Sustainable Aquaculture: Water Quality Management, Fish Health, and Environmentally Responsible Production Systems

Abstract

Aquaculture has become an important component of global food production, providing fish and other aquatic products for human consumption, employment, and economic development. However, the expansion of aquaculture has created challenges related to water quality deterioration, disease outbreaks, excessive nutrient discharge, feed management, and the environmental effects of intensive production systems. Sustainable aquaculture seeks to address these challenges through responsible resource use, improved fish health management, efficient feeding practices, and effective waste treatment. This paper reviews the major factors influencing sustainable aquaculture, with particular emphasis on water quality, aquatic animal health, feed efficiency, waste management, and emerging production technologies. It examines the potential of recirculating aquaculture systems, biofloc technology, integrated multi-trophic aquaculture, and biological approaches to disease prevention. The paper also considers economic limitations, technical barriers, regulatory requirements, and opportunities for small-scale fish farmers. The literature indicates that successful aquaculture management requires a coordinated approach that considers production efficiency alongside environmental protection and animal welfare. Although modern technologies can improve resource efficiency, their effectiveness depends on appropriate design, energy availability, technical knowledge, and regular monitoring. The paper concludes that locally adapted management strategies, stronger biosecurity, responsible feed practices, and improved access to training can contribute to resilient and environmentally responsible aquaculture systems.

Keywords: Sustainable aquaculture, fish health, water quality, biosecurity, aquaculture waste, fish nutrition, recirculating aquaculture systems, environmental management.

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1. Introduction

Aquaculture refers to the farming of aquatic organisms, including fish, crustaceans, molluscs, and aquatic plants, under managed conditions. It contributes to food availability, employment, rural livelihoods, and the development of fisheries-related industries. As demand for aquatic foods increases, aquaculture has an important role in supporting food and nutritional security.

Despite these benefits, the sustainability of aquaculture depends on how production systems use natural resources and manage environmental risks. Fish farming requires suitable water conditions, adequate nutrition, healthy breeding stock, disease prevention, and effective waste management. Poor management can lead to deteriorating water quality, reduced fish growth, increased mortality, and financial losses.

Intensive production systems may generate considerable quantities of organic waste and dissolved nutrients. Uneaten feed and fish excretion can increase ammonia concentrations and contribute to oxygen depletion when waste is not managed properly. Discharges from poorly managed farms may also affect nearby aquatic ecosystems.

Aquatic animal health represents another important concern. High stocking densities, unsuitable water conditions, inadequate nutrition, and insufficient biosecurity can increase the risk of disease transmission. Disease outbreaks may affect productivity and encourage inappropriate reliance on chemical treatments or antimicrobial substances.

The Food and Agriculture Organization of the United Nations has emphasized the importance of environmental assessment and monitoring in aquaculture development. More recent research has also examined the potential of improved technologies, biological interventions, and integrated management systems to support sustainable production (FAO, 2009; Ojewole et al., 2026).

Sustainable aquaculture therefore requires more than increasing production. It involves maintaining healthy aquatic environments, improving resource efficiency, protecting animal health, and ensuring that farming activities remain economically viable.

This paper reviews the principal challenges and opportunities associated with sustainable aquaculture and identifies practical approaches that can help fish farmers, researchers, and policymakers improve environmental and production outcomes.

2. Objectives of the Study

The primary objectives of this paper are:

1. To examine the importance of water quality management in aquaculture.
2. To identify major environmental factors affecting aquatic animal health.
3. To review sustainable feeding and waste management practices.
4. To discuss modern aquaculture technologies and their potential applications.
5. To evaluate the major economic, technical, and environmental challenges facing fish farmers.
6. To recommend strategies for improving sustainable aquaculture management.

3. Review of Literature

Research on sustainable aquaculture has increasingly focused on the relationships among water quality, animal health, resource efficiency, and environmental protection.

The Food and Agriculture Organization of the United Nations published a comprehensive assessment of environmental impact assessment and monitoring in aquaculture. The report emphasized the need to evaluate environmental risks, monitor farming operations, and develop management approaches appropriate for different production systems and regions (FAO, 2009).

Tom et al. (2021) reviewed wastewater treatment technologies used in aquaculture and discussed the importance of water recycling and reducing the discharge of untreated

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wastewater. Their work highlighted the potential of improved treatment systems to address environmental concerns associated with aquatic food production.

Yusoff et al. (2024) examined water quality management in aquaculture. Their work discussed how excessive feeding, high stocking densities, unsuitable chemical use, and polluted water sources can contribute to water quality deterioration. It also emphasized the importance of waste treatment, monitoring, and responsible management.

Ojewole et al. (2026) reviewed biotechnology applications in sustainable aquaculture and fish health management. Their discussion included probiotics, vaccines, molecular diagnostics, selective breeding, and other approaches intended to improve disease prevention and production sustainability. The authors also highlighted concerns relating to antimicrobial resistance, environmental effects, and the need for appropriate safeguards.

These studies suggest that aquaculture sustainability depends on coordinated management rather than reliance on a single technology. Water quality, nutrition, disease prevention, waste treatment, and environmental monitoring must be considered together.

4. Research Methodology

This paper adopts a narrative literature review methodology. It draws on published research articles and institutional reports concerning aquaculture sustainability, water quality, aquatic animal health, wastewater management, and environmentally responsible production systems.

The literature was organized into several themes: water quality management, fish nutrition, disease prevention, waste treatment, production technologies, environmental protection, and socioeconomic challenges.

The selected publications were examined qualitatively to identify recurring findings, management approaches, potential benefits, limitations, and areas requiring further research.

This paper does not present new field experiments, laboratory analyses, farmer surveys, or original production data. Its conclusions represent a synthesis and discussion of existing literature. The recommended approaches should be adapted to the fish species, production system, water source, and environmental conditions of individual farms.

5. Importance of Water Quality Management

Water quality is one of the most important determinants of fish growth, health, and survival. Aquatic organisms depend on suitable environmental conditions to obtain oxygen, regulate physiological processes, consume feed, and maintain normal activity.

Even when farmers provide appropriate feed and suitable breeding stock, poor water quality can reduce productivity and increase the likelihood of disease.

5.1 Dissolved oxygen

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Dissolved oxygen is essential for the respiration of fish and other aquatic organisms. Oxygen availability is influenced by temperature, water movement, stocking density, biological activity, and the decomposition of organic matter.

When oxygen concentrations become insufficient, fish may experience stress, reduce feeding, and show impaired growth. Severe oxygen depletion can result in substantial losses.

Aeration, appropriate stocking densities, effective waste management, and regular monitoring can help maintain suitable oxygen conditions. Aeration equipment should be selected according to the production system and operated with consideration for energy costs and equipment reliability.

5.2 Temperature management

Water temperature influences fish metabolism, feeding activity, growth, and immune responses. Different fish species have different temperature requirements, and sudden changes can create physiological stress.

Farmers should select species suited to local climatic conditions and monitor temperature during periods of seasonal change. Appropriate pond depth, water circulation, shading where suitable, and controlled water exchange may help manage temperature-related risks.

Temperature management must be species-specific because a condition suitable for one fish species may be unsuitable for another.

5.3 pH and water chemistry

The pH of water influences chemical reactions, nutrient availability, and the toxicity of certain substances. Sudden changes in pH can stress aquatic organisms, while unsuitable water chemistry may interfere with biological processes.

Water hardness, alkalinity, salinity, and other chemical properties may also affect fish health and production performance. The relevant parameters depend on the species and the type of aquaculture system.

Regular testing helps farmers identify changes before they cause serious problems. Corrective actions should be based on reliable measurements and appropriate technical guidance rather than assumptions.

5.4 Ammonia and nitrogen compounds

Ammonia is produced through fish excretion and the decomposition of organic material. Excessive concentrations can damage fish tissues and interfere with normal physiological functioning.

The proportion of more toxic un-ionized ammonia depends partly on water temperature and pH. Therefore, monitoring ammonia without considering other water conditions may provide an incomplete picture of risk.

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Good feeding practices, suitable stocking densities, biological filtration, and appropriate waste removal can help control ammonia accumulation. In systems that rely on biological filters, maintaining the health and function of beneficial microorganisms is particularly important.

5.5 Water quality monitoring

Water quality monitoring allows farmers to identify environmental problems and take corrective action. Depending on the system, monitoring may include dissolved oxygen, temperature, pH, ammonia, nitrite, turbidity, and other relevant indicators.

A consistent monitoring schedule, accurate records, and clear response procedures are essential. More advanced farms may use automatic sensors, but manual testing remains valuable where digital equipment is unavailable or unsuitable.

The central objective is to detect problems early enough to protect fish health and maintain stable production conditions.

6. Sustainable Fish Feeding and Nutrition

Feed is a major operating cost in many aquaculture systems. Feeding practices also influence fish growth, water quality, waste production, and the environmental footprint of farmed aquatic products.

6.1 Appropriate feed formulation

Fish require suitable amounts of protein, energy, fats, vitamins, and minerals. Nutritional requirements vary according to species, age, growth stage, and production conditions.

Poorly formulated feed may reduce growth and increase waste. Feed that does not meet nutritional requirements can also weaken fish health and reduce production efficiency.

Research into alternative feed ingredients, including suitable plant-derived proteins, insect meals, and other responsibly sourced ingredients, may help diversify feed supplies. However, alternative ingredients must be assessed for nutritional quality, digestibility, safety, availability, and cost.

6.2 Efficient feeding practices

Overfeeding increases the amount of uneaten feed and organic waste entering the water. Underfeeding, on the other hand, can limit growth and affect animal welfare.

Farmers should adjust feeding practices according to fish size, species, water temperature, observed feeding activity, and production goals. Feed quality and storage conditions should also be monitored.

Maintaining records of feed use and fish growth can help farmers identify inefficiencies and improve management decisions.

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6.3 Feed conversion efficiency

Feed conversion ratio is commonly used to assess the relationship between feed supplied and the weight gained by farmed animals. A lower ratio generally indicates that less feed was required for a given amount of weight gain, although comparisons must account for differences in species, systems, and calculation methods.

Improving feed efficiency can reduce production costs and may decrease the amount of nutrients entering the aquatic environment.

However, feed conversion should not be considered in isolation. Fish health, survival, feed composition, and the environmental impacts of producing feed ingredients also influence overall sustainability.

7. Fish Health and Disease Prevention

Fish health management is essential for maintaining stable production and protecting animal welfare. Disease outbreaks may result from pathogens, unsuitable environmental conditions, poor nutrition, or interactions among these factors.

7.1 Biosecurity measures

Biosecurity refers to management practices designed to prevent the introduction and spread of disease-causing organisms.

Important measures include obtaining healthy fingerlings from reliable suppliers, inspecting new stock, cleaning equipment, managing farm access, and preventing unnecessary movement of water or animals between production units.

Where appropriate, isolation and observation procedures can help identify potential health problems before new fish are introduced into established populations.

Effective biosecurity requires clear procedures, staff training, accurate records, and regular review.

7.2 Biological approaches to disease management

Research has examined the use of probiotics and other biological approaches to support aquatic animal health. Probiotics are beneficial microorganisms that may influence digestive processes, microbial communities, or other aspects of host health.

Their effectiveness varies with the microbial strain, fish species, application method, dosage, and environmental conditions. They should therefore be selected on the basis of appropriate evidence rather than marketing claims alone.

Vaccines and selective breeding for disease resistance may also contribute to prevention in suitable aquaculture systems. Their availability and effectiveness differ among species and pathogens.

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7.3 Responsible use of medicines

Medicines and chemical treatments may sometimes be necessary to address aquatic animal health problems. However, inappropriate use can create risks for animal welfare, environmental quality, food safety, and antimicrobial resistance.

Treatment decisions should be guided by qualified aquatic animal health professionals and relevant regulations. Farmers should avoid using medicines without appropriate diagnosis and should follow applicable instructions concerning treatment, withdrawal periods, and disposal.

Preventive management, sound nutrition, suitable water quality, and effective biosecurity can reduce the likelihood of conditions that contribute to disease outbreaks.

8. Aquaculture Waste Management

Waste management is central to the environmental sustainability of fish farming. Waste may include uneaten feed, faecal material, dissolved nutrients, suspended solids, and water used during cleaning or harvesting.

If discharged without suitable treatment, these materials can contribute to nutrient enrichment, oxygen depletion, sediment accumulation, and deterioration of receiving water bodies.

8.1 Mechanical filtration

Mechanical filtration removes suspended particles from water. Depending on the system, filters may include screens, settling tanks, or other equipment designed to capture solids.

Removing solids can improve water clarity and reduce the amount of organic material available for decomposition. However, captured waste must be collected, handled, and disposed of appropriately.

8.2 Biological treatment

Biological treatment uses microorganisms to transform certain waste compounds. In recirculating systems, biological filters can support the conversion of toxic ammonia into less toxic nitrogen compounds through nitrification.

These processes require suitable operating conditions, including adequate oxygen and appropriate filter management. Biological filtration does not eliminate every form of waste, so additional treatment and monitoring may be necessary.

8.3 Wastewater reuse and treatment

Water treatment and reuse can reduce freshwater demand and limit the discharge of untreated wastewater. Treatment options may include settling, filtration, biological processes, and other methods suited to the particular farm.

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Water reuse must be managed carefully to avoid the accumulation of harmful substances or pathogens. Treatment requirements depend on the incoming water, fish species, system design, and intended use of treated water.

Wastewater management should be planned as an integral component of farm design rather than as an afterthought.

9. Modern Technologies for Sustainable Aquaculture

Several production technologies aim to improve resource efficiency and reduce environmental impacts. Their suitability depends on investment capacity, technical expertise, local infrastructure, and the species being cultured.

9.1 Recirculating aquaculture systems

Recirculating aquaculture systems (RAS) treat and reuse water rather than relying entirely on continuous water replacement.

These systems commonly combine mechanical filtration, biological filtration, aeration or oxygenation, and water-quality monitoring.

Potential advantages include reduced freshwater demand, improved control over environmental conditions, and greater flexibility in production location.

However, RAS can require substantial capital investment, reliable electricity, specialized equipment, and skilled operators. Equipment failures may quickly affect water quality if backup systems and emergency procedures are inadequate.

9.2 Biofloc technology

Biofloc technology encourages the development of microbial communities that help manage certain nitrogen compounds and organic matter in aquatic production systems.

Under suitable conditions, microbial flocs may also provide an additional nutritional resource for cultured animals.

The system requires careful management of aeration, water chemistry, organic inputs, and microbial activity. Electricity requirements and operational complexity may create challenges for farms with limited technical support.

Biofloc is therefore not a universal solution; its value depends on the cultured species, production objectives, and local operating conditions.

9.3 Integrated multi-trophic aquaculture

Integrated multi-trophic aquaculture combines organisms that use different resources or occupy different ecological roles. For example, fish may be cultivated alongside organisms that can use some of the nutrients released by the fish production system.

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The approach aims to improve resource recovery and reduce waste by creating complementary production relationships.

Successful integration requires compatible species, suitable environmental conditions, careful planning, and monitoring. Not all waste can be recovered by other organisms, and the environmental benefits depend on the system's design and operation.

9.4 Digital monitoring and precision aquaculture

Sensors, automated feeding equipment, digital records, and data analysis can support more precise aquaculture management.

Automatic monitoring can help detect changes in dissolved oxygen, temperature, or other parameters. Digital feeding systems may improve consistency and reduce unnecessary feed use when appropriately calibrated.

These tools can help farmers respond more quickly to changing conditions. However, they require reliable equipment, maintenance, technical knowledge, and appropriate backup procedures.

Technology should support sound management practices rather than replace the need for trained personnel and regular observation.

10. Environmental Impacts and Conservation

Aquaculture can provide food and livelihoods, but poorly planned production may damage aquatic environments.

10.1 Nutrient pollution

Excessive nitrogen and phosphorus discharge can stimulate unwanted algal growth. When algae and other organic material decompose, oxygen levels may decline and aquatic ecosystems may be affected.

Appropriate feeding, solids removal, nutrient treatment, and responsible wastewater discharge can reduce these risks.

10.2 Habitat protection

The development of aquaculture facilities may affect wetlands, coastal habitats, waterways, and other sensitive environments if site selection and management are inadequate.

Environmental assessments can help identify potential impacts before construction. Farm planning should consider local ecosystems, water availability, land use, and the potential effects on surrounding communities.

10.3 Escape of farmed organisms

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Farmed aquatic organisms may escape into surrounding waters because of damaged enclosures, flooding, or inadequate containment. Depending on the species and location, escapes may create ecological or genetic risks.

Appropriate barriers, regular equipment inspection, responsible species selection, and emergency planning can reduce these risks.

10.4 Monitoring environmental performance

Environmental monitoring should assess relevant indicators such as water quality, nutrient discharge, waste handling, habitat condition, and fish health.

The results can guide management adjustments and help determine whether production is meeting environmental objectives.

Consistent monitoring is particularly important where multiple farms share a water source or operate in the same coastal or inland water body.

11. Economic and Social Challenges

Sustainable aquaculture must remain economically practical while meeting environmental and animal health objectives.

11.1 Initial investment

Modern filtration systems, monitoring equipment, aeration, and wastewater treatment can require significant upfront spending. Small-scale farmers may lack access to affordable finance or technical assistance.

Financial planning should consider installation, electricity, maintenance, replacement parts, and the cost of staff training.

11.2 Access to knowledge

Farmers need reliable guidance on water testing, feeding, fish health, stocking densities, and waste management.

Agricultural and fisheries extension services can provide practical training, demonstrations, and assistance with problem-solving. Local research institutions can help adapt recommendations to regional species and production systems.

11.3 Market access and profitability

Access to suitable markets, cold storage, transportation, and processing facilities affects the financial viability of aquaculture.

Farmers may benefit from better coordination with suppliers and buyers, improved production records, and quality management. However, investment decisions should be based on realistic market assessments rather than assumed increases in demand.

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11.4 Employment and rural development

Aquaculture can support employment in fish production, feed supply, processing, transport, equipment maintenance, and marketing.

Training opportunities and inclusive business arrangements can help distribute these benefits more widely. Sustainable development should also consider the interests of nearby communities and other users of shared water resources.

12. Recommendations for Sustainable Aquaculture

The following recommendations can support improved aquaculture management:

1. **Establish routine water quality monitoring:** Use suitable testing methods and maintain clear records of important water parameters.
2. **Improve feeding efficiency:** Select appropriate feeds, adjust feeding practices, and monitor feed use relative to fish growth.
3. **Strengthen biosecurity:** Source healthy stock, maintain clean equipment, and develop procedures for preventing and responding to disease.
4. **Manage waste responsibly:** Remove solids, treat wastewater when necessary, and prevent avoidable pollution of natural water bodies.
5. **Select suitable production technologies:** Evaluate the costs, resource requirements, and technical demands of systems before investing.
6. **Expand farmer education:** Provide practical training in fish nutrition, water management, disease prevention, and environmental protection.
7. **Improve access to technical support:** Strengthen links between fish farmers, research institutions, veterinary professionals, and fisheries extension services.
8. **Support responsible regulation:** Establish clear environmental requirements and provide guidance that helps farms meet them.
9. **Encourage applied research:** Investigate locally appropriate feeds, disease prevention methods, treatment technologies, and production systems.
10. **Monitor economic and environmental performance together:** Evaluate production, survival, resource use, costs, and environmental effects rather than relying on yield alone.

These recommendations should be adapted to local conditions, production scales, and the requirements of individual aquatic species.

13. Future Research Directions

Future research should investigate how aquaculture systems can improve production while reducing dependence on freshwater, energy, and resource-intensive feed ingredients.

Long-term studies could compare the environmental and economic performance of pond systems, recirculating systems, biofloc technology, and integrated production systems under comparable conditions.

Further work is needed to identify reliable indicators of fish welfare and health and to determine how environmental conditions influence disease susceptibility. Research into

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probiotics, vaccines, selective breeding, and other preventive approaches should include appropriate evaluation of safety, effectiveness, and practical implementation.

Waste treatment research should explore methods that recover useful nutrients while maintaining water quality and controlling potential environmental risks.

Digital technologies also require further evaluation, particularly regarding affordability, reliability, maintenance, and accessibility for small-scale farmers.

Finally, research should include the experiences of aquaculture producers and local communities. Understanding practical constraints will help ensure that proposed improvements are technically effective, economically feasible, and environmentally appropriate.

14. Discussion

The literature reviewed in this paper demonstrates that water quality, fish health, feeding efficiency, and waste management are closely interconnected components of sustainable aquaculture.

For example, excessive feeding can increase waste accumulation, which may contribute to poor water quality. Poor water quality can stress fish and increase their susceptibility to disease, potentially leading to lower production and higher treatment costs. Improving feeding practices and monitoring water conditions can therefore address several problems simultaneously.

Modern technologies offer additional opportunities. Recirculating systems can reduce water demand, biological treatment can help manage nitrogen compounds, and integrated production systems may recover some nutrients that would otherwise be lost. Nevertheless, these approaches involve different costs, operational requirements, and environmental trade-offs.

Technology alone cannot guarantee sustainability. Successful aquaculture depends on trained personnel, suitable system design, preventive management, reliable infrastructure, and ongoing monitoring.

Environmental outcomes must also be considered beyond the farm boundary. Wastewater discharge, escaped organisms, and competition for water resources can affect surrounding ecosystems and communities. Consequently, responsible farm management should be supported by appropriate environmental planning and regulation.

An integrated approach that combines technical improvements with education, economic planning, and environmental safeguards offers the strongest basis for long-term sustainability.

15. Conclusion

Sustainable aquaculture is important for supporting aquatic food production while protecting natural resources and maintaining healthy fish populations. This paper has examined the roles

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of water quality management, efficient feeding, disease prevention, wastewater treatment, modern production technologies, and environmental monitoring.

The literature indicates that responsible management can improve production efficiency and reduce avoidable environmental risks. However, the success of individual interventions depends on species requirements, farm design, water availability, technical capacity, energy costs, and local environmental conditions.

Financial constraints, inadequate training, limited infrastructure, and operational complexity remain important challenges, particularly for small-scale producers. Addressing these barriers requires accessible technical assistance, appropriate investment, practical education, applied research, and effective environmental governance.

Ultimately, sustainable aquaculture should balance production, aquatic animal health, environmental protection, and economic viability. Continued cooperation among fish farmers, researchers, governments, and local communities can help develop resilient aquaculture systems that contribute to food security and responsible natural resource management.

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