteira M and Dias JM (2021) A habitat suitability model for aquaculture site selection: Ria de Aveiro and Rias Baixas. *Science of the Total Environment* **801**, 149687. https://doi.org/10.1016/j.scitotenv.2021.149687

Valiela I, Bowen JL and York JK (2001) Mangrove Forests: one of the world's threatened major tropical Environments: at least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. *Bioscience* **51**, 807–815. https://doi.org/10.1641/0006-3568(2001)051[0807:MFOOTW]2.0.CO;2

Wang H, Qi M, Bo Y, Zhou C, Yan X, Wang G and Cheng P (2021) Treatment of fishery wastewater by co-culture of *Thalassiosira pseudonana* with *Isochrysis galbana* and evaluation of their active components. *Algal Research* **60**, 102498. https://doi.org/10.1016/j.algal.2021.102498

Wang H, Deng L, Qi Z and Wang W (2022) Constructed microalgal-bacterial symbiotic (MBS) system: Classification, performance, partnerships and perspectives. *Science of The Total Environment* **803**, 150082. https://doi.org/10.1016/j.scitotenv.2021.150082

Watson SB., Monis P, Baker P, and Giglio S (2016) Biochemistry and genetics of taste and odor-producing cyanobacteria. *Harmful Algae* **54**, 112-127. https://doi.org/10.1016/j.hal.2015.11.008

Wei TY, Tindik ES, Fui CF, Haviluddin H and Hijazi MHA (2023) Automated water quality monitoring and regression-based forecasting system for aquaculture. *Bulletin of Electrical Engineering and Informatics* **12**, 570-579. https://doi.org/10.11591/eei.v12i1.4464

Wood D, Capuzzo E, Kirby D, Mooney-McAuley K and Kerrison P (2017) UK macroalgae aquaculture: What are the key environmental and licensing considerations?. *Marine policy* **83**, 29-39. https://doi.org/10.1016/j.marpol.2017.05.021

Wu H, Zou Y, Lv J and Hu Z (2018a) Impacts of aeration management and polylactic acid addition on dissolved organic matter characteristics in intensified aquaponic systems. *Chemosphere* **205**, 579-586. https://doi.org/10.1016/j.chemosphere.2018.04.089

Wu S, Hu Z, Hu T, Chen J, Yu K, Zou J and Liu S (2018b) Annual methane and nitrous oxide emissions from rice paddies and inland fish aquaculture wetlands in southeast China. *Atmospheric Environment* **175**, 135-144. https://doi.org/10.1016/j.atmosenv.2017.12.008

Wu Y, Duan Y, Wei Y, An D and Liu J (2022) Application of intelligent and unmanned equipment in aquaculture: A review. *Computers and Electronics in Agriculture* **199**, 107201. https://doi.org/10.1016/j.compag.2022.107201

Xiang J, Cui T, Li X, Zhang Q, Mu B, Liu R and Zhao W (2023) Evaluating the effectiveness of coastal environmental management policies in China: The case of Bohai Sea. *Journal of Environmental Management* **338**, 117812. https://doi.org/10.1016/j.jenvman.2023.117812

Xu G, Zhang Y, Yang T, Wu H, Lorke A, Pan M, Xiao B and Wu X (2023) Effect of light-mediated variations of colony morphology on the buoyancy regulation of *Microcystis* colonies. *Water Research* **235**, 119839. https://doi.org/10.1016/j.watres.2023.119839

Xu J, Du Y, Qiu T, Zhou L, Li Y, Chen F and Sun J (2021) Application of hybrid electrocoagulation–filtration methods in the pretreatment of marine aquaculture wastewater. *Water Science and Technology* **83**, 1315-1326. https://doi.org/10.2166/wst.2021.044

Xu Z, Dai X and Chai X (2019) Biological denitrification using PHBV polymer as solid carbon source and biofilm carrier. *Biochemical Engineering Journal* **146**, 186-193. https://doi.org/10.1016/j.bej.2019.03.019

Xue Q, Xie L, Cheng C, Su X and Zhao Y (2023) Different environmental factors drive the concentrations of microcystin in particulates, dissolved water, and sediments peaked at different times in a large shallow lake. *Journal of Environmental Management* **326**, 116833. https://doi.org/10.1016/j.jenvman.2022.116833

Yang P, Zhang Y, Lai DY, Tan L, Jin B and Tong C (2018) Fluxes of carbon dioxide and methane across the water–atmosphere interface of aquaculture shrimp ponds in two subtropical estuaries: The effect of temperature, substrate, salinity and nitrate. *Science of the Total Environment* **635**, 1025-1035. https://doi.org/10.1016/j.scitotenv.2018.04.102

Yang P, Zhao G, Tong C, Tang KW, Lai DY, Li L and Tang C (2021) Assessing nutrient budgets and environmental impacts of coastal land-based aquaculture system in southeastern China. *Agriculture, Ecosystems and Environment* **322**, 107662. https://doi.org/10.1016/j.agee.2021.107662

Yanuhar U, Musa M, Evanuarini H, Wuragil DK, Permata FS (2022) Water quality in Koi Fish (*Cyprinus carpio*) concrete ponds with filtration in Nglegok District, Blitar Regency. *Universal Journal of Agricultural Research* **10**, 814 - 820. https://doi.org/10.13189/ujar.2022.100619

Yep B and Zheng Y (2019) Aquaponic trends and challenges–A review. *Journal of Cleaner Production* **228**, 1586-1599. https://doi.org/10.1016/j.jclepro.2019.04.290

Yñiguez AT and Ottong ZJ (2020) Predicting fish kills and toxic blooms in an intensive mariculture site in the Philippines using a machine learning model. *Science of The Total Environment* **707**, 136173. https://doi.org/10.1016/j.scitotenv.2019.136173

Yñiguez AT, Lim PT, Leaw CP, Jipanin SJ, Iwataki M, Benico G and Azanza RV (2021) Over 30 years of HABs in the Philippines and Malaysia: What have we learned?. *Harmful Algae* **102**, 101776. https://doi.org/10.1016/j.hal.2020.101776

Yogev U, Vogler M, Nir O, Londong J and Gross A (2020) Phosphorous recovery from a novel recirculating aquaculture system followed by its sustainable reuse as a fertilizer. *Science of The Total Environment* **722**, 137949. https://doi.org/10.1016/j.scitotenv.2020.137949

You G, Xu B, Su H, Zhang S, Pan J, Hou X, Li J and Ding R (2021) Evaluation of aquaculture water quality based on improved fuzzy comprehensive evaluation method. *Water* **13**, 1019. https://doi.org/10.3390/w13081019

Yu H, Yang L, Li D and Chen Y (2021) A hybrid intelligent soft computing method for ammonia nitrogen prediction in aquaculture. *Information Processing in Agriculture* **8**, 64-74. https://doi.org/10.1016/j.inpa.2020.04.002

Yuan J, Liu D, Xiang J, He T, Kang H and Ding W (2021) Methane and nitrous oxide have separated production zones and distinct emission pathways in freshwater aquaculture ponds. *Water Research* **190**, 116739. https://doi.org/10.1016/j.watres.2020.116739

Zhang F, Ma C, Huang X, Liu J, Lu L, Peng K and Li S (2021) Research progress in solid carbon source–based denitrification technologies for different target water bodies. *Science of the Total Environment* **782**, 146669. https://doi.org/10.1016/j.scitotenv.2021.146669

Zhang J, Zhu Z, Mo WY, Liu SM, Wang DR and Zhang GS (2018) Hypoxia and nutrient dynamics affected by marine aquaculture in a monsoon-regulated tropical coastal lagoon. *Environmental monitoring and assessment* **190**, 656. https://doi.org/10.1007/s10661-018-7001-z

Zhang M, Wang S, Sun Z, Jiang H, Qian Y, Wang R and Li M (2022a) The effects of acute and chronic ammonia exposure on growth, survival, and free amino acid abundance in juvenile Japanese sea perch *Lateolabrax japonicus*. *Aquaculture* **560**, 738512. https://doi.org/10.1016/j.aquaculture.2022.738512

Zhang MQ, Yang JL, Lai XX, Li W, Zhan MJ, Zhang CP, Jiang JZ and Shu H (2022b) Effects of integrated multi-trophic aquaculture on microbial communities, antibiotic resistance genes, and cultured species: a case study of four mariculture systems. *Aquaculture* **557**, 738322. https://doi.org/10.1016/j.aquaculture.2022.738322

Zhao J, Zhang M, Xiao W, Jia L, Zhang X, Wang J, Zhang Z, Xie Y, Pu Y, Liu S, Feng Z and Lee X (2021) Large methane emission from freshwater aquaculture ponds revealed by long-term eddy covariance observation. *Agricultural and Forest Meteorology* **308**, 108600. https://doi.org/10.1016/j.agrformet.2021.108600

Figure 1

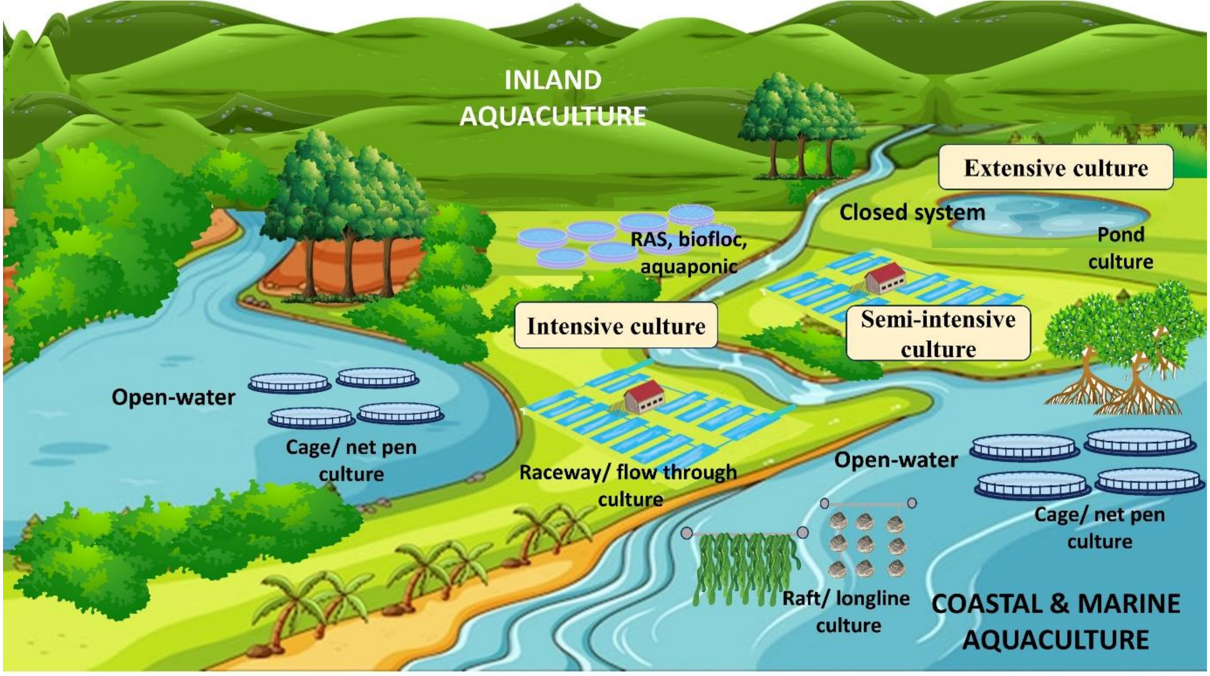

INLAND AQUACULTURE
Extensive culture
Closed system
Pond culture
RAS, biofloc, aquaponic
Intensive culture
Semi-intensive culture
Open-water
Cage/ net pen culture
Raceway/ flow through culture
Open-water
Cage/ net pen culture
Raft/ longline culture
COASTAL & MARINE AQUACULTURE

Figure 2

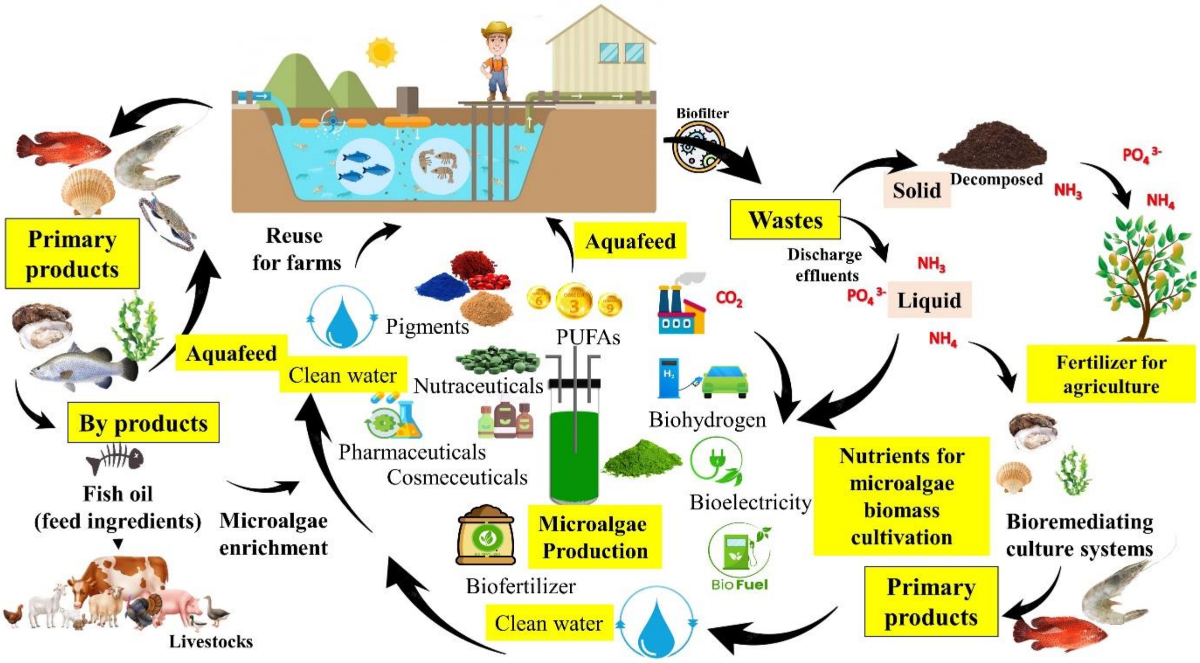
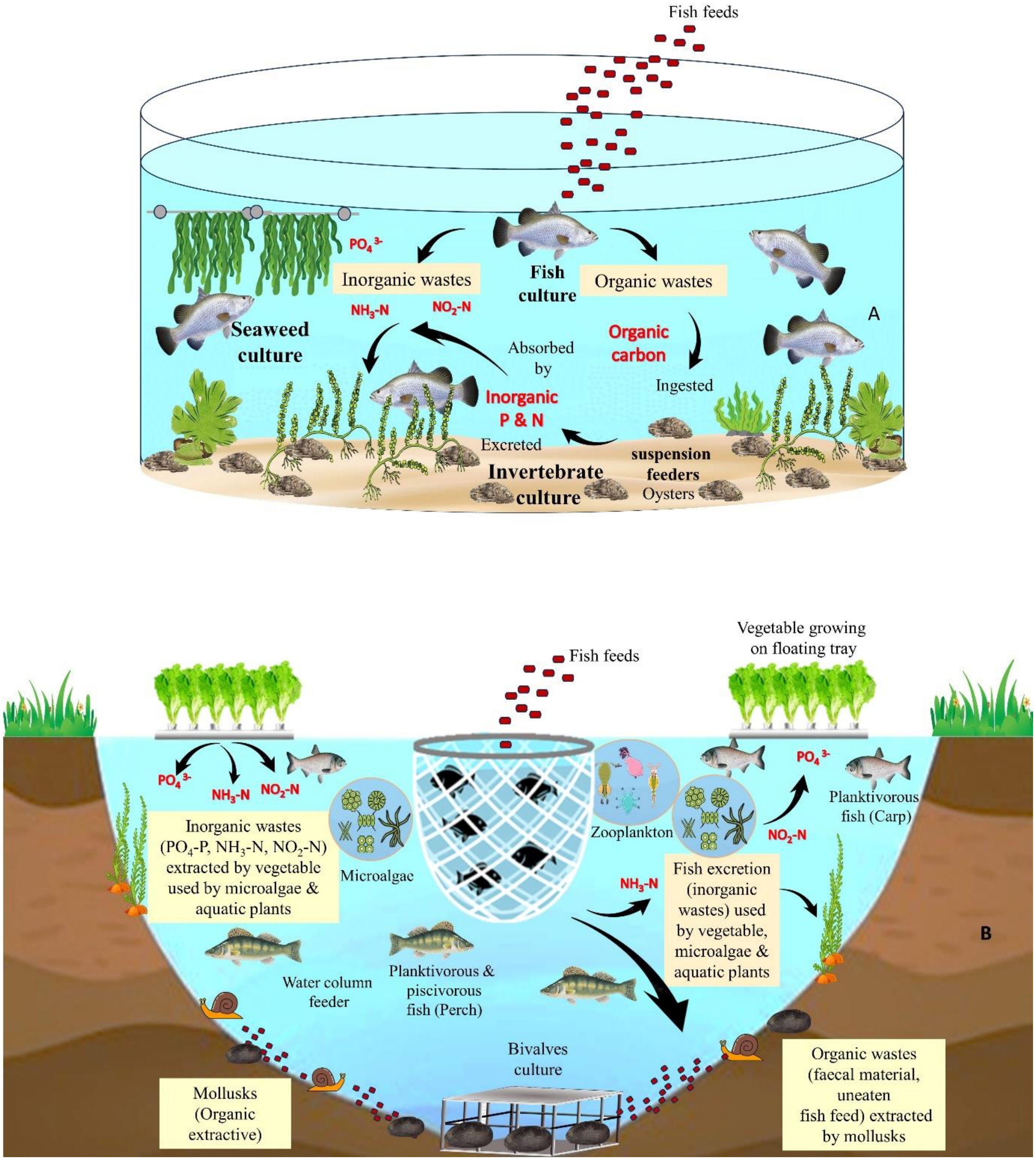

Biofilter
Primary products
Reuse for farms
Aquafeed
Wastes
Solid
Decomposed
PO_4^{3-}
NH_3
NH_4
Discharge effluents
Liquid
CO_2
Pigments
PUFAs
Clean water
Nutraceuticals
Aquafeed
By products
Pharmaceuticals
Cosmeceuticals
Biohydrogen
Fertilizer for agriculture
Nutrients for microalgae biomass cultivation
Fish oil (feed ingredients)
Microalgae enrichment
Microalgae Production
Bioelectricity
Bioremediating culture systems
Biofertilizer
Bio Fuel
Primary products
Clean water
Livestocks

Figure 3


Fish feeds
PO_4^{3-}
Inorganic wastes
Fish culture
Organic wastes
NH_3-N
NO_2-N
Seaweed culture
Absorbed by
Organic carbon
A
Ingested
Inorganic P & N
Excreted
Invertebrate culture
suspension feeders
Oysters
Vegetable growing on floating tray
Fish feeds
PO_4^{3-}
NH_3-N
NO_2-N
Inorganic wastes (PO_4-P, NH_3-N, NO_2-N) extracted by vegetable used by microalgae & aquatic plants
Microalgae
Zooplankton
PO_4^{3-}
Planktivorous fish (Carp)
NO_2-N
NH_3-N
Fish excretion (inorganic wastes) used by vegetable, microalgae & aquatic plants
B
Water column feeder
Planktivorous & piscivorous fish (Perch)
Bivalves culture
Mollusks (Organic extractive)
Organic wastes (faecal material, uneaten fish feed) extracted by mollusks

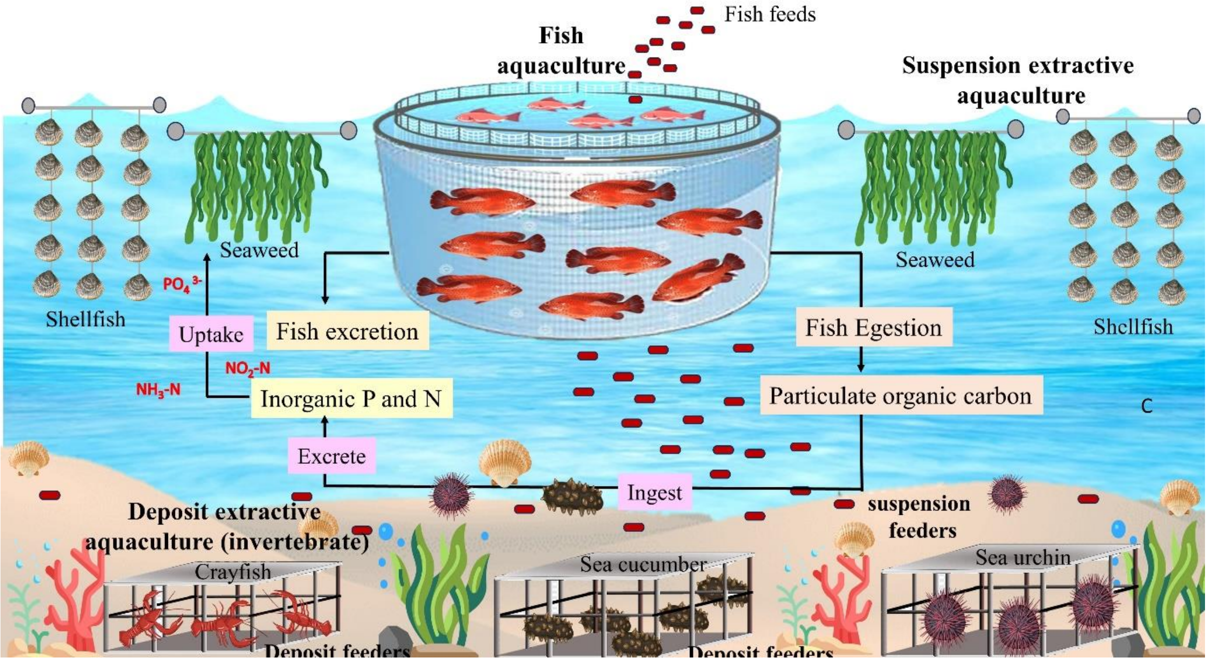

Fish feeds
Fish aquaculture
Suspension extractive aquaculture
Seaweed
Seaweed
Shellfish
Shellfish
PO_4^{3-}
Uptake
Fish excretion
NO_2-N
NH_3-N
Inorganic P and N
Excrete
Fish Egestion
Particulate organic carbon
C
Ingest
Deposit extractive aquaculture (invertebrate)
suspension feeders
Crayfish
Sea cucumber
Sea urchin
Deposit feeders
Deposit feeders

Figure 4

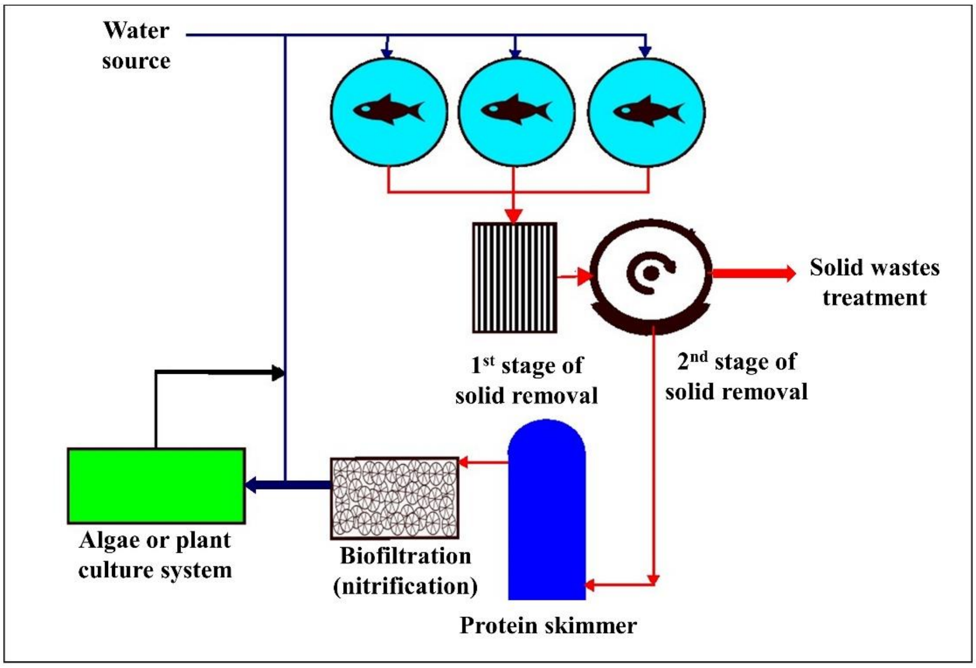
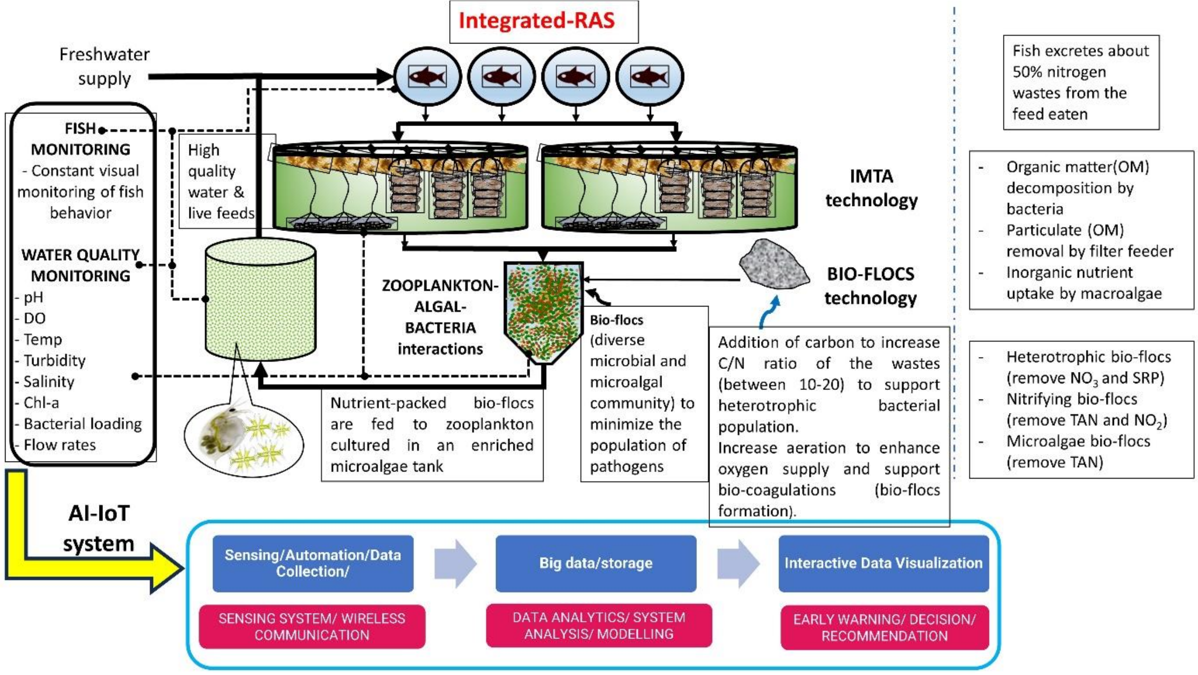

Water source
1st stage of solid removal
2nd stage of solid removal
Solid wastes treatment
Algae or plant culture system
Biofiltration (nitrification)
Protein skimmer

Figure 5


Integrated-RAS
Freshwater supply
FISH MONITORING
- Constant visual monitoring of fish behavior
WATER QUALITY MONITORING
- pH
- DO
- Temp
- Turbidity
- Salinity
- Chl-a
- Bacterial loading
- Flow rates
High quality water & live feeds
IMTA technology
BIO-FLOCS technology
ZOOPLANKTON-ALGAL-BACTERIA interactions
Nutrient-packed bio-flocs are fed to zooplankton cultured in an enriched microalgae tank
Bio-flocs (diverse microbial and microalgal community) to minimize the population of pathogens
Addition of carbon to increase C/N ratio of the wastes (between 10-20) to support heterotrophic bacterial population.
Increase aeration to enhance oxygen supply and support bio-coagulations (bio-flocs formation).
Fish excretes about 50% nitrogen wastes from the feed eaten
- Organic matter(OM) decomposition by bacteria
- Particulate (OM) removal by filter feeder
- Inorganic nutrient uptake by macroalgae
- Heterotrophic bio-flocs (remove NO_3 and SRP)
- Nitrifying bio-flocs (remove TAN and NO_2)
- Microalgae bio-flocs (remove TAN)
AI-IoT system
Sensing/Automation/Data Collection/
Big data/storage
Interactive Data Visualization
SENSING SYSTEM/ WIRELESS COMMUNICATION
DATA ANALYTICS/ SYSTEM ANALYSIS/ MODELLING
EARLY WARNING/ DECISION/ RECOMMENDATION