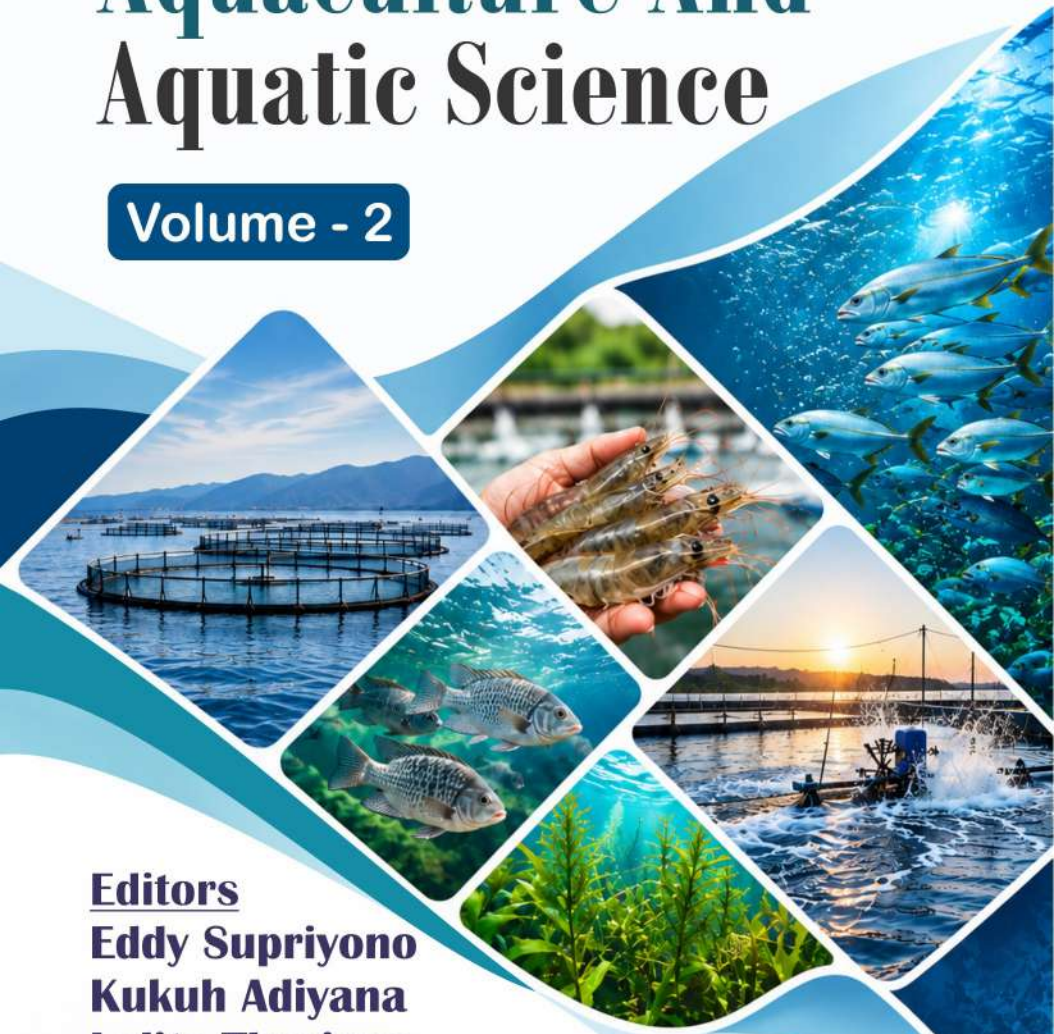
Sustainable Aquaculture And Aquatic Science

Volume - 2



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Sustainable Aquaculture and Aquatic Science (Volume – 2)

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PREFACE

Amid the stagnation of capture fisheries and the rapid growth of the global population, the intensification of aquaculture has emerged as a strategic pillar of food security, while simultaneously precipitating ecological challenges such as water quality degradation, waste accumulation and food safety risks. To address the challenge of meeting global animal protein demand without exceeding the planet's ecological carrying capacity, a transformation toward sustainable aquaculture is essential. This edited volume presents a comprehensive, upstream-to-downstream resolution to actualise this sustainability through the integration of regulatory governance, technological engineering and biological innovation.

The discourse within this work commences with the establishment of a conceptual framework for halal aquaculture, which synergises food safety standards through adherence to both Indonesian and global Good Aquaculture Practices (GAP), with a macro-level analysis of environmental footprints, encompassing nutrient mass balance calculations and the mitigation of ecotoxicological impacts stemming from pesticide contamination in freshwater ecosystems. To operationalise solutions to these challenges, the subsequent sections amalgamate ecological approaches rooted in local wisdom, such as Rice-Fish Farming, with modern closed-loop intensive technologies, namely Recirculating Aquaculture Systems (RAS) and Biofloc Technology (BFT). These advanced systems have demonstrated substantial efficacy in managing in-situ water quality and converting nitrogenous waste to enhance feed efficiency during the nursery phase of major commodities such as Nile tilapia and common carp.

Ultimately, the success of system engineering and environmental amelioration efforts depends on the intrinsic biological quality of cultured commodities. To address this critical aspect, this book examines genetic improvement and selective breeding approaches that generate superior, adaptive and resilient seed stocks capable of performing under intensive production systems. By bringing together environmental governance, cutting-edge aquaculture engineering and genetic innovation, this volume equips academics, practitioners and policymakers with the knowledge required to develop sustainable fisheries production systems and strengthen food security at both national and global scales.

Cibinong-Indonesia, June 2026

Authors

DEDICATION

We dedicate this volume to the global scientific community, aquaculture practitioners and emerging researchers who are shaping the future of sustainable aquaculture. Through this work, we seek to promote the integration of technological innovation and environmental stewardship to support food security and preserve aquatic ecosystems for future generations.

ACKNOWLEDGEMENTS

Numerous individuals and institutions contributed significantly to the preparation of this edited volume through their continuous support, collaboration and intellectual engagement. We express our sincere gratitude to the National Research and Innovation Agency (BRIN) and IPB University for providing essential institutional support, research facilities and an enabling academic environment that nurtured the development of the ideas and innovations presented in this book.

Our deepest appreciation goes to all the chapter authors who have dedicated their time, effort and expertise to disseminating their cutting-edge research in sustainable aquaculture. We are also profoundly grateful to the peer reviewers who provided critical, constructive feedback, ensuring the academic rigour and scientific validity of each manuscript.

Furthermore, we would like to express our heartfelt thanks to our families, fellow researchers and all the technical and administrative support staff who seamlessly facilitated this endeavour, from the initial stages of field research to the final publication of this book. We sincerely hope that this collaboration will continue to flourish, yielding extensive benefits for the advancement of global aquatic science.

COMPETING INTERESTS

The editors and all chapter authors of this edited volume hereby declare that they have no known competing financial interests or personal relationships that could have appeared to influence the objectivity and scientific validity of the work reported in this book. All institutional support and research facilities provided by the National Research and Innovation Agency (BRIN), IPB University and other partner institutions are strictly facilitative in nature. These funding bodies and affiliated institutions had no role or intervention in the study design, data collection and analysis, decision to publish or preparation of the respective manuscripts. Each chapter in this volume has been prepared independently and objectively and is dedicated solely to advancing scientific knowledge and technological development in aquatic science and sustainable aquaculture.

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1
CHAPTER

A Conceptual Framework for Halal Aquaculture: Linking Sustainability, Food Safety and CBIB–GAP Implementation

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Abstract

Aquaculture is a strategic food-production sector because aquatic foods are increasingly needed to support nutrition, protein security and livelihoods. However, the expansion of aquaculture has been accompanied by various concerns related to environmental issues, biological and chemical hazards, food safety, animal welfare, traceability and non-compliance with production standards. In Muslim-majority societies and halal-oriented markets, these concerns are not limited to the legal permissibility of fish species. Rather, halal aquaculture should be understood as an integrated production system in which inputs, farming practices, handling, documentation, certification and product distribution are controlled to ensure halal integrity as well as *tayyib* values such as safety, cleanliness, fitness for consumption and responsibility. This chapter develops a conceptual framework that links halal assurance, sustainability principles, food safety control and Good Aquaculture Practices, with particular attention to the CBIB framework in Indonesia. The proposed framework is structured based on an input process output logic and is supported by circular production thinking. It is emphasized that halal aquaculture can be operationalized when halal inputs, responsible environmental management, hazard prevention, biosecurity, welfare-oriented handling and traceability are integrated into daily farm management. This framework is intended to provide a conceptual basis for research, certification

design, industry upgrading and policy harmonization in halal-oriented aquaculture systems.

Keywords: halal aquaculture; *tayyib*; CBIB; Good Aquaculture Practices; food safety; sustainability; traceability.

Introduction

Aquaculture is increasingly recognized as a key sector in global aquatic food systems. Global fisheries and aquaculture production reached a historic high in 2022 and for the first time, aquaculture surpassed capture fisheries in the production of aquatic animals. A large proportion of aquatic animal production is used directly for human consumption, indicating that farmed aquatic foods are no longer merely supplementary commodities but have become a major source of animal protein, micronutrients and livelihood opportunities [1]. This structural shift strengthens the role of aquaculture in food security, but it also raises expectations that aquaculture should be managed through robust systems in terms of environmental sustainability, safety, ethics and market assurance.

The growth of aquaculture is accompanied by multidimensional challenges. Intensification can increase productivity [2,3], while supporting economic benefits, such as higher farm profits and reduced operational costs if managed sustainably [2,4,5]. However, it can also increase organic waste [6], nutrient release [7], disease [8], antimicrobial abuse [9], feed dependency [7], chemical residues [10] and risks of product contamination if production is poorly managed [11].

At the same time, consumers and regulatory authorities increasingly demand evidence that aquatic foods are safe, traceable, responsibly produced and aligned with sustainability commitments. These expectations are particularly relevant in halal-oriented markets, where the legitimacy of food products is not determined solely by the permissibility of the species. A fish may be considered halal under Islamic law, yet the final product may still be doubted if it involves non-halal inputs, contamination, unethical handling, unclear documentation or unsafe production environments [12,13]. Feed ingredients, such as animal waste or non-halal by-products, are a significant concern, especially for producers targeting halal markets [14,15]. Therefore, halal aquaculture should be understood as an integrated concept covering the entire production chain, from broodstock, seed, feed ingredients, additives and other inputs, to water sources, culture environments, harvesting, transportation

and post-harvest handling. In this context, halal is closely associated with the concept of *tayyib*, which reflects aspects of fitness for consumption, safety, cleanliness, quality and beneficial value. The integration of halal and *tayyib* is thus regarded as a bridge that connects Sharia compliance, food safety, environmental responsibility and consumer trust.

This chapter discusses the conceptual framework for halal aquaculture by linking three key pillars: sustainability, food safety and Good Aquaculture Practices (GAP). Particular attention is paid to CBIB (Cara Budidaya Ikan yang Baik), a good aquaculture practice framework in Indonesia, as it has been used to support responsible fisheries management, food safety, hygiene and environmental control in aquaculture units. Although CBIB was not originally developed as a halal standard, many of its operational elements are compatible with halal-tayyib requirements. Therefore, a harmonized model can be proposed in which halal assurance, CBIB-GAP implementation, food safety control and sustainability principles are mutually reinforcing.

This chapter is conceptual rather than regulatory in nature. It is not intended to replace existing halal certification schemes or national fisheries standards. The halal framework is developed to explain how halal aquaculture can be operationalized through practical indicators, risk-based management, documentation, traceability and system integration. The proposed framework is expected to be beneficial for researchers, certification bodies, policymakers, extension officers, producers and industry stakeholders seeking to develop halal-oriented aquaculture systems that are trustworthy, safe, environmentally sustainable and acceptable to consumers.

Foundations of Halal Aquaculture

Principles of Halal in Aquaculture Systems

In aquaculture, halal principles are often perceived as relatively simple because, in principle, fish are considered permissible [12]. However, from a production system perspective, halal status is not determined solely by species type. Aquaculture products are generated through a series of biological, technical and logistical activities, in which non-halal or unsafe materials may be introduced into the process. Feed ingredients, binders, enzymes, attractants, pigments, probiotics, medicines, disinfectants, culture media and handling materials may affect the compliance of the production process. Therefore, halal aquaculture should be understood as a controlled system in which the integrity of inputs, processes and outputs is maintained [15–17].

Input factors refer to the *halalness* and safety of materials entering the aquaculture environment [16]. Feed is considered the most important input, as it is continuously provided to fish throughout the culture period and directly affects fish growth, health, environmental waste and consumer perception [14,15]. The use of drugs and chemicals must be regulated based on necessity, legal compliance, residue control and consistency with the principles of halal-*tayyib*. Halal-oriented aquaculture practices are required to document the origin and composition of feed ingredients, particularly components of animal origin, processing aids, additives and potential cross-contamination during feed production or storage. If fish are fed with ingredients derived from non-halal sources (such as blood, carcasses or pork products), their halal status may be questioned. In such cases, fish that show significant changes in the taste, odor or color of their meat due to non-halal feed are considered haram or makruh [18]. Fish fed with non-halal substances (*al-Jallalah*) require special consideration in determining their halal status. Quarantine process can be applied to restore the halal status of fish that have been exposed to impure feed [19].

Process factors include how fish are cultured, monitored, harvested and handled. Water quality, stocking density, disease prevention, biosecurity, waste management, animal welfare and hygiene are not only technical aspects but also considered part of the ethical and safety foundations of *tayyib* production [20]. In this context, poor water quality, uncontrolled disease, excessive use of chemicals or improper handling can undermine claims that the product is healthy and responsibly produced [21]. Process factors also include the separation and prevention of contamination from non-halal or hazardous materials, especially in systems integrated with livestock, farming or processing activities. Aquaculture systems must be managed in a way that prevents contamination and upholds halal standards. The equipment used must be free from non-halal substances and the risk of contamination from machinery or the external environment must be minimized [16,17]. A controlled system is necessary to ensure that all stages of production meet halal requirements.

Output factors refer to the harvested product and the evidence supporting its halal, safe and sustainable status. Product integrity is strengthened when records such as input documentation, health management records, harvest records, water quality data and transportation information can be verified. This requirement is consistent with the halal supply chain literature, which emphasizes that halal integrity should be protected through traceability, risk

control and supply chain coordination rather than solely through final product inspection [22]. Therefore, it is crucial that the entire aquaculture production supply chain is ensured to comply with halal principles to maintain its halal certification.

Halal Compliance and Assurance System

A halal compliance and assurance system in aquaculture should be designed as a preventive and documentation-based system. Preventive control is required because the loss of halal status and food safety hazards are often difficult to rectify once contamination has occurred. A preventive approach enables risks such as contamination, improper feed use and environmental pollution to be anticipated at an early stage, in line with the concept of *halalan tayyiban* [15,16,23]. Documentation is required because certification and consumer trust depend on auditable evidence. A documentary system enables the traceability of materials and processes, ensuring that each stage of production can be verified in accordance with halal standards [24,25]. In practice, halal assurance should include documented procedures governing the approval of input materials (raw materials and additives), supplier selection, storage segregation, feed management, control of chemicals usage and health management, sanitation, harvesting processes, transportation and internal audits [26,27].

As halal assurance relies on both preventive control and auditable documentation, traceability becomes a central mechanism for demonstrating compliance throughout the aquaculture value chain. It enables the systematic recording and verification of inputs, process and output, thereby ensuring that halal integrity is maintained from the selection of materials to the delivery of the final product. The main benefits of traceability systems include:

- Food Safety and Quality Assurance: Traceability systems help identify sources of contamination and ensure product safety at every stage of the supply chain [28].
- Consumer Confidence: Providing detailed information on the origin, production methods and quality of fish products can increase consumer confidence and reduce risks associated with food consumption [29,30].
- Market Competitiveness: Traceability enhances public image, supports product differentiation and opens access to international markets [28,30].

- Sustainability: By monitoring production methods and preventing illegal fishing practices, traceability systems contribute to sustainable aquaculture practices [31].

This allows a product, batch or production unit to be linked to its origin, inputs and management history. In aquaculture, traceability must be developed from seed source to harvest and distribution. Batch-level records can include seed origin, stocking date, pond or tank identity, feed, health care, mortality, water quality monitoring, harvest date and transportation destination. Digital systems can improve record-keeping accuracy, especially when integrated with QR codes, mobile apps, blockchain, sensors or Internet of Things (IoT) platforms. Blockchain and IoT-based halal traceability frameworks have been proposed as a way to strengthen food safety and halal assurance in Indonesia [32]. Technologies supporting traceability:

- DNA Markers: Used for genotyping fish to trace their origin, particularly in complex aquaculture industries like Norwegian salmon farming [33].
- Wireless Sensor Networks (WSN): Enable real-time monitoring of recirculation aquaculture systems, ensuring data accuracy and ease of installation [34].
- Radio Frequency Identification (RFID): Combined with barcodes, RFID tags track aquatic products from breeding to sales, improving efficiency and reducing costs [35].
- Blockchain: for transparency and secure data handling across supply chains, supporting regulatory compliance and sustainability [36,37].
- Artificial Intelligence (AI): AI integrates predictive analytics, genome sequencing and IoT platforms for real-time monitoring, disease detection and operational optimization [37,38].

Halal certification plays a strategic role, not only in fulfilling religious standards but also as an important element in building consumer trust. Certification must be supported by operational readiness at the farm level. Producers are not only expected to obtain a label, but also to commit to maintaining a system that ensures ongoing halal compliance over time. This implies that human resources, internal monitoring, training, standard operating procedures, supplier documentation and corrective action mechanisms must be established. The system must be practical for small-scale farmers, as aquaculture production in many countries is dominated by small-

and medium-scale operations [25]. Therefore, halal aquaculture certification should be aligned with existing GAP schemes so that overlapping requirements can be integrated rather than duplicated.

Sustainability and Food Safety Dimensions

Environmental Sustainability

Environmental sustainability is a fundamental foundation and a strategic necessity for ensuring long-term food security without damaging ecosystems. Because production based on the principles of *tayyib* must integrate ecological responsibility. The concept of *halalan-tayyiban* encompasses permissibility, hygiene, safety, environmental protection, ethical production and social welfare [39]. Aquaculture is highly dependent on water, feed and ecosystems. Therefore, poor management can result in nutrient release, chemical residues, disease transmission and broader environmental and public health risks [40].

The performance of aquaculture systems is determined by system design, feed management, environmental integration and governance. Well-designed systems and effective management enable production efficiency while minimizing negative impacts on ecosystems. However, challenges related to feed availability, disease control and long-term sustainability remain significant [41,42].

Several production systems have been developed to improve the sustainability of aquaculture systems. Recirculating Aquaculture Systems (RAS) allow water reuse and precise environmental control, improving biosecurity and efficiency, but require high energy, investment and technical capacity [43,44]. Biofloc Technology (BFT) uses microbial processes to recycle nutrients and stabilize water quality, reducing water exchange and increasing feed efficiency [45–48]. Aquaponics integrates aquaculture with crop production, allowing nutrient recycling and water reuse, although system balance and performance depend on design, productivity and energy efficiency [49–52].

Traditional ponds and floating net cages (KJA) play a crucial role in the economy of small-scale farmers, but their sustainability depends on strict management to address water quality degradation and environmental impacts such as stocking density, feeding and waste control. Pond systems can experience water quality degradation due to organic accumulation, while KJA systems are more vulnerable to environmental pollution and eutrophication due to their open water nature [53–56].

Compliance within the halal framework is not only determined by natural conditions but also by the level of control over inputs, contamination risk and traceability throughout the production chain [57]. Therefore, the KJA system can be considered conditionally compliant (*tayyib*-oriented), but requires stronger operational, sanitation and traceability controls to ensure halal compliance [58,59]. Table 1 presents a comparative analysis of aquaculture systems based on halal parameters including environmental control, feed inputs, traceability, contamination risk and integration of halal–*tayyib* principles to assess the overall level of halal compliance across different production systems.

Table 1: Comparative Assessment of Aquaculture Systems Based on Halal Parameters

Parameter	Biofloc	RAS	Aquaponics	Traditional	KJA
Environmental Control	High (low contamination)	High (needs optimization)	High (nutrient circularity)	Moderate (low productivity)	Low (open system, high risks)
Halal Feed Inputs	Sustainable alternatives	Moderate (feed-dependent)	Sustainable alternatives	Risk of non-halal feed	Risk of non-halal feed
Traceability	Moderate (tech adaptable)	High (tech adaptable)	High (tech adaptable)	Low	Low
Contamination Risks	Low	Moderate	Low	Moderate	High
Halal-Tayyib Integration	Strong	Moderate	Strong	Moderate	Weak

Food Safety Framework

Food safety in aquaculture is shaped by controlling three main types of hazards: biological, chemical and physical. These three factors must be controlled from upstream (ponds/ponds) to downstream (processing and distribution) to ensure fishery products are safe for consumption and free from contaminants that are detrimental to health. Biological hazards can include pathogenic bacteria, viruses, parasites and spoilage organisms. Chemical hazards can include heavy metals, pesticide residues, veterinary drug residues, algal toxins, persistent pollutants, microplastics and inappropriate disinfectant residues. Physical hazards can include foreign materials introduced during harvest, transportation or processing. A One Health perspective has been recommended for fishery and aquaculture food safety because aquatic food risks are related to environmental quality, animal health, production practices and human handling [60].

The integration of halal principles and preventive food safety systems (such as HACCP or risk management) is the most effective approach to ensuring aquaculture products are not only halal in substance but also thayyib (good, safe and healthy) [61]. The principles of Hazard Analysis and Critical Control Points (HACCP) are considered relevant, as hazards can be systematically identified, critical control points can be established, monitoring procedures can be implemented and corrective actions can be documented. It has been emphasized that food safety in aquaculture is increasingly assured through the control of risks associated with inputs, environmental conditions and handling practices throughout the production and post-harvest stages. At the farm level, HACCP-based practices can be applied to key operational aspects, including feed storage, water intake, chemical use, disease treatment, harvest hygiene, ice and water quality and transport containers. In the context of modern halal assurance, the Halal-Tayyib (halal and good/safe) approach indeed demands integration between compliance with sharia and food safety standards (such as HACCP/GMP).

Food safety control in the aquaculture sector must be implemented systematically, comprehensively from upstream to downstream (pre-production to distribution) and integrated with routine monitoring of water quality parameters, including dissolved oxygen, temperature, pH, ammonia, nitrite, salinity, turbidity and microbial load. Water quality parameters are critical factors affecting fish health and product safety. Therefore they need to be monitored regularly [62]. Feed storage conditions must be well managed to prevent contamination from mold, pests, moisture, rancidity and other sources of quality degradation. The use of aquaculture inputs (raw materials and additives) must be strictly controlled, with proper documentation to minimize potential risks to consumers. Harvesting and transportation processes must be carried out under hygienic conditions, with containers and water clean and free from contamination [63]. These practices align with the precautionary principles in Good Aquaculture Practices (GAP) and Good Fish Farming Practices (CBIB) and can be systematically incorporated into halal assurance documentation.

Ethical and Social Considerations

Halal aquaculture is closely associated with ethical and social considerations and is not limited solely to compliance with Islamic legal principles (*fiqh*). This approach encompasses the entire production chain, which should reflect Islamic moral values, sustainability and responsibility

toward others. Fish welfare has become an increasing concern in aquaculture because intensification may result in high stocking densities, poor water quality, stress and disease.

Responsible fish welfare management has become a key component of modern aquaculture [64]. In Indonesia, this principle aligns with government efforts to improve productivity through the implementation of Good Fish Farming Practices (CBIB). Physical indicators such as body condition, fin damage, deformities and behavior are considered practical indicators for monitoring the welfare of cultured fish [65]. Fish welfare conditions are closely related to food safety and product quality because fish exposed to stress or poor health conditions are more susceptible to disease, mortality and post-harvest quality deterioration [64]. Therefore, welfare indicators need to be systematically integrated with operational controls, including water quality monitoring, stocking density, harvesting procedures and post-harvest handling.

Consumer trust in fishery products is strengthened when aquaculture practices are supported by transparent verification systems and traceable documentation. It has been demonstrated that certification schemes are more effective when accompanied by traceability, accountability and verifiable standards, particularly in markets where consumers have high awareness of sustainability and food safety issues [28]. Consumers no longer focus on only one aspect of a product but also demand products that are safe, ethical, environmentally friendly and compliant with religious requirements. Therefore, implementing a system that integrates halal assurance, sustainability principles and food safety is important to enhance consumer trust and increase the added value of aquaculture products.

CBIB–GAP Integration Framework

Overview of CBIB and GAP

The implementation of CBIB and GAP in aquaculture still faces various technical, economic and institutional barriers. Small-scale farmers, especially in developing countries, often lack the capital, skills, training and infrastructure to meet certification standards. As a result, standard implementation is often suboptimal or inconsistent, thus under-utilizing benefits. Studies in Vietnam indicate that shrimp farmers face significant capital and technology barriers to meeting international certification standards [66]. Another challenge is the lack of knowledge dissemination and extension

services. The successful implementation of CBIB and GAP depends heavily on farmers' understanding of biosecurity, water quality and traceability. However, inadequate extension support and ongoing training hinder knowledge transfer. In Bangladesh, a weak extension system and limited access to technical information are among the causes of low adoption of good aquaculture practices, despite the country being a major global aquaculture producer [67].

Market conditions significantly influence the implementation of aquaculture standards. Certification can open export market opportunities, but the economic benefits are not always immediately felt by farmers. In Thailand, a national shrimp certification was established to improve food safety, environmental performance and market confidence. However, implementation remains limited because each farmer group has different considerations regarding costs, ease of implementation and benefits [68].

Several studies have shown that the success of standard implementation is strongly influenced by institutional support. In Indonesia, the implementation of CBIB is supported by government policies, technical training and national certification, helping to improve production quality and expand market access for aquaculture products [69]. This demonstrates the importance of the government's role in adapting global standards to local conditions.

Collaboration between the government, researchers and the private sector is also a critical success factor. The rapid development of salmon aquaculture in Norway is due to the strong synergy between these three parties. Strong regulatory support, technological innovation and supply chain transparency make farming practices more sustainable and efficient, serving as a model for the implementation of modern aquaculture standards [70].

Furthermore, market incentives also encourage the implementation of aquaculture standards. Increasing consumer awareness of food safety and sustainability has increased demand for certified products. In Chile, the salmon industry has successfully increased its competitiveness through certification, resulting in increased market confidence and access to premium markets [71]. This suggests that if the economic benefits are clearly visible and clearly explained, producers will be more motivated to implement and maintain these standards.

Experiences from various countries demonstrate that while implementing CBIB and GAP faces many challenges, success can be achieved through strong institutional support, farmer capacity building, cross-sector collaboration and clear market benefits. An approach tailored to local conditions while adhering to global standards is crucial for the long-term sustainability of aquaculture.

Case Studies from Indonesia and Beyond

The integration of sustainability, food safety and halal assurance in aquaculture is becoming increasingly important as modern aquaculture focuses not only on increased production but also on environmental management, product safety, traceability and ethical responsibility. In Indonesia, Good Aquaculture Practices (GAP) serve as national guidelines for fish farming and harvesting activities to ensure food safety. These guidelines cover sanitation, feed, veterinary medicine, chemical management and biological aspects.

Research on vannamei shrimp farming shows that implementing GAP principles can help maintain water quality, such as pH, temperature, salinity, dissolved oxygen, nitrite and ammonia, to maintain suitability for shrimp farming [72]. Furthermore, implementing GAP also supports disease control, improved feed management and improved fishery product quality and safety [73]. Traceability and biosecurity are also crucial in reducing the risk of contamination during production and distribution. In the context of halal-*tayyib*, implementing good aquaculture standards not only aims to produce safe products but also ensures that the production process complies with sharia and ethical principles. A good aquaculture system supports supply chain transparency, raw material oversight and controls the risk of non-halal contamination [58]. Therefore, the integration of CBIB, food safety and halal assurance is a crucial foundation for responsible and sustainable aquaculture development.

An example of the implementation of halal-based aquaculture governance can be seen in Malaysia. The country has integrated halal certification with its food safety and quality system through the supervision of the Malaysian Islamic Development Agency (JAKIM). This system ensures that feed processing, handling and supply chain comply with Sharia principles. Research shows that halal certification can increase consumer trust, market acceptance and product competitiveness, especially in Muslim-majority countries and export markets [57,74]. Malaysia's experience demonstrates that

strong institutional support, clear regulations and industry involvement are crucial for implementing a halal system. Meanwhile, several countries, such as Norway and Chile, have demonstrated that aquaculture systems supported by strong governance, technology, certification and transparent supply chains can improve product sustainability and competitiveness in the global market [70,71,75]. While not specifically focused on halal, this approach illustrates that the integration of technical standards, food safety, traceability and good governance can form a strong foundation for the development of a halal aquaculture system.

In general, the development of halal aquaculture requires the integration of technical cultivation standards, food safety, sustainability principles and halal assurance. This approach is crucial for improving product quality, strengthening consumer trust and supporting the competitiveness of aquaculture products in both domestic and international markets.

Integrated Model Development

The integrated model discussed in this chapter consists of four main pillars. The first pillar is a halal assurance system that ensures raw materials, processes, documentation, certification and traceability remain in accordance with halal principles. The second pillar is sustainability, which focuses on efficient use of water and feed, waste reduction, biodiversity protection and responsible resource use. The third pillar is food safety, which encompasses hazard identification, monitoring, preventive measures, corrective actions and residue control. The fourth pillar is the implementation of CBIB–GAP, which translates these principles into daily aquaculture practices.

These four pillars are mutually supportive. A product that is halal but unsafe still poses a risk to consumers. Conversely, a product that is safe but does not meet halal standards is not necessarily acceptable to Muslim consumers. Sustainability without traceability is difficult to prove, while implementing CBIB–GAP without considering halal aspects can lead to problems with the use of materials or aquaculture inputs. Therefore, this model positions halal aquaculture as an interconnected system, where each pillar complements the shortcomings of the others. Practically, this model can be implemented through six steps:

1. All cultivation materials and inputs are inspected and categorized based on their halal status, safety risk level, supplier origin and environmental impact.
2. The entire production process is mapped, from seed storage and maintenance to harvesting and transportation.
3. Potential risks are identified, such as non-halal materials, biological, chemical and physical hazards, environmental pollution and fish welfare issues.
4. Control measures are established for each risk, such as supplier inspections, water treatment, feed storage, sanitation, biosecurity, drug withdrawal periods and monitoring schedules.
5. All data and records are maintained in a simple, easy-to-understand and auditable format.
6. Internal evaluations are conducted periodically to assess compliance, identify problems, make improvements and continuously improve the system.

Integration Challenges and Opportunities

Combining halal requirements with aquaculture sustainability, food safety and market needs is crucial, but challenging. Fish farmers must simultaneously meet multiple rules and standards, including government regulations, food safety, sustainability certification, buyer standards and halal assurance. This often leads to uncoordinated management systems, varying business capabilities, inconsistent certification requirements and poorly integrated monitoring and traceability systems. However, this situation also presents an opportunity to improve coordination between standards, strengthen institutional collaboration and utilize digital technology to make the halal aquaculture system more integrated and reliable [76].

In practice, halal aquaculture does not adhere to a single standard. The halal system must work in conjunction with food safety standards, environmental certification, traceability, export regulations and buyer requirements. This multiplicity of standards often leads to repeated audits, the use of different terminology, overlapping documentation and confusion in determining which standards should be prioritized. This situation also occurs in various aquaculture certification systems, especially for small-scale farmers with limited resources and capabilities [68]. Furthermore, food safety and halal standards are often implemented separately, even though they both aim to maintain product quality, control production processes and increase consumer confidence.

The experience of shrimp farming in Thailand shows that a multitude of certification standards does not always improve the performance of the aquaculture sector. Standards implementation remains low when regulations have varying scopes and levels of requirements and when farmers do not see clear benefits [68]. However, harmonizing standards does not mean all standards must be created equal. Differences in business conditions, production systems, market objectives and institutional capabilities still need to be considered. The most important thing is that these standards complement each other, thus reducing the burden of compliance without compromising credibility.

In practice, this can be achieved through integrated audits, the use of shared documents, a multistep certification pathway or a certification system that allows farmers to progress from basic compliance to higher-value certifications. Such an approach is considered to reduce compliance costs and support the implementation of certification that encompasses food safety, sustainability and legality simultaneously [77]. Table 2 summarizes the alignment between Halal Aquaculture principles and the Good Aquaculture Practices (GAP) framework.

Table 2: Halal Aquaculture Principles and GAP Alignment

Principles	Halal Principles	GAP Aligment
Water Quality and Purity	Halal aquaculture requires water free from harmful substances and contamination to preserve halal integrity [78,79]	GAP emphasizes maintaining water quality to ensure fish health and prevent contamination [16,80]
Feed and Nutrition	Halal aquaculture prohibits the use of non-halal or impure feed ingredients [79,81]	GAP includes guidelines for feed quality and management to avoid contamination [15,16]
Equipment and Facility Hygiene	Halal aquaculture mandates that equipment must not come into contact with non-halal substances [79]	GAP requires clean and well-maintained equipment to prevent contamination [16]
Sustainability and Environmental Responsibility	Halal aquaculture integrates Maqasid Al-Shari'ah principles, emphasizing environmental stewardship [79,81,82]	GAP promotes sustainable practices, including effluent management and environmental monitoring [13,80]

Traceability and Certification	Halal aquaculture advocates for halal certification and traceability to maintain consumer trust [79]	GAP includes certification systems to ensure compliance with food safety and quality standards [80,83]
Ethical and Social Responsibility	Halal aquaculture aligns with Islamic ethical principles, including fairness and social well-being [84,85]	GAP supports ethical practices, such as fair labor and community engagement [13,80]

Future Directions and Recommendations

The future of halal aquaculture requires an integrated approach that combines sustainability, food safety and compliance with halal principles. Although CBIB and GAP already serve as important foundations in aquaculture practices, the implementation of halal principles introduces additional challenges that require stronger support from research, policy and industry practices.

Research Gaps and Priorities

Halal aquaculture still requires extensive research. One of the main issues is the limited number of studies that simultaneously address environmental sustainability, food safety and halal compliance. So far, these three aspects are often discussed separately, resulting in the absence of a fully integrated system. Therefore, future research should develop assessment methods that combine environmental, economic and Sharia aspects in a holistic manner [76,86].

Another important issue is the standardization of halal certification within aquaculture supply chains. Currently, halal standards differ among countries, which can create inconsistencies and reduce consumer trust. Comparative studies involving countries such as Indonesia, Turkey and Saudi Arabia may help identify more harmonized halal certification systems [86–88].

Research on halal and environmentally sustainable aquaculture feed also needs further development. Feed greatly influences both environmental impact and halal status. Therefore, studies should explore alternative protein sources, such as plant-based and insect proteins, that comply with halal principles while reducing ecological impacts [89,90].

In addition, socio-economic research is necessary to understand why aquaculture producers are willing or unwilling to adopt integrated certification

systems. Factors such as costs, knowledge, risk perception and market benefits strongly influence producers decisions [91].

Policy Implications

The implementation of halal principles in aquaculture also requires strong government support. One important step is harmonizing CBIB, GAP and halal certification regulations so that they are easier to implement and do not overlap [87]. Coordination among institutions is also essential. Halal aquaculture management requires collaboration between fisheries authorities, food safety agencies and halal certification bodies. Governments also need to support small-scale farmers through training, extension services, financial assistance and access to credit so they can more easily comply with applicable standards. In addition, investment in laboratories, certification institutions and digital traceability systems is needed.

In international trade, governments should help expand market access for halal products through international cooperation and alignment between national and international standards. Collaboration with international organizations can also help reduce trade barriers and improve the competitiveness of halal products in global markets.

Industry Best Practices

The aquaculture industry plays an important role in implementing integrated halal systems. Using management systems that combine sustainability, food safety and halal requirements within a single framework can reduce repetitive work and improve production efficiency. Traceability is a key component of industry best practices. A strong traceability system helps producers monitor and record the entire production process, ensuring compliance with both technical and halal standards. The use of digital technologies such as IoT and data analytics systems can also improve monitoring accuracy and transparency [92].

Collaboration among producers, processors, distributors and retailers is also essential to ensure consistent implementation of production standards. Industry associations can support this process through training, certification and business assistance programs. In addition, marketing strategies are important for increasing the value of halal aquaculture products. Certification, branding and consumer education can strengthen market trust and improve product competitiveness in global markets [93].

Overall, the future of halal aquaculture depends on collaboration among research institutions, policymakers and industry stakeholders. Strengthening regulations, implementing best practices and advancing research are important steps toward building a halal aquaculture system that is sustainable, safe and globally competitive.

Conclusion

Halal aquaculture should not only be understood as products carrying a halal label, but as a comprehensive production system. This system includes compliance with Sharia principles, tayyib values, environmental sustainability, food safety, animal welfare and traceable governance. Since aquaculture products are influenced by the materials used, environmental conditions, management practices and handling processes, halal assurance must be maintained from the beginning of production until the final product.

The conceptual framework discussed in this chapter connects halal assurance, sustainability principles, food safety and the implementation of CBIB–GAP through an input–process–output model. At the input stage, the materials used must be halal, safe and properly documented. At the process stage, CBIB–GAP serves as a guideline for managing water quality, feed, biosecurity, fish health, fish welfare, sanitation and record keeping. At the output stage, the final product must be proven to be halal, safe, traceable and responsibly produced. Aquaculture systems such as RAS, biofloc and aquaponics can also support halal–tayyib production if nutrient flows, material use and contamination risks are properly controlled.

This framework can serve as a foundation for industry development, research, training, certification and policy making. Its main contribution is positioning halal aquaculture as an assurance system that combines religious principles with modern demands related to sustainability and food safety. This approach is important for increasing consumer trust and supporting the future development of better halal aquatic food systems.

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CHAPTER

Comprehensive Assessment of Nutrient Budgets in Global Aquaculture Systems Focusing on Environmental Impacts Carrying Capacity and Mitigation Strategies

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Abstract

The global intensification of aquaculture has fundamentally altered aquatic biogeochemical cycles, particularly through the manipulation of nitrogen (N) and phosphorus (P) fluxes. This study presents a comprehensive synthesis of nutrient mass balance in shrimp pond systems and floating net cages (FNCs) by integrating global data from 2018 to 2025. The analysis indicates that in intensive pond systems, feed accounts for more than 80% of total nutrient inputs; however, nutrient retention in harvested biomass is often low (<20%), rendering sediments the primary phosphorus sink with a high risk of remobilization. In contrast, FNC systems function as open thermodynamic systems, where waste is directly discharged into the water column. Comparative studies reveal that nutrient loading in tropical tilapia aquaculture remains substantially higher than in salmonid systems, although the adoption of extruded feeds has been shown to significantly reduce nitrogen and phosphorus waste outputs. Crucially, findings suggest that phosphorus-based environmental carrying capacity models (ECCp) are increasingly challenged

by rising water temperatures, which diminish the assimilative capacity of aquatic ecosystems. Furthermore, pond systems have been identified as significant sources of nitrous oxide (N_2O) emissions, with emission factors exceeding Intergovernmental Panel on Climate Change (IPCC) estimates by up to 32 fold, primarily due to incomplete denitrification processes. As a mitigation strategy, this manuscript recommends an integrative approach encompassing phytase enzyme supplementation, Biofloc Technology (BFT) for in situ waste recycling and Integrated Multi Trophic Aquaculture (IMTA) to transform aquaculture systems from linear nutrient flows into sustainable closed loop nutrient cycles.

Keywords: Nutrient Budget, Sustainable Aquaculture, Environmental Carrying Capacity, N_2O Emission.

Introduction: Biogeochemistry in Sustainable Aquaculture

The global expansion of the aquaculture sector has firmly established its role as a fundamental component of the world food system, now supplying a greater proportion of aquatic animal protein for human consumption than capture fisheries. However, this rapid intensification entails profound alterations to biogeochemical cycles, particularly through the manipulation of nitrogen (N) and phosphorus (P) fluxes. In aquatic environments, these elements function as limiting nutrients; while their artificial introduction via feed and fertilizers enhances productivity, excessive inputs can trigger eutrophication, hypoxia and systemic ecological degradation. A comprehensive understanding of the fate of N and P which quantified through nutrient mass balance, is therefore an urgent operational and regulatory necessity for the sustainability of aquaculture practices.

A central challenge lies in nutrient retention efficiency. Despite significant advances in feed formulation and genetic selection, the majority of nitrogen and phosphorus inputs in aquaculture systems are not recovered in harvested biomass. Instead, these nutrients are released into the environment through uneaten feed, fecal excretion, metabolic waste (e.g., ammonia) and various biogeochemical transformations such as volatilization and denitrification. The magnitude and pathways of these losses vary considerably across production systems, ranging from sediment accumulation dynamics in shrimp ponds in Southeast Asia and Latin America to direct water column dispersion characteristic of floating net cage systems in the African Great Lakes and Nordic fjords.

This report provides an indepth review of nitrogen and phosphorus budgets in modern aquaculture. It synthesizes foundational knowledge with recent global studies (2018–2025) to update current understanding of nutrient loading rates, environmental assimilative capacity and the effectiveness of mitigation technologies. By comparing intensive and semi intensive systems, examining the specific impacts of feed technologies such as extrusion and phytase supplementation and incorporating emerging concerns regarding nitrous oxide (N_2O) emissions, this analysis aims to delineate the biological and chemical boundaries of sustainable aquaculture.

Nutrient Dynamics in Coastal Shrimp Aquaculture

Coastal shrimp aquaculture, particularly of Pacific white shrimp (*Litopenaeus vannamei*) and tiger shrimp (*Penaeus monodon*), represents one of the most chemically intensive forms of coastal aquaculture. The semi closed nature of pond systems creates a unique sediment trapping dynamic, in which benthic zones function as the primary sink for nutrient accumulation. Understanding the distribution and fate of nitrogen and phosphorus within shrimp ponds is therefore essential for evaluating production efficiency and environmental sustainability. Table 3 presents nitrogen and phosphorus budgets reported for various shrimp farming systems.

Dominance of Feed Inputs and Biological Retention

In nearly all semi intensive and intensive shrimp aquaculture systems, formulated feed constitutes the dominant source of nutrient input. Historical data from Bangladesh in the early 2000s indicate that commercial feed contributed more than 90% of total nitrogen (N) input and 95% of total phosphorus (P) input during the production cycle [1]. More recent studies confirm that this trend has intensified alongside the shift toward higher stocking densities. For instance, in intensive *L. vannamei* ponds in central Vietnam, feed accounts for 81.9% of total nitrogen input and 87.8% of total phosphorus input [2].

The efficiency with which these inputs are converted into shrimp biomass, commonly expressed as Nutrient Use Efficiency (NUE), remains a critical constraint. While certain high-performance systems can achieve nitrogen retention rates approaching 49% [1], the global average is typically much lower. In sandy-bottom ponds in south-central Vietnam, for example, only 13.8% of nitrogen and 11.4% of phosphorus are retained in harvested shrimp biomass [2]. Such low retention implies that more than 85% of nutrient

inputs are lost to the environment, partitioned among the water column, sediments and atmosphere.

Variability in retention efficiency is often closely linked to the Feed Conversion Ratio (FCR). Intensive shrimp farms in Thailand and Vietnam operating with FCR values between 1.2 and 1.5 generally exhibit better nutrient recovery compared to semi intensive systems, where FCR can exceed 1.8 due to suboptimal feeding management or reliance on lower-quality diets [3]. However, even under optimal FCR conditions, nutrient loading increases with intensification. A study in intensive shrimp ponds in Thailand demonstrated that reducing FCR from 2.0 to 1.8 could prevent the release of approximately 9 kg of nitrogen and 2.2 kg of phosphorus per production cycle, highlighting the direct relationship between feeding efficiency and environmental performance [3].

Sediments as a Sink: Accumulation and Remobilization

A defining characteristic of pond based aquaculture is the accumulation of nutrients in bottom sediments (sludge). Unlike cage systems, where wastes are dispersed, pond geomorphology facilitates the deposition of uneaten feed, feces and senescent plankton. Numerous studies consistently identify sediments as the primary sink for phosphorus. In semi intensive ponds in Bangladesh, sediment accumulation accounts for 56–68% of total phosphorus outputs [1]. Similarly, in intensive systems in Vietnam, sludge accumulation remains the dominant pathway for phosphorus loss, often exceeding the amount discharged through effluent [4].

During the production cycle, sediments act as a temporary buffer by sequestering phosphorus and mitigating immediate eutrophication risks in the water column. However, this accumulated nutrient pool poses significant long-term environmental risks. During pond drying at harvest or routine pond cleaning between cycles, resuspension of nutrient-rich sediments can release substantial amounts of dissolved inorganic nitrogen and phosphorus into adjacent estuarine systems [5]. In the Min River estuary, China, annual drainage from aquaculture ponds has been estimated to discharge more than 49 tons of nitrogen and 4.7 tons of phosphorus, posing a direct threat to local water quality [6].

Sludge management represents a critical differentiating factor among aquaculture production models. In the Tam Giang Lagoon, Vietnam, specific sludge disposal regimes have been systematically evaluated. The analysis

revealed that although sludge removal is necessary to maintain pond hygiene, the extracted waste often lacks appropriate disposal pathways. Consequently, pollution loads are effectively transferred from the aquatic environment to terrestrial systems or are reintroduced into adjacent canals through runoff [4]. In contrast, studies from Mexico emphasize the role of mechanical aeration and water exchange in maintaining suspended solids for subsequent discharge. While this approach reduces benthic accumulation, it simultaneously increases direct nutrient loading into coastal lagoons [7].

In more vulnerable coastal areas, such as sandy soils in south-central Vietnam, highly permeable substrates introduce an additional dimension of risk. Wastewater and nutrients derived from sludge can infiltrate groundwater systems, transporting significant nitrogen loads and posing a threat to freshwater resources utilized by surrounding communities [2]. This highlights that nutrient budget assessments must incorporate site-specific geological characteristics, rather than focusing solely on surface water parameters.

Comparative Analysis: Asian vs. Latin American Models

Nutrient budgets in shrimp aquaculture reveal distinct regional paradigms. The Asian model (e.g., Vietnam, Thailand, China and India) is characterized by relatively small pond units, high stocking densities (often exceeding 100 post-larvae m^{-2}) and heavy reliance on aeration and commercial pelleted feeds. This results in high nutrient inputs and outputs per unit area, typically accompanied by more controlled water exchange to maintain biosecurity. Consequently, nutrient concentrations in pond effluents in Asian systems can be substantially elevated, necessitating the use of treatment reservoirs [8].

In contrast, the Latin American model (e.g., Ecuador, Honduras and Mexico) has historically relied on extensive pond systems (up to 10–20 ha), lower stocking densities (10–20 post-larvae m^{-2}) and semi intensive management that leverages natural productivity alongside fertilization [9]. Early nutrient budget studies from Honduras indicate that ponds may derive a significant proportion of nitrogen inputs (up to 63%) from incoming water, reflecting the eutrophic nature of estuarine systems. Under certain seasonal conditions, these systems can function as net nutrient sinks for nitrogen, although they remain net sources of phosphorus [9].

Ecuador, now the global leader in shrimp production, has undergone rapid intensification (with a compound annual growth rate of approximately 25%),

adopting automated feeding technologies and aeration systems that align its nutrient footprint more closely with intensive Asian models [10]. Nevertheless, the extensive spatial footprint of Latin American ponds results in moderate discharge concentrations but substantial total waste loads. A study in the Gulf of California (Mexico) demonstrated that although effluents from individual ponds may be diluted, their cumulative impact exceeds the carrying capacity of coastal lagoons during peak production seasons, leading to shifts in net ecosystem metabolism [11].

Nitrogen Loss Pathways: Denitrification, Volatilization and N_2O Emissions

A persistent anomaly in pond nutrient budgets is the fraction of nitrogen that remains unaccounted for, typically ranging from 10% to more than 50% of total inputs [12]. This missing nitrogen is generally attributed to gaseous losses, specifically ammonia (NH_3) volatilization and denitrification processes (producing N_2 and N_2O). In high-pH pond environments, particularly those frequently limed, as commonly observed in China and Vietnam, ammonia volatilization can become a significant pathway. Recent studies have highlighted the extensive use of quicklime (CaO) as a disinfectant in shrimp ponds located near mangrove ecosystems in China, which not only alters pH conditions but also disrupts N/P ratios in adjacent wetlands [12].

However, biological denitrification, the microbial reduction of nitrate to gaseous nitrogen, is increasingly recognized as the dominant nitrogen loss pathway, particularly in ponds with anaerobic sediment layers [12]. While this process provides an important ecosystem service by removing reactive nitrogen, it can also generate nitrous oxide (N_2O), a potent greenhouse gas, when reduction is incomplete.

Recent investigations in the Bohai Rim region and the Min River estuary have identified aquaculture ponds as significant anthropogenic sources of N_2O. Emission factors (EF_5) for these systems were found to exceed default values reported by the Intergovernmental Panel on Climate Change by approximately 5.9- to 32 fold, fundamentally shifting the environmental assessment of shrimp aquaculture from a local water quality issue to a matter of global climate concern [12]. These emissions show strong correlations with ammonium and nitrite concentrations and are further exacerbated by redox fluctuations at the sediment water interface [13].

Nutrient Loading in Floating Net Cage (FNC) Aquaculture Systems

Floating net cage aquaculture represents an open thermodynamic system in which the boundary between the farm and the surrounding environment is highly permeable. Unlike pond systems, there is no hydraulic retention time to facilitate sedimentation or biological processing of wastes within the farming structure. As a result, particulate and dissolved nutrients originating from feed losses, fecal deposition and fish metabolism are discharged directly into adjacent aquatic ecosystems, where they may contribute to nutrient enrichment and environmental degradation. The extent of nutrient loading depends on multiple factors, including fish species, feed composition, feeding efficiency and production intensity. A compilation of nutrient loading rates reported for various fish commodities cultured in floating net cages is presented in Table 4.

Feed to Waste Pathways in Cage Systems

Nutrient budgets in cage aquaculture are primarily governed by feed inputs and fish biomass retention. In the absence of fertilization, 100% of nutrient loading is exogenous. Early models estimated that for every ton of fish produced, approximately 132.5 kg of nitrogen and 25 kg of phosphorus are released into the environment [1]. However, these values are highly sensitive to Feed Conversion Ratio (FCR) and feed dry matter content.

When expressed on a dry matter basis, nutrient loading becomes substantially higher. A conceptual reassessment of cage system budgets suggests that losses may reach as much as 462.5 kg of nitrogen and 80 kg of phosphorus per ton of dry fish biomass produced under conditions of high feed wastage [6]. This discrepancy underscores the critical importance of feed management.

In Lake Malawi, inefficient production strategies, characterized by poor quality feed and overstocking, resulted in environmental nutrient losses of 59–80% for nitrogen and 85–92% for phosphorus [14]. These findings are particularly significant, as they demonstrate how operational inefficiencies can amplify environmental impacts far beyond theoretical estimates.

Comparative Species Analysis: Salmonids vs. Tilapia

Salmonid Aquaculture:

Salmon farming, particularly in temperate fjord systems (e.g., Norway, Chile and Scotland), represents the technological frontier of cage aquaculture.

The adoption of high energy extruded feeds and automated feeding systems has reduced FCR values to approximately 1.1–1.2. Consequently, nutrient loading per unit production has declined significantly over the past three decades.

In Nordic aquaculture systems, phosphorus discharge has decreased from approximately 31 kg per ton of production in 1974 to below 5 kg per ton in recent years [1]. Despite these efficiency gains, the large scale of production means that total nutrient outputs remain substantial. Current estimates for Atlantic salmon indicate retention rates of approximately 45–50% for nitrogen and 35–40% for phosphorus, with the remainder released as dissolved inorganic nutrients (e.g., ammonium and phosphate) or particulate organic matter [15].

Tilapia Aquaculture :

In contrast, tilapia aquaculture in tropical freshwater systems (e.g., Lake Victoria, Lake Kariba and Brazilian reservoirs) typically operates with higher feed conversion ratios (FCRs) (1.5–2.0) and lower quality feeds. A study on tilapia cage culture under tropical conditions estimated total nutrient loading at 44.95 kg of nitrogen and 14.26 kg of phosphorus per ton of fish produced [16]. This corresponds to losses of approximately 65% of nitrogen and 72% of phosphorus supplied through feed.

The environmental sensitivity of these tropical freshwater systems is considerably higher than that of marine fjords. Phosphorus acts as the primary limiting nutrient in freshwater ecosystems; therefore, even small additions of P from cage-derived wastes can trigger disproportionate algal blooms and eutrophication [17].

The Fish In Fish Out (FIFO) ratio also differs markedly between systems. While salmon aquaculture still relies on fishmeal inputs (with ratios around 2.45), modern tilapia feeds can achieve a FIFO ratio of 0.0. This shift substantially improves sustainability from a marine resource perspective but does not necessarily reduce local nutrient loading impacts [18].

Feed Technology Impacts: Extruded vs. Pelleted Feeds

The physical properties of feed play a decisive role in nutrient budgeting. Extruded feeds, which are buoyant and exhibit greater water stability, have become the industry standard for intensive cage aquaculture. These feeds enable farmers to directly observe feeding behavior and minimize wastage. In

contrast, sinking pelleted feeds, still used in some developing regions, are more prone to disintegration and are more difficult to manage efficiently.

Comparative studies confirm that extruded feeds significantly reduce environmental impacts. In rainbow trout cage systems, farms utilizing extruded feeds exhibited lower mortality and improved FCR compared to those using pelleted feeds, resulting in reduced nitrogen and phosphorus loading [19].

Empirical evidence from Lake Maninjau (Indonesia) further highlights this effect: the use of floating (extruded) feeds resulted in lower nutrient loads (39.31 kg N and 19.07 kg P per ton of fish) compared to sinking feeds (51.69 kg N per ton), primarily due to reduced feed wastage [20]. Additionally, the extrusion process enhances nutrient digestibility through starch gelatinization, directly reducing fecal output and organic loading to the environment [21].

Benthic Impacts and Recovery

The deposition of particulate organic matter (feces and uneaten feed) directly beneath cages alters sediment chemistry and benthic ecology. This impacted zone is typically characterized by organic enrichment, anoxic conditions and the dominance of opportunistic species (e.g., *Capitella* sp.). Recent studies employing environmental DNA (eDNA) metabarcoding in salmon cage systems have identified universal core bacterial taxa that serve as indicators of benthic disturbance, regardless of geographic location [22].

In tropical environments, benthic community recovery can occur relatively rapidly due to high microbial activity; however, disturbance thresholds may be considerably lower. In Martinique, significant degradation of macrobenthic communities has been observed at organic deposition fluxes as low as 1.2–3.0 kg organic matter m^{-2} yr^{-1} [23]. These findings suggest that regulatory frameworks in tropical regions may require stricter deposition thresholds than those currently applied in temperate salmon aquaculture systems.

Carrying Capacity Models and Mass Balance

To manage the cumulative impacts of aquaculture, particularly in enclosed water bodies such as lakes and reservoirs, the concept of Carrying Capacity (CC) has become central to environmental planning. This framework involves estimating the maximum biomass that a water body can sustain without exceeding water quality standards (ecological carrying capacity) or generating social conflicts (social carrying capacity).

Phosphorus Mass Balance Model (Dillon-Rigler)

In freshwater cage aquaculture, phosphorus serves as the key currency of carrying capacity. The Dillon-Rigler model, originally developed for temperate lakes, remains a cornerstone of such assessments, although it requires adaptation for tropical conditions. This model estimates equilibrium phosphorus concentrations based on loading rates, lake morphometry, flushing rate and sedimentation velocity.

In semi-arid regions of Brazil, phosphorus mass balance modeling has been applied to estimate the carrying capacity of the Santa Cruz and Umari reservoirs under extreme drought conditions. The study established critical thresholds (30 $\mu g\ L^{-1}$ and 60 $\mu g\ L^{-1}$ P) and found that carrying capacity varied widely, ranging from 63 to 680 tons, depending on reservoir volume and hydraulic retention time [24]. These findings highlight that carrying capacity is not a static value but a dynamic variable influenced by climatic conditions (e.g., rainfall and drought) and hydrological processes.

Similarly, a case study in Lake Kariba (Zimbabwe, Zambia) estimated a carrying capacity of approximately 33,200 tons per year using phosphorus budget modeling [25]. Such models are essential for spatial planning; for instance, Lake Victoria has been estimated to support up to 3 million tons of tilapia annually, provided that spatial zoning avoids shallow embayments with poor flushing conditions [26].

Phosphorus Based Environmental Carrying Capacity (ECCp) and Thermal Effects

Recent advancements have led to the development of more sophisticated frameworks, such as phosphorus based Environmental Carrying Capacity (ECCp). A 2025 study applied the ECCp framework to tropical reservoirs using bioenergetic modeling and Monte Carlo simulations to account for environmental variability, including temperature fluctuations. The model demonstrated that elevated water temperatures, common in tropical regions, reduce phosphorus retention in fish biomass (declining from 51% at 21°C to 20% at 29°C), thereby substantially increasing phosphorus loading to the environment [27].

This inverse relationship between temperature and nutrient retention efficiency represents a critical phenomenon. It implies that climate change, particularly water warming, will effectively reduce the carrying capacity of lakes for aquaculture. Fish exposed to thermal stress exhibit elevated

metabolic rates, allocating more energy to maintenance rather than growth and consequently excreting higher amounts of nutrients per unit of feed consumed. Therefore, future aquaculture planning must incorporate thermal safety margins into production licensing frameworks to ensure environmental sustainability under changing climatic conditions.

Marine Carrying Capacity and Spatial Zoning

In marine environments, carrying capacity models increasingly integrate hydrodynamic and depositional modelling tools (e.g., DEPOMOD) to predict the spatial footprint of particulate waste. In the Philippines, carrying capacity estimates for milkfish cage aquaculture in the Bolinao Anda area have already been exceeded, resulting in severe dissolved oxygen depletion and mass fish mortality events. This has necessitated reductions in the number of permitted cages to align production levels with offshore water flushing rates [28].

Recent methodologies in Africa have combined marine spatial planning with metabolic constraints to estimate marine carrying capacity ranging from 382,471 tons (conservative scenario) to over 1.6 million tons (aggressive scenario) for cobia production within Exclusive Economic Zones (EEZs) [26]. These models highlight the substantial, yet spatially constrained, potential of offshore cage aquaculture.

Emerging Environmental Concerns: Climate Linkages

Nitrous Oxide (N_2O) Emissions from Aquaculture Ponds

Aquaculture ponds function as active bioreactors for nitrogen transformation. The nitrogen cycle involves nitrification (oxidation of ammonia to nitrate) and denitrification (reduction of nitrate to gaseous nitrogen). Nitrous oxide (N_2O) is a byproduct of both processes; however, it is predominantly generated during incomplete denitrification under hypoxic conditions. Such conditions are commonly observed at the sediment–water interface in both shrimp and fishponds.

Global assessments and recent studies in China (2020–2025) indicate that aquaculture ponds are significant sources of N_2O emissions. In the Min River estuary, shrimp ponds have been reported to produce approximately 504.9 mg N_2O m^{-2} yr^{-1}, with substantial fluxes occurring even during non-production periods (e.g., pond drying) [12]. Emission factors (EF_5) for these systems exceed default values established by the Intergovernmental Panel on Climate Change by 5.9 to 32 times, suggesting a substantial underestimation of aquaculture-related emissions in global inventories [13]. Given the rapid

expansion of aquaculture worldwide, understanding the magnitude and drivers of N_2O emissions has become essential for improving the environmental sustainability of the sector. A compilation of N_2O emission rates and associated environmental parameters reported for various aquaculture pond systems is presented in Table 5.

Emission Mechanisms

N_2O production is positively correlated with ammonium (NH_4^+) and nitrite (NO_2^-) concentrations in the water column, particularly in intensive systems characterized by high nitrogen inputs from feed. Furthermore, fluctuating redox conditions in pond sediments, alternating between aerobic and anaerobic states due to aeration cycles and periodic drying, create optimal conditions for incomplete microbial denitrification, thereby maximizing N_2O release [12]. Recent findings suggest that these emissions are not only a water quality concern but may also position aquaculture under increased scrutiny within national greenhouse gas inventories.

Mitigation Strategies and Technological Innovations

Nutritional Strategy: Phytase Enzyme Supplementation

Phosphorus discharge in aquaculture is largely driven by the low digestibility of phytate-bound phosphorus present in plant-based feed ingredients (e.g., soybean meal and corn). Fish lack endogenous phytase enzymes necessary to hydrolyze this complex. The supplementation of microbial phytase in aquafeeds has been demonstrated to be a highly effective mitigation strategy.

Recent trials in tilapia cage aquaculture have shown that phytase supplementation at 4,000 FTU kg^{-1} feed reduced environmental phosphorus loading by 54% and nitrogen loading by 32% compared to control diets [29]. This enzyme liberates bound phosphorus, thereby enhancing its bioavailability for fish growth and significantly reducing fecal excretion. Such a single intervention has the potential to effectively double the carrying capacity of phosphorus-limited lakes by halving phosphorus discharge per unit of fish production.

Biofloc Technology (BFT): Converting Waste into Feed

Biofloc Technology (BFT) represents a paradigm shift from nutrient waste discharge to nutrient recycling. BFT systems are established by maintaining a high carbon to nitrogen (C:N) ratio in the water, typically

through the addition of external carbohydrate sources, which stimulates the proliferation of heterotrophic bacteria. These microbial communities assimilate toxic ammonia into microbial biomass (bioflocs), which can subsequently be consumed by cultured species such as shrimp or tilapia.

Nutrient budget analyses of BFT systems demonstrate substantially improved retention efficiencies. In tilapia-based BFT systems, nutrient retention in fish biomass has been reported at 45.38% for nitrogen and 46.34% for phosphorus, significantly higher than in conventional systems [30]. Furthermore, BFT systems operate under zero or minimal water exchange, effectively eliminating the discharge of nutrient rich effluents into surrounding aquatic environments. Nitrogenous wastes are recycled into microbial protein, thereby reducing feed conversion ratios (FCR) and dependence on external feed inputs. However, these advantages must be balanced against the high energy demand of BFT systems, particularly due to intensive aeration requirements needed to maintain flocs in suspension [30].

Integrated Multi Trophic Aquaculture (IMTA)

Integrated Multi-Trophic Aquaculture (IMTA) mimics natural ecosystem processes by combining fed species (e.g., fish or shrimp) with extractive species (e.g., seaweeds and bivalves) that utilize dissolved inorganic and particulate organic wastes.

Studies on integrated systems involving *Litopenaeus vannamei* and seaweeds (e.g., Gracilaria or Ulva) confirm that seaweeds can recover significant quantities of dissolved nitrogen and phosphorus. For example, co-culture with *Ulva fasciata* has been shown to facilitate the recovery of 5.5% of nitrogen and 7.6% of phosphorus that would otherwise be lost [31].

In open water environments, the co-location of bivalves with fish cages has been proposed as a strategy to capture particulate wastes. However, the spatial scale required to offset a substantial portion of waste outputs from large-scale fish farms is often extensive, posing logistical challenges. Despite this, the concept of bio extraction using bivalves remains highly promising, particularly as a nutrient mitigation strategy in eutrophic estuarine systems. This approach has been modelled in Long Island Sound, where shellfish aquaculture provides ecosystem service values amounting to millions of dollars through nitrogen removal [32].

Sediment Management and Remediation

For pond based systems, management of benthic nutrient sinks is unavoidable. Traditional approaches involve drying and physical removal of sludge, which often merely transfers the pollution burden elsewhere.

More recent strategies include the application of bacterial amendments (bioremediation) during production cycles to enhance the mineralization of organic matter. Additionally, the cultivation of halophytes (salt tolerant plants) or mangroves in drainage canals can function as biofilters, trapping suspended solids and assimilating dissolved nutrients before they reach adjacent estuarine environments [33].

Conclusions and Future Perspectives

The global nutrient budget of aquaculture reflects a dynamic interplay between efficiency gains and expanding production scales. While the industry has made significant progress in reducing nutrient loading per unit of production, exemplified by the reduction of phosphorus discharge in salmon aquaculture from 31 kg ton^{-1} to less than 5 kg ton^{-1}, continued expansion in total production volume implies an overall increase in cumulative nutrient loads.

The evidence synthesized in this review suggests three overarching trends for the coming decade:

1. Convergence of Intensification:

Developing regions (e.g., Latin America and Africa) are rapidly adopting intensive aquaculture technologies, such as extruded feeds, aeration systems and high stocking densities, previously pioneered in Europe and Asia. This convergence is likely to standardize global nutrient loading profiles, enhancing the transferability of technologies such as phytase supplementation and high-efficiency feed systems.

2. Phosphorus as the Limiting Factor:

In freshwater aquaculture, phosphorus loading represents the primary constraint on future expansion. Growth in African lakes and Brazilian reservoirs will be tightly regulated by phosphorus based carrying capacity models (ECCp). Sustainable intensification in these systems will depend on reducing phosphorus discharge through low P, highly digestible feeds (e.g., phytase supplementation) and genetic selection for improved nutrient

retention. The finding that elevated water temperatures reduce phosphorus retention further amplifies the urgency of these strategies.

3. Climate Linkages:

The identification of aquaculture ponds as significant sources of N_2O emissions necessitates a reevaluation of green aquaculture. Nitrogen management is no longer solely concerned with preventing ammonia toxicity or eutrophication but must also address greenhouse gas mitigation. This may drive stricter pond management practices, such as reducing anaerobic denitrification zones or accelerate the adoption of recirculating aquaculture systems (RAS) as part of climate mitigation strategies.

The future of sustainable aquaculture lies in closing nutrient loops to prevent losses to both aquatic and atmospheric environments. Whether through microbial recycling in Biofloc systems, trophic integration in IMTA or precision nutrition enabled by phytase-enhanced feeds, the overarching goal is to transform aquaculture from a linear nutrient flow system into a circular, retention based system. Nutrient budget analysis provides a critical roadmap for this transformation, quantifying the invisible fluxes that ultimately determine the ecological integrity of aquatic ecosystems.

Comprehensive Data Table

Table 3: Nitrogen (N) and Phosphorus (P) Budgets in Various Shrimp Pond Systems

System type	Location	Species	N Input Source	P Input Source	N Output (Harvest)	N Output (Lost to Environment)	P Output (Harvest)	P Output (Lost to Environment)	Main Sink	Reference
Semi-Intensive	Bangladesh	*P. monodon*	Feed (29%), Water (55%)	Feed (25%), Water (52%)	12%	78% (Water)	3.3%	52% (Water)	Sediment	[1]
Intensive	China (Min River)	*L. vannamei*	Feed (>90%)	Feed (>95%)	43-49%	28-44% (Sediment)	27-31%	56-68% (Sedimen)	Sediment	[1]
Intensive	Vietnam (Tam Giang)	*L. vannamei*	Feed (>90%)	Feed (>90%)	37.5%	23.2% (Efluent)	18,3%	53.2% (Sludge)	Sludge	[4]
Semi-Intensive	Honduras	*L. vannamei*	Water (63%), Feed (36%)	Water (51%), Feed (47%)	14%	72% (Water)	9%	56% (Air)	Water/ Sediment	[8]
Biofloc (BFT)	Experimental	*L. vannamei*	Feed	Feed	~45%	Minimum	~46%	Minimun	Biomass	[30]

Table 4: Nutrient Loading Rates in Cage Aquaculture (Global Comparison)

Species	Location	System	Feed Type	N Load (kg/ton fish)	P Load (kg/ton fish)	Notes	Reference
Salmon	Norway	Sea Cage	Extruded	~35-50	< 5	High tech, low FCR (~1.1)	[15]
Tilapia	Brazil (Reservoir)	Freshwater Cage	Extruded	~45	3.3 – 20.5	P load varies with temperature	[24]
Tilapia	Lake Malawi	Freshwater Cage	Mixed	59-80% of input	85-92% of input	Poor feed, high FCR	[14]

Tilapia	Lake Maninjau	Freshwater Cage	Pelleted(Sinking)	51.7	17.4-18.5	High wastage	[20]
Tilapia	Lake Maninjau	Freshwater Cage	Extruded (Floating)	39.3	18,8	Better management	[20]
Mixed	Global Model	Sea Cage	Theoretical	132.5	25.0	Based on old FCR	[1]
Tilapia	Experimental	Freshwater Cage	Phytase (4000 FTU)	Reduced by 32%	Reduced by 54%	enzyme effects	[29]

Table 5: Greenhouse Gas (N_2O) Emissions from Aquaculture Ponds

Parameter	Value/Observation	Implication	Reference
Emission Rate	~504.9 mg N_2O m^{-2} yr^{-1}	High source strength	[12]
Emission Factor (EF_5)	0.0117 – 0.0648	5.9 - 32x higher than IPCC limit	[13]
Main Driver	Incomplete denitrification	Occurs at sediment-water interface	[34]
Seasonal Peak	Non-culture period (drainage)	Unaccounted N becomes GHG	[12]
Global Estimation	3.83 x 10^{11} g N (in 2030)	~5.7% of anthropogenic N_2O	[34]

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3
CHAPTER

Pesticide Pollution in Freshwater Systems: Ecotoxicological Impacts of Molluscicides on Aquaculture Sustainability

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Abstract

Pesticide pollution in freshwater systems, particularly from the application of molluscicides such as niclosamide in agriculture, poses a growing threat to aquaculture sustainability. These compounds enter aquatic environments through runoff, leaching and direct application, leading to widespread exposure of non-target organisms. While acute toxicity has been widely documented, limited integration of sublethal, molecular and ecosystem-level responses remains a critical gap in current assessments. This study aims to synthesize existing knowledge on the ecotoxicological impacts of molluscicides with a specific focus on freshwater aquaculture systems. The review covers chemical characteristics, environmental pathways and multi-level biological effects, including physiological, histopathological and molecular responses such as oxidative stress and gene expression alterations. In addition, the study highlights the implications for aquaculture systems, including reduced productivity, impaired water quality, microbial imbalance and bioaccumulation risks affecting food safety. Environmental risk assessment approaches, including LC_{50}, NOEC and emerging biomarker- and

omics-based methods, are critically discussed in the context of complex multi-pollutant exposure scenarios. The findings underscore the need for integrated and ecosystem-based management strategies, incorporating environmentally friendly alternatives, improved water treatment technologies and Best Management Practices (BMPs). Ultimately, advancing multidisciplinary approaches that bridge ecotoxicology, molecular biology and aquaculture management is essential to support resilient and sustainable aquaculture.

Keyword: Molluscicides; Niclosamide; Freshwater pollution; Sustainable Aquaculture; Ecotoxicology

Introduction

Agricultural intensification, particularly in rice paddies, has increased the use of chemical pesticides that negatively impact the quality of aquatic environments and freshwater ecosystems. Pesticide residues enter water bodies through runoff, washing and *spray drift*, which increases pollutant concentrations and impacts non-target organisms, especially fish [1, 2, 3]. The impacts include declining fish populations, acute toxicity, developmental disorders and disruption of the food chain due to reduced primary producers such as phytoplankton [2, 3, 4]. In this context, golden snail (*Pomacea canaliculata*), as the main pest of rice, is controlled using molluscicides with the active ingredient niclosamide, but its non-selective use poses ecological risks because it is toxic to non-target organisms and has the potential to experience bioaccumulation in the food chain [1, 5].

Molluscicides such as niclosamide exhibit complex environmental behavior, influenced by physicochemical properties such as solubility, persistence and adsorption that determine their distribution in the water and sediment columns. This compound has a moderate persistence with a half-life of days to weeks, thus increasing the potential for chronic and sublethal exposure in aquatic organisms [6, 7, 8]. Interactions with environmental factors such as pH, temperature and organic matter also affect their degradation and bioavailability, while their non-selective toxicity can disrupt the balance of ecosystems and trigger oxidative stress and metabolic disorders [5, 9, 10, 11]. Accumulation in the food chain also increases risks to human health, so a more comprehensive ecotoxicology study is needed regarding the long-term impacts and their transformation products [6, 12].

The vulnerability of freshwater aquaculture to pesticide contamination is increasing due to its proximity to farmland, so that aquaculture species such as tilapia, carp and catfish are often exposed to harmful compounds. This

exposure triggers a variety of physiological and biochemical disorders, including oxidative stress, histopathological damage, neurotransmitter enzyme disorders, immunosuppression and increased mortality [13, 14, 15, 16, 17]. Additionally, chronic exposure to pesticides can stunt growth, decrease survival and interfere with fish reproduction [2]. This cumulative impact not only decreases productivity but also threatens the sustainability of aquaculture and potentially endangers human health through bioaccumulation [18].

The accumulation of molluscicides in aquatic systems underscores the importance of a thorough understanding of their sources, behaviors and impacts, given that these compounds can come from agricultural runoff in both synthetic and plant-based forms [2,19]. The persistence and bioaccumulation of molluscicidess contribute to food web disruption and biodiversity decline, as well as increase the risk of toxicity in non-target organisms through mechanisms such as oxidative stress and reproductive disruption [15, 20, 21]. Therefore, careful management strategies are needed, including the development of environmentally friendly alternatives and the implementation of integrated pest control to balance agricultural productivity with ecosystem sustainability [22].

Although research on pesticide toxicity is evolving, integrative studies linking molluscicidess pollution to aquaculture sustainability at various ecological, physiological and molecular levels are still limited, especially in tropical freshwater ecosystems. This gap is important because most research is still based on laboratory conditions that do not fully represent field conditions. Therefore, this chapter presents an integrative perspective by examining the sources, environmental behavior and ecotoxicological impacts of molluscicidess, as well as their implications for sustainable aquaculture. By syntheizing the latest developments, this study is expected to support the development of more environmentally responsible pest management strategies and strengthen the resilience of aquaculture systems [22].

Types and Chemical Characteristics of Molluscicides

Molluscicides are a group of pesticides used to control the population of snails as pests in rice fields. Among the various compounds used, niclosamide is one of the most widely applied molluscicides due to its high effectiveness and rapid action against target organisms. However, its non-selective toxicity raises serious concerns for non-target aquatic organisms, including fish [23].

Niclosamide is the most widely used molluscicides in rice fields due to its effectiveness in controlling snail pests, with the main mechanism of action being a disruption of mitochondrial oxidative phosphorylation that inhibits ATP production and causes energy depletion until the death of the target organism [9, 24]. Chemically, these compounds have moderate hydrophobicity properties and limited water solubility, which contributes to environmental persistence and affects their bioavailability in waters [9, 25]. These characteristics allow niclosamide to persist long enough in aquatic environments, thereby increasing the potential for exposure and toxic risk to non-target organisms, including fish and invertebrates. In addition, research shows that its effectiveness can be increased through synergistic effects with other compounds, although this also has the potential to prolong its ecological impact [9]. Therefore, although niclosamide is effective as a pest control, its persistence and toxicity demand the development of safer formulations to balance control effectiveness with ecosystem sustainability.

The relatively high mobility of niclosamide in soil and water makes it susceptible to washing and runoff processes, thereby increasing the potential for contamination of freshwater systems, especially in areas with intensive agricultural activities. These characteristics allow the compound to reach surface water bodies and groundwater, thereby increasing the risk of exposure to aquatic organisms and contributing to the pollution of aquatic ecosystems [2], [26]. On the other hand, although niclosamide has potential in sustainable pest control strategies, its effectiveness is greatly influenced by environmental conditions, thus showing variability in efficacy as well as limited stability due to degradation processes [27, 28]. This poses challenges in large-scale implementation and demands the development of innovative approaches, including more stable formulations and more precise application methods, to balance the effectiveness of pest control with environmental protection.

The environmental behavior of molluscicides is largely determined by their physicochemical properties, such as solubility, lipophilicity, stability and adsorption capacity, which control the processes of transport, distribution and the fate of compounds in aquatic systems. Compounds with high solubility tend to disperse more easily in the water column and increase their bioavailability to aquatic organisms [29] , while compounds with high lipophilicity are more likely to experience bioaccumulation in biota tissues and pose greater ecological risks [30]. In addition, stability and interaction with sediments are affected by environmental factors such as pH, temperature and organic matter content, which can alter the rate of degradation as well as affect

the persistence and bioavailability of such compounds [31]. These variations in environmental conditions ultimately determine the level of exposure and ecological impact of molluscicides in aquatic ecosystems. Therefore, a comprehensive understanding of physicochemical characteristics and their interaction with environmental factors is essential for predicting ecological risks as well as designing effective management strategies, especially in the context of protecting freshwater aquaculture from pesticide contamination.

Molluscicides Contamination Pathways in Freshwater Systems

Molluscicides enter freshwater ecosystems through various environmental pathways that are mainly influenced by agricultural activities, particularly in rice fields, as the use of chemical agents for pest control and vectors increases their presence in aquatic systems. Among these pathways, surface runoff is recognized as the dominant mechanism that transports pesticide residues from cultivated land to nearby water bodies, especially during rainfall events, thus acting as the main channel for contaminant transport. This process is reinforced by the presence of agricultural storm drainage systems that improve connectivity between land and water, where some inlets reportedly account for more than 10% of the pesticide load to streams during rainfall [26]. Temporally, concentrations of molluscicides such as metaldehyde can peak in certain application seasons, e.g., autumn and December [32]. As a result, high concentrations of pesticides, including molluscicidess, have been detected in water bodies up to 62 µg/L in drainage channels, posing a significant risk to aquatic ecosystems and human health due to their persistence and mobility [26, 33]. In addition to their dissolved form, pesticides can also be transported through the particulate phase, potentially prolonging the duration of contamination in aquatic environments[34]. Despite the increasing interest in biodegradable molluscicides alternatives, their application is still limited by cost and effectiveness constraints, reflecting the ongoing challenge of balancing agricultural productivity with environmental protection.

The runoff process is strongly influenced by a variety of environmental and technical factors, including rainfall intensity, land slope, soil characteristics and irrigation application methods and practices, which together determine the magnitude of molluscicidess mobilization and transport from farmland to aquatic systems. In agricultural landscapes such as rice fields, the use of molluscicides to control snail pests can be quickly mobilized and carried into irrigation canals and ponds, especially in tropical

regions with high rainfall, accelerating the entry of pesticides into freshwater ecosystems. High-intensity rainfall events are known to increase surface runoff and encourage the transport of pesticides, both in dissolved and particulate phases, where concentrations in sediments can be higher than in water columns [34]. In addition, steeper land slopes contribute to increased runoff volume, with sloped land up to 20% reported to produce substantial surface flow [35], while soil type and structure also determine the speed and efficiency of contaminant mobilization during rain. In terms of management, irrigation methods and controlled drainage systems have been proven to be able to suppress nutrient loss and runoff, thus potentially reducing pesticide transportation [36] and the use of more advanced hydrological models can help understand runoff dynamics in rice-based watersheds to support more effective management strategies [37]. Although runoff is often associated with negative impacts on the environment, some specific agricultural practices can also improve water retention and suppress the movement of pollutants, thus confirming the importance of a management approach that balances agricultural productivity and ecosystem protection.

In addition to runoff, leaching is another important pathway, especially for high-mobility compounds such as metaldehyde. Through leaching, molluscs can infiltrate the soil layer and contaminate the groundwater system, which can later be discharged into the surface waters. This pathway is particularly relevant in areas with permeable soils and intensive pesticide use [32].

Spray deviations also contribute to contamination, especially when molluscs are applied near water bodies. Niclosamide droplets are carried by the wind and deposited directly into the aquatic system, even when application occurs from a distance. These pathways can contribute significantly to contamination in water bodies and aquaculture ponds [2, 38].

Direct application of molluscicides to water bodies to control snail populations can lead to direct exposure to non-target organisms, including fish and plankton, potentially causing ecological imbalances and biodiversity declines [39]. After entering the aquatic system, the molluscicidess will be distributed between the water column and the sediment according to their physicochemical properties; hydrophobic Compounds tend to be adsorbed to suspended particles and accumulate in sediments, which can then act as a long-term source of contamination as they can potentially be remobilized through water flow or activity [40].

The fate and transport of molluscicides in the aquatic environment is also greatly influenced by environmental factors such as temperature, pH [29] and organic matter content. Higher temperatures can accelerate degradation [32], while organic matter increases adsorption and decreases bioavailability [41]. This response varies spatially and temporally depending on local conditions. In addition, hydrological connectivity between farmland and aquaculture systems increases the risk of contamination, as many aquaculture systems rely on water sources that are directly connected to irrigation, thus allowing for chronic exposure to low levels that have the potential to cause toxic effects on aquaculture [22].

On the other hand, the contribution of contamination can also come from urban and domestic waste, especially in areas that use molluscicides in public health programs, where inadequate waste management can increase the accumulation of residues in waters [42, 43]. Overall, these pathways show that molluscicidess contamination in freshwater ecosystems is a complex process and is influenced by the interaction of environmental, chemical and human activity factors, so a comprehensive understanding is needed to design effective mitigation strategies and risk assessment frameworks, particularly in areas with close links between agriculture and aquaculture [2, 44].

The Impact of Ecotoxicology on Fish

Molluscicides exert a significant ecotoxicological impact on freshwater fish due to their non-selective nature in the aquatic environment. Although designed to target mollusks, their biochemical mechanisms also affect basic cellular processes in non-target organisms, including fish. As a result, exposure to molluscicides can trigger disturbances at various levels of biological organization, ranging from physiological to biochemical to molecular. Physiologically, exposure to compounds such as fipronil and flupyradifurone causes anemia and oxygen transport disorders due to decreased erythrocyte counts and hemoglobin levels [45, 46]. In addition, impaired respiratory function and osmoregulation also occur, especially through damage to the gills as the main organ of gas exchange. For example, exposure to endosulfan causes edema, hyperplasia and necrosis of the tilapia gill, leading to hypoxia [47].

At the biochemical and molecular level, molluscicides disrupt metabolism and trigger significant oxidative stress. Changes in protein metabolism and increased free amino acids have been reported as a result of exposure to phenoxaprop-P-ethyl, accompanied by proteomic changes in

brain tissue that affect nerve function [48, 49]. Oxidative stress occurs through increased production of reactive oxygen species (ROS), both from endogenous and exogenous sources, which then leads to lipid peroxidation, protein damage and DNA degradation [50]. The response to this condition is indicated by changes in the activity of antioxidant enzymes such as SOD, CAT and GPx [51]. At a deeper molecular level, exposure to molluscicidess also induces changes in gene expression associated with detoxification, stress and the immune system, as well as disrupting the pathways of energy metabolism, inflammation and apoptosis [52, 53, 54].

Acute exposure to molluscicides can cause rapid death in fish, usually using LC_{50} values. Acute toxicity is often associated with respiratory distress, loss of balance and impaired ion regulation. Like Niclosamide, it shows high acute toxicity in some freshwater fish species. These effects are mainly related to disruption of cellular respiration and energy metabolism, primarily through inhibition of mitochondrial oxidative phosphorylation [36].

Chronic impacts on sublethal concentrations are a major concern in the context of ecology and aquaculture. Long-term exposure has been shown to interfere with growth, decrease reproductive capacity and alter the development process of fish, resulting in decreased productivity and population stability. Studies show that exposure to cypermethrin lowers the number of red blood cells and hemoglobin in *Oreochromis niloticus* [55], while heavy metals such as lead and cadmium cause biochemical and hematologic changes that impact reproduction and growth [56]. In addition, CuO nanoparticles are also known to trigger oxidative stress and genetic damage in Labeo rohita [57].

Histopathological changes are another important indicator of the impact of ecotoxicology on fish. Structural damage has been observed in vital organs such as the gills, liver and kidneys. In the gills, exposure to various contaminants causes lamellar fusion, necrosis, hypertrophy and epithelial degeneration [16,58,59]. Meanwhile, hepatocyte degeneration and necrosis occur in the liver due to exposure to paraquat and thiamethoxam [58, 60] and in the kidneys, tubular degeneration and interstitial inflammation were found [16, 59]. This damage directly interferes with important physiological functions and worsens the health condition of the fish.

In addition, behavioral changes are an early indicator of toxic exposure that is highly relevant in aquaculture systems. Exposed fish exhibit abnormal swimming patterns, decreased appetite, increased mucus secretion and

lethargic conditions, which ultimately lead to decreased growth and feed efficiency. These impacts are reinforced by the finding that toxic exposure decreases growth rates and feed conversion ratios in species such as *Clarias gariepinus* and *Labeo rohita*, as well as increases mortality rates as toxin concentrations increase [13, 61, 62].

Another concern is the potential for molluscicidess bioaccumulation in fish tissue. Lipophilic compounds such as PBDE and deltametrin can accumulate in fat tissue, especially in the liver and muscles, with varying concentration distributions between organs [63, 64, 65]. This accumulation not only impacts fish health but also poses a risk to humans as consumers, especially in regions that rely on aquaculture as a primary source of protein.

Overall, the impact of molluscicidess ecotoxicology on fish is complex and occurs at multiple levels, ranging from physiological disorders to profound molecular changes. This effect not only increases the risk of acute mortality but also causes chronic disruptions that can decrease aquaculture productivity and threaten the stability of aquatic ecosystems. Therefore, a thorough understanding of these toxicity mechanisms is crucial in the development of environmental management strategies and sustainable aquaculture practices [22].

Molluscicides Ecotoxicity in Freshwater Fish

Molluscicides exert a significant ecotoxicological impact on freshwater fish due to their non-selective nature in the aquatic environment. Although designed to target mollusks, these compounds also affect basic cellular processes in non-target organisms, including fish, thereby exerting toxic effects at the physiological, biochemical and molecular levels. Physiologically, exposure to molluscicides such as fipronil and flupyradifurone causes anemia and oxygen transport disorders due to decreased erythrocyte counts and hemoglobin levels. A decrease in dose-dependent hematological parameters was also observed in *Cyprinus carpio*, even at sublethal concentrations [46]. In addition, acute exposure to molluscicides can cause rapid death measured by LC_{50} values, with symptoms such as respiratory disturbances, loss of balance and ion regulation dysfunction. Compounds such as niclosamide exhibit high acute toxicity through inhibition of mitochondrial oxidative phosphorylation that interferes with energy metabolism.

At the biochemical and molecular level, molluscicides disrupt metabolism and oxidative balance. Exposure to compounds such as fenoxaprop-P-ethyl and triclosan causes changes in protein metabolism, increased protease activity, as well as changes in amino acid profiles; In addition, there is an increase in oxidative stress characterized by the production of reactive oxygen species (ROS) and changes in the activity of antioxidant enzymes such as SOD, CAT and GPx [66, 68]. The mechanism of toxicity also involves inhibition of cholinesterase activity that causes neurotoxic effects, as well as disruption of detoxifying enzyme systems such as cytochrome P450, which indicates the presence of metabolic stress [69].

Chronic exposure to molluscicides at sublethal concentrations is a major concern in aquaculture systems because long-term exposure can interfere with fish growth, reproduction and development. Studies show that exposure to pollutants such as silver nanoparticles (Ag-NP) and cypermethrin significantly decreases growth rates in *Poecilia sphenops* and *Oreochromis niloticus* [70, 55] Additionally, chronic exposure can decrease reproductive success, including decreased fertilization rates and increased embryo malformations due to exposure to pentachlorophenol [71] Developmental disorders are also seen in the embryonic and larval phases, as well as physiological changes due to exposure to substances such as clothianidin that affect metabolism and nerve function [72]

Histopathological effects are an important indicator of the impact of molluscicidess ecotoxicology. Structural damage to vital organs such as the gills, liver and kidneys is frequently reported, which directly impacts respiration, detoxification and osmoregulatory functions. In gills, changes include lamellar fusion, epithelial necrosis and hyperplasia due to exposure to various contaminants such as ammonia and methylparaben [73, 74, 75, 76]. Meanwhile, the liver exhibits necrosis and inflammation of cells that interfere with the detoxification process and the kidneys undergo tubular damage that affects the ionic balance [58, 73, 74].

Behavioral changes are an early indicator of toxic exposure that is particularly relevant in the context of aquaculture. Exposed fish showed uncoordinated swimming patterns, hyperactivity followed by hypoactivity, increased mucus secretion and decreased feeding activity [13, 69]. This impact contributes to decreased feed efficiency and growth, as seen in atrazine exposure, which decreases feed conversion rates [62]. Overall, these behavioral changes can decrease the survival rate of fish in aquaculture systems.

In addition, sensitivity to molluscicides varies between fish species. *Oreochromis niloticus* is comparatively more tolerant than *Cyprinus carpio*, which is more sensitive and is often used as a model organism in toxicology studies. Nevertheless, even more tolerant species can still experience significant sublethal effects from long-term exposure. This variation in response was also seen in tilapia species such as *Oreochromis mossambicus* and *Oreochromis niloticus*, which showed differences in physiological and behavioral responses to exposure to pesticides such as deltamethrin and dichlorvos [13, 69]. Overall, the impact of molluscicidess ecotoxicology on fish is complex and multi-level, encompassing acute to chronic effects that affect individual health, aquaculture productivity and aquatic ecosystem stability. Therefore, an in-depth understanding of the mechanisms of fish toxicity and biological responses is critical to support environmental management and sustainable aquaculture practices.

Sublethal and Molecular Responses

Exposure to molluscicides at sublethal concentrations often does not cause immediate acute effects, but has a significant impact on fish health in the long term. At the molecular level, compounds such as niclosamide are known to interfere with the expression of genes that play a role in energy metabolism, the immune system and cellular stress response. Chronic exposure can also trigger changes in transcription pathways that regulate detoxification processes, including genes encoding cytochrome P450 enzymes and *heat shock proteins*, which play an important role in maintaining cellular homeostasis [48,77].

In addition, metabolic disorders are one of the main consequences of molluscicidess exposure. Studies show that compounds such as thiram and diethylstilbestrol can cause significant changes to metabolic pathways, thereby affecting the overall energy synthesis, growth and reproduction of fish [77, 78]. These changes indicate that sublethal effects are not only physiological, but also integrated down to the biochemical and molecular levels.

The development of *omics* approaches, such as transcriptomics, proteomics and metabolomics, has provided a more comprehensive understanding of the mechanisms of molluscicides toxicity. Transcriptomic analysis showed that niclosamide exposure can disrupt lipid and energy metabolic pathways as well as activate inflammatory responses, as reported in zebrafish studies [79]. Meanwhile, proteomics studies reveal changes in

proteins associated with cellular homeostasis and antioxidant defense systems, reflecting the organism's stress response to toxic exposure [80].

Molecular biomarkers then emerged as an important tool in detecting the initial impact of molluscicides exposure. Increased expression of genes associated with oxidative stress, such as *sod*, *paint* and *gpx*, as well as inflammatory genes such as *tnf-α* and *il-1β*, has been identified as a sensitive indicator of contaminant exposure [17, 81]. This response reflects the occurrence of cell damage and activation of the biological defense system, even before the emergence of disturbances at the organism level.

In the context of aquaculture, the use of these biomarkers is very important for early detection of molluscicide exposure. This approach allows managers to identify potential risks before they develop into more serious ecological impacts, thereby supporting more sustainable aquaculture practices [3, 82]. This early detection is crucial, especially in intensive systems that are susceptible to the accumulation of environmental stress.

On the other hand, disturbances in the fish's immune system are also a major concern due to exposure to molluscicides. Decreased non-specific immune responses, such as phagocytic activity and production of antibodies, may increase the susceptibility of fish to pathogenic infections. This condition is further exacerbated in high-density aquaculture systems, where environmental pressure is already quite large.

As a mitigation effort, the use of immunostimulants and immunomodulators began to be widely developed. Natural extracts such as *Gracilaria verrucosa have* been shown to enhance the non-specific immune response of fish and increase resistance to bacterial infections such as *Aeromonas hydrophila* [83]. In addition, immunomodulators also play a role in reducing the impact of environmental stress and improving overall fish health in aquaculture systems [84].

Impact on the Aquaculture System

Molluscicides pollution in aquaculture systems has a direct impact on decreased productivity, especially through the accumulation of sublethal effects that are not always accompanied by mass mortality. Growth disturbances, decreased feed efficiency and increased susceptibility to diseases collectively reduce fish production performance in the long term [22]. These conditions suggest that chronic exposure, although not lethal directly, still has significant consequences for the success of aquaculture.

In addition, the presence of molluscicide residues can interfere with water quality in the aquaculture system. These compounds affect microbial and plankton communities that play an important role in maintaining the balance of aquatic ecosystems. Disruption of microbial biofilms can inhibit nutrient cycling processes, including the degradation of organic matter as well as the conversion of ammonia and nitrogen, thereby increasing toxicity in water [85]. These changes then have an impact on fluctuations in water quality parameters such as dissolved oxygen and ammonia, which are crucial for survival rate [15, 86].

On the other hand, the bioaccumulation of molluscicides in fish tissues is an important issue in modern aquaculture systems. Compounds such as niclosamide are known to accumulate in the liver and muscle tissue of fish, which not only impacts the health of the organism but also poses a risk to human consumers [5]. The persistence of pesticides in aquatic environments magnifies the potential for biomagnification in the food chain, which can lead to further toxic effects such as oxidative stress and neuroendocrine disorders [15]. In fact, some studies show that certain compounds have carcinogenic potential, further raising concerns about food safety [87].

The implications of this contamination also extend to the competitiveness aspect of aquaculture products in the global market. The presence of harmful chemical residues in fishery products can lower consumer confidence and lead to market rejection, especially in export markets with strict food safety standards [88, 89]. This makes the issue of molluscicides pollution not only an environmental problem, but also a strategic challenge for the aquaculture industry.

From an economic perspective, the impact of pesticide pollution is very real in increasing production costs. Exposure to molluscicides can trigger physiological stress and reduce the survival rate of fish, especially in the juvenile phase, thus having a direct impact on crop yields and profitability [15]. In addition, the need for more intensive disease management, including the use of drugs and antibiotics, increases the operational burden for cultivators [73, 90]. The combination of declining productivity, increased costs and the risk of market rejection confirms that molluscicides pollution is a serious threat to the sustainability of the overall aquaculture system.

Environmental Risk Assessment and Threshold

Risk assessment of molluscicides in aquatic ecosystems is a crucial step to understand and manage their environmental impacts, especially in

aquaculture systems. This process generally includes three main components, namely *hazard identification*, *exposure assessment* and *risk characterization*, which are used to evaluate the level of hazard and the probability of exposure to cultivated organisms. The results of the risk characterization suggest that some pesticides, such as triadimephone, may be categorized as low-risk under certain conditions, but the potential long-term ecological impact remains a concern. In contrast, in certain scenarios, especially in the worst-case conditions, compounds such as OPPS may exhibit a higher level of risk [29, 91].

In practice, risk assessment relies heavily on key toxicity parameters such as LC_{50} (*Lethal Concentration 50%),* NOEC (*No Observed Effect Concentration*) and LOEC (*Lowest Observed Effect Concentration*), which are used to determine safe thresholds in aquatic environments. For example, a study on mercury chloride showed a 96-hour LC_{50} value of 0.07 mg/L in fish larvae, with a NOEC of 0.01 mg/L and a LOEC of 0.05 mg/L [92]. However, studies have confirmed that sublethal effects can occur at concentrations much lower than LC_{50} values, making biomarker-based approaches and *omics* technology increasingly important in detecting early impacts that are not identified through conventional parameters.

In terms of regulation, the management of molluscicides use shows variation between countries, especially in the determination of *maximum residue limits* (MRLs) on fishery products. Developed countries generally have stricter regulatory frameworks, while in many developing countries, policy implementation still faces obstacles, such as limited monitoring and supervision systems [22]. This condition has the potential to increase the risk of chronic exposure to aquatic organisms as well as the accumulation of residues in the food chain.

Traditional approaches in *risk assessment* often do not fully consider multi-pollutant exposure and complex interactions between chemical compounds. Under real environmental conditions, aquatic organisms are generally exposed to a mixture of various contaminants that can produce synergistic as well as antagonistic effects. For example, the combination of zinc oxide nanoparticles with chlorhexidine can exhibit a toxic response that varies depending on the concentration and ratio of the mixture [93]. Interactions between cadmium and certain agrochemicals have also been reported to synergistically increase toxicity, including increased mortality in zebrafish larvae [94]. In addition, pesticide mixtures such as imidacloprid, acetochlor and

tebuconazole have been shown to cause significant reproductive toxicity through endocrine system disruptions, which in some cases are more severe than exposure to single compounds [95]. These findings confirm the need to develop a more integrative and realistic risk assessment approach in dealing with the complexity of exposure in aquatic environments.

Mitigation and Management Strategy

Efforts to mitigate the impact of molluscicides in aquaculture require a comprehensive approach that integrates technological, ecological and policy aspects. One of the main strategies being developed is the use of plant-based biopesticides as an environmentally friendly alternative. Natural compounds such as saponins and various plant extracts are known to have lower toxicity to non-target organisms and are biodegradable, making them safer for aquatic ecosystems [96]. In addition, these biopesticides are relatively more economical and have a diverse mechanism of action due to their complex phytochemical content [97]. However, the main challenges still lie in the stability of formulations, consistency of effectiveness and low adoption rates due to limited comprehensive scientific data [97, 98].

In addition to chemical substitution, reducing pesticide runoff into water bodies is an important step in pollution mitigation. The implementation *of Best Management Practices* (BMP), such as the establishment of vegetative buffer zones, drainage system management and adjustment of pesticide application time, has proven effective in suppressing the entry of pollutants into waters. Vegetative zones, for example, are able to hold up to 73–98% of fungicide residues during runoff events [99] while drainage management practices can significantly reduce sediment and nutrient loads [100]. Proper application scheduling also plays a role in minimizing the risk of contamination, especially during high rainfall [101].

On the other hand, the application of water treatment technology makes a great contribution to improving the quality of the aquaculture environment. Systems such as biofilters, *constructed wetlands* and phytoremediation take advantage of the role of aquatic plants and microorganisms in absorbing and degrading harmful chemical compounds. This technology is effective in lowering the concentration of pesticide residues and supporting natural purification processes in aquatic systems [38, 102]. However, its implementation requires careful planning and a significant investment of resources.

An ecosystem-based approach is also an important strategy in sustainable management, for example, through the use of natural predators or habitat manipulation to control pest populations without chemicals. This strategy not only reduces dependence on molluscicides but also maintains long-term ecological balance. In the context of management, strengthening monitoring and regulatory systems is needed, including the use of biomarkers and *omics* technology for early detection and proactive risk management, which needs to be supported by education and capacity building of cultivators [22].

However, there is still a significant knowledge gap, especially regarding long-term, multigenerational and complex multi-pollutant interactions. Therefore, the integration of multi-omics approaches such as genomics, transcriptomics and proteomics with the study of ecology and physiology becomes very important. This approach allows for a more in-depth identification of toxicity mechanisms as well as an understanding of the organism's adaptive response to environmental stress [103]. Other studies have also shown that long-term exposure to pollutants, such as microplastics and PFAS, can trigger physiological and behavioral changes across generations, further underscoring the importance of a holistic approach in sustainable aquaculture management [104, 105].

Conclusion

Molluscicides pollution in freshwater systems is a complex issue that has far-reaching implications for aquaculture sustainability. Different types of molluscicides with different physicochemical characteristics show potential for persistence and bioaccumulation in the environment, as well as entering ecosystems through various contamination pathways such as agricultural runoff and aquaculture activities. Its ecotoxicological impact on fish is not only acute, but also chronic, including physiological, growth and reproduction, as well as changes at the molecular level.

Sublethal and molecular responses, including changes in gene expression, oxidative stress and metabolic disorders, suggest that molluscicide effects can occur at low concentrations and in the long term. These impacts then accumulate in aquaculture systems through decreased productivity, water quality disturbances, changes in microbial communities and bioaccumulation risks that have an impact on food safety and product competitiveness. Environmental risk assessments are important in determining safe thresholds, although conventional approaches are often not able to capture the complexity of multi-pollutant exposures and synergistic effects in the environment.

The implications for aquaculture sustainability demand a balance between pest control and ecosystem protection. The decline in biodiversity and ecosystem stability due to pollution further emphasizes the need for an ecosystem-based approach in aquaculture management. Therefore, an effective mitigation strategy must integrate the use of environmentally friendly alternatives, the implementation of *Best Management Practices*, water treatment technology and ecology-based innovations.

Strengthening regulations, monitoring and the use of *omics* technology are key to early detection and adaptive risk management. Going forward, the integration of multidisciplinary approaches that include ecological, physiological and molecular aspects is needed to address knowledge gaps, especially related to long-term effects and multi-pollutant interactions. Thus, more prudent and science-based management of molluscicides is the main foundation in supporting sustainable, resilient and safe aquaculture for the environment and human health.

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4
CHAPTER

Rice-Fish Farming As a Sustainable Aquaculture System: Ecological Functions, Nutrient Dynamics and Technological Perspectives

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Abstract

Rice-fish farming is a traditional integrated agro-aquaculture system that has gained renewed attention as a model for sustainable food production. By combining rice cultivation and fish farming within the same production unit, this system enhances resource-use efficiency, promotes ecological balance and improves farmers' livelihoods. This chapter examines the ecological principles underlying rice-fish systems, with particular emphasis on natural feed dynamics and nutrient cycling. A field case study conducted in Cianjur,

Indonesia, demonstrates that nutrient enrichment strategies can significantly enhance natural feed availability, leading to improved fish growth (0.13 g/day) and survival (66%). The study highlights the importance of ecosystem-based management in optimizing system productivity. Furthermore, the integration of low-cost monitoring technologies is discussed as a future pathway for enhancing system resilience and management efficiency. Rice-fish farming is therefore positioned as a viable and scalable model for sustainable aquaculture development.

Keywords: Rice-fish farming; Sustainable aquaculture; Natural feed; Nutrient cycling; Ecological intensification.

Introduction

Aquaculture has become one of the fastest growing food production sectors globally and plays an essential role in supplying animal protein [1]. However, the rapid expansion of aquaculture has also raised concerns regarding environmental sustainability, including water pollution, high resource consumption and dependence on artificial feed and chemical inputs. These issues have driven the search for more sustainable and integrated production systems that balance productivity with environmental conservation. One such approach is integrated agro-aquaculture, which combines agricultural and aquaculture practices within a single system to optimize resource use and enhance ecological efficiency. Among these systems, rice-fish farming integrates fish culture within rice fields, allowing synergistic interactions between aquatic and terrestrial components [2,3]. This system represents a nature-based solution that has been practiced for centuries.

Rice-fish farming is an ancient practice that has evolved into a dynamic and adaptive system across different regions and cultures. In countries such as China, Indonesia, Vietnam and Bangladesh, rice-fish systems have long been recognized for their ability to increase productivity while maintaining ecological balance. In Indonesia, this integrated farming method is known as *minapadi*. Historical evidence suggests that rice-fish farming has been practiced in West Java since the 9th century [2]. The system continues to develop through traditional farming practices that prioritize natural ecological processes rather than external inputs.

The ecological foundation of rice-fish farming lies in the interactions among fish, rice plants and aquatic organisms within the paddy field ecosystem. Fish contribute to nutrient recycling through waste excretion and

stirring up sediment, while also helping to control pests and weeds. At the same time, rice plants provide shelter, regulate microclimatic conditions and support the development of natural food webs [4]. These interactions create a self-sustaining system that enhances both rice and fish production. However, the performance of rice-fish systems is influenced by various environmental and management factors, including water quality, nutrient availability, field design and natural feed productivity [5]. In many traditional systems, inadequate management of these factors can limit fish growth and survival, thereby reducing the overall benefits of integration. Therefore, improving the ecological performance of rice-fish systems, particularly through enhanced nutrient cycling and natural feed availability, is essential for maximizing system productivity.

Recent studies have increasingly emphasized the role of natural feed organisms, such as phytoplankton, zooplankton and benthic fauna, in supporting fish growth within integrated farming systems. The abundance of these organisms is closely linked to nutrient dynamics, particularly the balance of nitrogen, phosphorus and other essential elements [6]. However, practical approaches to enhance natural feed productivity under field conditions are still needed, especially for small-scale farming operations. In addition, the development of modern aquaculture technologies offers new opportunities to improve the management of traditional rice-fish farming systems. The integration of low-cost monitoring tools and ecosystem-based management strategies can enhance system resilience, improve decision-making and support sustainable intensification.

This chapter aims to explore rice-fish farming as a sustainable aquaculture system, with particular emphasis on ecological interactions, natural feed dynamics and nutrient cycling. Furthermore, the chapter discusses how management strategies can enhance natural feed productivity and improve fish performance. Finally, the chapter addresses future perspectives, including the integration of technological innovations and the role of rice-fish farming within larger sustainable food systems.

Historical Development of Rice-fish Farming

Rice-fish farming is considered one of the world's oldest integrated agro-aquaculture systems [7]. This practice has gradually evolved over centuries, particularly in regions where rice cultivation dominates agricultural landscapes across Asia [7]. The system is widely recognized as a form of traditional ecological knowledge in which agriculture and aquaculture interact

in a mutually beneficial manner. The earliest documented rice-fish farming practices originated in China more than 2,000 years ago, where fish were intentionally placed into rice fields to improve productivity and provide an additional food source. Over time, the practice spread to other parts of Asia, including Southeast Asia, South Asia and East Asia, adapting to local environmental, cultural and farming conditions. According to Mohanty et al. (2008), rice-fish systems have been implemented across several continents, including Asia, Africa, Europe and the Americas, demonstrating their adaptability and global relevance [3]. In Indonesia, rice-fish farming has a long history and is believed to have been practiced before the 9th century [2,8]. The system became more widely recognized during the colonial and post-independence periods. In particular, farmers in Java and West Java integrated fish culture into irrigated rice fields. The development of padi-fish farming was closely linked to traditional farming practices. In these practices, farmers relied on natural ecological processes rather than external inputs. This made the system both economically accessible and environmentally sustainable.

During the middle of the 20th century, rice-fish farming declined in many regions due to the intensification of rice monoculture associated with the Green Revolution. The increased use of chemical fertilizers and pesticides reduced the compatibility between rice cultivation and fish survival. However, starting the late 20th century, interest in integrated farming systems has re-emerged, driven by growing concerns regarding environmental degradation, sustainability and food security. Several countries, including China, Vietnam, Bangladesh and Indonesia, have reintroduced and modernized rice-fish systems through research and development programs. In China, rice-fish farming has been designated by the Food and Agriculture Organization (FAO) as a Globally Important Agricultural Heritage System (GIAHS), highlighting its ecological, cultural and economic importance [9]. Similarly, integrated rice-fish systems have been promoted in Southeast Asia as climate-resilient farming practices that enhance biodiversity and reduce dependence on agrochemicals. In recent decades, the concept of rice-fish farming has evolved beyond traditional practices into more diversified and technology-supported systems. Innovations such as improved field design, nutrient management strategies and water quality monitoring technologies have contributed to enhancing productivity and system resilience. At the same time, the core ecological principles of rice-fish farming remain essential to its sustainability, including nutrient cycling, natural feed utilization and biological interactions.

Overall, the historical development of rice-fish farming shows a transition from traditional ecological practices to modern sustainable aquaculture systems. This evolution demonstrates the potential of rice-fish farming not only as a heritage farming system but also as a future oriented solution for sustainable food production.

System Types

Rice-fish farming systems can be classified into several types based on the temporal integration between rice cultivation and fish rearing. These classifications reflect different management approaches adapted to local environmental conditions, water availability and farmers' production objectives. In general, rice-fish systems are grouped according to the timing of fish culture relative to the rice cultivation cycle, including concurrent (co-culture), sequential (pre-planting) and rotational (post-harvest) systems [10]. Each system type has distinct ecological interactions and management characteristics, resulting in different implications for productivity and sustainability [11]. The suitability of each system depends on site-specific factors such as water management, climate and farming practices. Therefore, the selection of an appropriate rice-fish farming system should consider both ecological efficiency and socio-economic feasibility to ensure long-term sustainability.

The concurrent system refers to raising rice and fish together in the same field at the same time. In this system, fish are introduced shortly after rice transplanting and maintained during the early vegetative growth stage of the crop (Yamin et al., unpublished data). This arrangement promotes strong ecological interactions between rice plants and fish. Fish contribute to biological pest and weed control by consuming insects and unwanted aquatic vegetation, while fish excretion enhances nutrient availability for rice growth. In turn, rice plants provide shelter and help stabilize water temperature, creating a more favorable microhabitat for fish [7]. Due to these mutual ecological benefits, the concurrent system is considered the most ecologically integrated and widely practiced form of rice-fish farming.

In contrast, the sequential system involves fish culture before rice planting, typically during the fallow or land preparation period. Fish are reared in flooded fields prior to rice transplanting, allowing farmers to utilize idle land and water resources more efficiently [12]. This system is particularly suitable in areas with seasonal water availability, as it provides an additional source of income before the rice cultivation period begins. However,

ecological interactions between rice and fish are relatively limited because the two components occur at different times.

The rotational system is implemented after rice harvest, where fish are cultured in residual water remaining in the paddy fields. This system extends the productive use of agricultural land beyond the rice-growing season and can improve overall farm productivity. It is particularly suitable in regions with prolonged water retention or opportunities for secondary cropping. Although the rotational system does not directly benefit rice cultivation, it contributes to nutrient recycling through the utilization of residual organic matter and may improve soil fertility for subsequent planting cycles. The three main rice-fish farming system types, sequential (pre-planting), concurrent (co-culture) and rotational (post-harvest), are illustrated in Fig1.

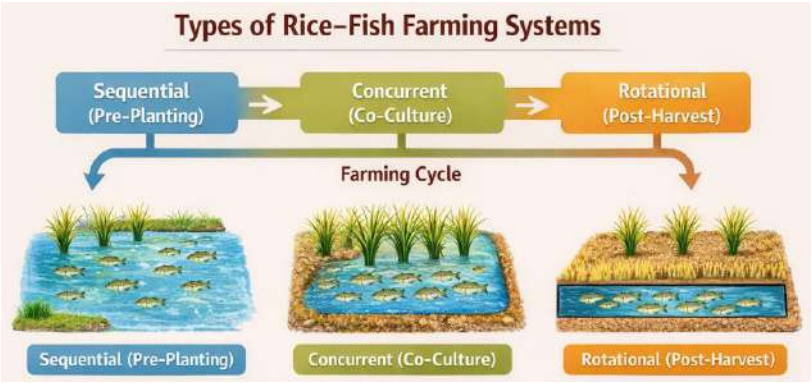

Fig 1: Major Types of Rice-fish Farming Systems Based on Temporal Integration Between Rice Cultivation and Fish Rearing

Ecological Interactions and Health Management

The sustainability of rice-fish farming systems depends on ecological interactions among rice plants, fish, aquatic organisms and the surrounding environment. Unlike conventional monoculture systems, rice-fish farming relies on natural biological processes that enhance productivity through ecosystem functions rather than high external inputs. Fish play important ecological roles within the system by preying on insect pests, larvae and weeds, thereby reducing the need for chemical pesticides and herbicides. In addition, fish contribute to nutrient cycling through excretion and stirring up sediment, which increase nutrient availability for rice plants and primary producers[13]. In turn, rice plants provide ecological benefits for fish by regulating microclimatic conditions within the paddy field. The rice canopy

reduces direct sunlight exposure and stabilizes water temperature, creating a more suitable habitat for fish, particularly in shallow water environments.

The system also encourages the formation of natural food webs consisting of phytoplankton, zooplankton and macrobenthic organisms, which provide as natural feed for fish. These biological interactions enhance ecological stability, reduce dependence on external feed inputs and contribute to overall system resilience. Ecological balance also plays an important role in fish health management. Stable environmental conditions and reduced chemical use can minimize stress and disease outbreaks in fish populations. Therefore, effective water management, ecological monitoring and the availability of refuge areas are essential components of sustainable rice-fish farming systems.

Overall, the combination of ecological interactions and health management strategies creates a synergistic production system that enhances productivity, environmental sustainability and resilience, making rice-fish farming a representative model of nature-based aquaculture (Fig. 2).

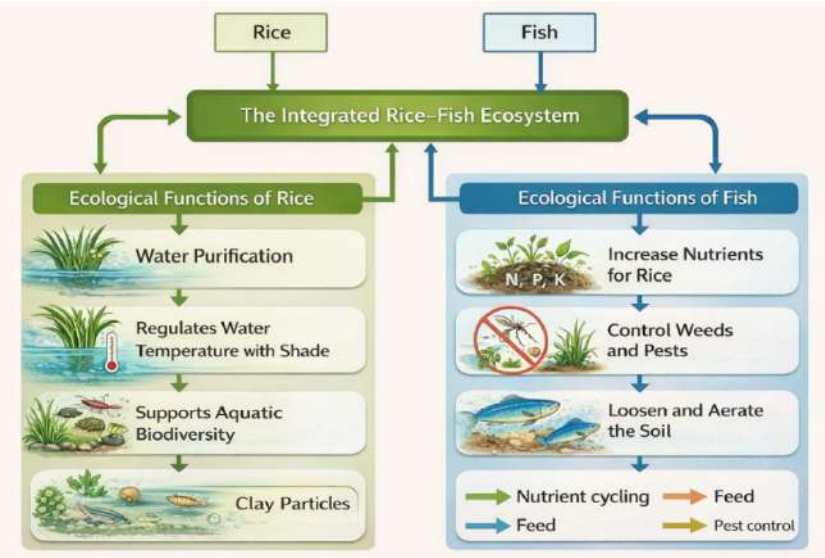

Fig 2: Conceptual illustration of ecological interactions in rice-fish farming systems. Fish contribute to nutrient cycling, pest control and soil disturbance, while rice plants provide shelter and environmental regulation. These interactions support natural food web development and ecological sustainability.

Role of Rice-fish farming in Sustainable Aquaculture

Rice-fish farming is widely recognized as a sustainable aquaculture model due to its ability to integrate ecological processes with agricultural production. The system embodies key sustainability principles, including efficient resource utilization, reduced dependence on external inputs, environmental conservation and socio-economic resilience. By integrating rice cultivation and fish farming within a single production unit, Rice-fish farming provides a multifunctional approach that aligns with global efforts toward sustainable food systems.

Resource Efficiency

One of the major advantages of rice-fish farming is its high efficiency in resource use. The system optimizes the utilization of land and water by producing two commodities, rice and fish, within the same area and production period. This dual production strategy allows farmers to increase productivity per unit area without requiring additional land expansion, which is particularly important in regions with limited land availability.

Water, as a critical resource for both rice cultivation and fish culture, is also utilized more efficiently in rice-fish farming systems. The same water body simultaneously supports rice growth and fish rearing, thereby reducing overall water consumption compared with separate production systems. In addition, the presence of fish contributes to water quality maintenance through biological processes such as nutrient recycling and sediment stirring, which further enhance overall system productivity.

Low External Input System

Rice-fish farming is characterized as a low external input system that relies primarily on natural ecological processes rather than synthetic inputs. A key component of this system is the availability of natural feed organisms, including phytoplankton, zooplankton and macrobenthos, which serve as the primary food sources for fish. These organisms naturally grow within the rice field ecosystem as a result of nutrient availability and favorable environmental conditions. Furthermore, the system takes advantage of internal nutrient cycling. Organic matter, fish waste and decomposing plant materials contribute to the continuous recycling of essential nutrients such as nitrogen and phosphorus. This internal nutrient flow reduces the need for synthetic fertilizers and external feed inputs, thereby lowering production costs and minimizing environmental impacts. As a result, rice-fish farming systems are

less dependent on commercial feed, pesticides and chemical fertilizers compared with conventional aquaculture and agricultural systems. This not only improves economic efficiency but also promotes environmentally sustainable farming practices.

Environmental Sustainability

Rice-fish farming plays an important role in environmental sustainability through a variety of ecological functions. One of its main advantages is the reduction in agrochemical use. The presence of fish helps control pests and weeds biologically, thereby reducing the need for chemical pesticides and herbicides that may damage aquatic ecosystems and pose risks to human health[13].

Furthermore, rice-fish systems promote biodiversity by providing habitats for various aquatic and terrestrial organisms, including plankton, benthic fauna, insects and microorganisms. This increased biodiversity enhances ecosystem stability and resilience, making the system more adaptable to environmental changes.

The integration of rice and fish farming also improves both soil and water quality. Nutrient recycling processes enhance soil fertility, while biological activities within the water column help maintain water quality[14]. Compared with intensive monoculture systems, rice-fish farming generally has a lower environmental footprint due to reduced chemical inputs and more efficient resource utilization.

Socio-Economic Benefits

In addition to its ecological advantages, rice–fish farming provides substantial socio-economic benefits for farming communities. One of the most immediate benefits is the additional income generated from fish harvesting, which may occur either before or simultaneously with rice harvest. Jirasinha et al. [15] reported that integrated rice–fish systems in the Ayeyarwady Delta, Myanmar generated net economic benefits approximately three times higher than those of rice monoculture systems. The system also contributes to risk diversification. By producing both rice and fish, farmers become less vulnerable to crop failure or market fluctuations affecting a single commodity. This diversification strengthens the resilience of farming households against economic and environmental uncertainties. Moreover, rice–fish farming supports rural livelihoods by creating employment opportunities and strengthening local value chains, including fish seed production, feed supply,

processing and marketing activities. The integration of aquaculture into traditional farming systems can therefore play an important role in poverty reduction and rural development.

Integration of Fish Culture with Non-Rice Crops

Integrated agro-aquaculture systems, commonly referred to as integrated agriculture–aquaculture (IAA) systems, have been developed using non-rice crops such as chili, tomato, water spinach and water lettuce. These systems apply the ecological principles of rice-fish farming into more diversified production models that are adapted to different environmental and agricultural conditions. Unlike traditional rice-fish farming systems, which depend on flooded rice fields, some non-rice crops systems are commonly implemented in semi-wet environments, shallow ponds, raised beds or controlled irrigation systems [16]. Similar to rice-fish farming, these integrated systems utilize nutrient exchange between fish and plants. Fish waste provides dissolved nutrients, particularly nitrogen and phosphorus, which can support plant growth, while plants improve water quality by absorbing these nutrients. Although the ecological interaction in these systems is generally less stable and less complex than in flooded rice-fish systems, non-rice crops-fish based integration offers greater flexibility and more diversification opportunities for small-scale farmers. Compared to aquaponics, non-rice crops-fish systems typically require lower technological input and operational costs, making them more accessible in rural areas.

Rice–fish farming, however, remains the most ecologically integrated and widely adopted system due to the strong natural compatibility between rice cultivation and fish production. Nevertheless, the development of non-rice crop–fish systems demonstrates the broader potential of integrated agro-aquaculture as a pathway toward diversified and sustainable food production systems. The evolution of integrated agro-aquaculture systems can be viewed as a continuum ranging from traditional ecological systems to highly controlled technological systems (Fig. 3). In addition to improving land-use efficiency and increasing economic returns, agro-aquaculture combinations can simultaneously enhance nutrient productivity and economic productivity, thereby promoting nutrition-sensitive agriculture (NSA) [17]. Beyond traditional rice or non-rice crop–fish co-culture systems, modern aquaculture-integrated agriculture systems (AIAS) increasingly emphasize water reuse, nutrient recycling and multi-purpose resource utilization [18].

Fig 3: Continuum of integrated agro-aquaculture systems from traditional ecological systems to technology-driven approaches. Rice-fish farming represents a nature-based system with strong ecological integration and low external inputs, while aquaponics represents a highly controlled and technology-intensive system

Natural Feed and Nutrient Cycling

A key component of sustainability in rice-fish farming systems is the availability of natural feed within the paddy ecosystem. Unlike intensive aquaculture systems that depend on manufactured feeds, rice-fish farming primarily relies on naturally occurring food organisms that develop through ecological processes within the field. These organisms include phytoplankton, zooplankton and macrobenthos, which together form the foundation of the aquatic food web.

Phytoplankton act as primary producers that convert inorganic nutrients into organic matter through photosynthesis. These microscopic algae support fish production either directly, when fish graze on them or indirectly through energy transfer to zooplankton. Zooplankton serve as an important intermediate link in the food chain by transferring energy from phytoplankton to fish larvae and juvenile fish. Meanwhile, macrobenthic organisms such as worms, mollusks and insect larvae inhabit the sediment layer and function as natural feed, particularly for fish that feed at the bottom. Together, these biological communities create a self-sustaining food web that reduces dependence on external feed inputs [6].

The productivity of natural feed organisms is closely associated with nutrient cycling processes within the rice-fish ecosystem. Nutrients come from soil organic matter, fertilizer application, decomposing plant material and fish excretion. Among the essential nutrients, nitrogen (N) plays an important role in stimulating phytoplankton growth and supporting primary productivity. Phosphorus (P), which is often a limiting nutrient in freshwater ecosystems,

strongly influences phytoplankton biomass and overall aquatic productivity. In addition, magnesium (Mg) contributes to chlorophyll formation and various enzymatic processes that support biological productivity.

Efficient nutrient cycling enhances primary productivity and trophic interactions within the ecosystem, ultimately improving fish growth and survival. This ecological efficiency is a defining characteristic of sustainable rice-fish farming systems, where nutrients and energy are continuously recycled within the production environment.

Field observations conducted in rice-fish farming areas in Cianjur, Indonesia, further demonstrated the importance of nutrient-driven natural feed dynamics. Nutrient enrichment strategies increased the abundance of phytoplankton communities, particularly *Chlorella* sp. and *Nitzschia* sp., as well as macrobenthic organisms such as *Viviparus* sp. These ecological changes contributed to improved natural food availability and were associated with enhanced fish growth and survival under low-input farming conditions.

However, the findings also emphasized the importance of balanced nutrient management. Excessive or unbalanced nutrient inputs may negatively affect water quality parameters, such as pH, indicating that ecological productivity must be supported by appropriate environmental management practices.

In summary, natural feed dynamics and nutrient cycling form the ecological foundation of rice-fish farming systems. By optimizing these processes, rice-fish farming can enhance fish productivity while maintaining environmental balance and reducing dependence on external inputs. This ecological approach reinforces the role of rice-fish farming as a sustainable and nature-based aquaculture system. Fig. 4 illustrates the interactions among nutrient cycling, natural feed productivity and ecological processes within rice-fish farming systems.

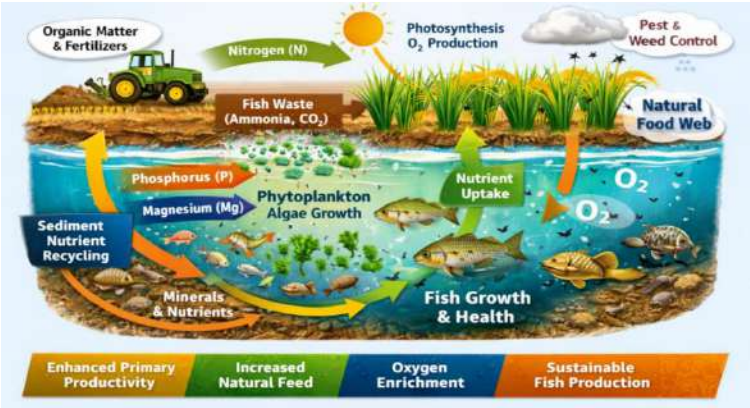

Fig 4: Conceptual diagram of nutrient cycling and natural feed dynamics in rice-fish farming systems. Nutrient inputs stimulate primary productivity and natural food web development, supporting fish growth and ecological sustainability.

Constraints and Challenges

Besides ecological and economic benefits, rice-fish farming systems still face several technical and environmental constraints that can limit their productivity and adoption. These issues are often site-specific but generally relate to water quality management, system design and ecological balance within the paddy field. Addressing these constraints is essential to ensure the long-term sustainability and scalability of rice-fish farming systems.

One of the major challenges in rice-fish farming is high temperature fluctuation, particularly in shallow water environments. Paddy fields usually have low water depth, often ranging from 5 to 15 cm, making them susceptible to rapid temperature changes. During periods of intense solar radiation, water temperature can rise significantly, sometimes exceeding optimal levels for fish growth. These elevated temperatures can increase metabolic stress in fish, reduce feed intake efficiency and in extreme cases, lead to mortality. Some studies report that in tropical paddy field, the temperatures can reach levels 33 – 40°C during midday[19], indicating the need for improved water depth management and shading strategies.

Another significant constraint is the occurrence of low dissolved oxygen (DO) levels, particularly during nighttime and early morning periods. In rice-fish systems, oxygen levels are influenced by biological processes such as respiration by plants, fish and microorganisms. At night, the absence of photosynthesis leads to oxygen depletion, creating poor conditions for fish.

Low DO levels may reduce fish growth, increase stress and elevate susceptibility to disease. This issue is often worsened in systems with high organic matter or dense biological communities.

The inadequate design of rice fields for fish shelter also poses a significant limitation. Traditional paddy fields are primarily designed for rice production and often lack structural features that support fish survival. In the absence of refuge areas, such as trenches or deeper zones (commonly known as refuge ponds), fish are exposed to environmental stress, including extremes temperature and predators. Proper field modification is therefore necessary to create microhabitats that provide shelter and help fish retention during water drainage or dry periods.

In addition, limited natural feed productivity can constrain fish growth, particularly in systems where nutrient availability is insufficient to support plankton and benthic organism development. Since rice-fish farming relies on natural food sources, inadequate nutrient levels may lead to poor food web structure and reduced fish performance. This highlights the importance of managing nutrient inputs to stimulate natural feed production without causing ecological imbalance.

Another important issue is the inappropriate use of agrochemicals, such as pesticides and herbicides. In conventional rice farming, chemical inputs are often applied to control pests and weeds. However, these substances can be toxic to fish and other aquatic organisms. Even low concentrations of certain chemicals can be toxic to aquatic ecosystems, reduce biodiversity and negatively affect fish health and survival. Therefore, careful management and reduction of agrochemical use are essential in rice-fish systems.

These constraints collectively highlight the need for improved system management and ecological optimization in rice-fish farming. Strategies such as better water management, enhanced field design, controlled nutrient inputs and environmentally friendly pest control methods are essential to overcome these issues. By addressing these limitations, rice-fish farming systems can be further developed into resilient and efficient models of sustainable aquaculture.

Ecological Enhancement in Rice-fish Farming

A field study conducted in Cianjur, Indonesia, demonstrated the importance of ecological management in improving natural feed productivity within rice-fish farming systems. The study evaluated nutrient enrichment

strategies under typical rice-fish farming conditions, where fish were reared without supplementary feeding to evaluate the role of naturally available food organisms. Nutrient enrichment increased the abundance of phytoplankton communities, particularly species such as *Chlorella* sp. and *Nitzschia* sp., as well as macrobenthic organisms such as *Viviparus* sp. These organisms formed a more productive natural food web that supported fish growth and survival. Fish reared under nutrient-enriched conditions achieved growth rates of approximately 0.13 g per day, with survival rates reaching 66% [20]. The findings indicate that well-balanced nutrient management can significantly improve ecological productivity in rice-fish systems by stimulating natural feed development and strengthening food web interactions. However, the study also highlights the importance of maintaining ecological balance, as excessive nutrient inputs may temporarily affect water quality parameters such as pH. Overall, the study demonstrates that ecosystem-based management and ecological intensification can enhance fish performance while reducing dependence on external commercial feed inputs. These findings reinforce the potential of rice-fish farming as a sustainable and low-input aquaculture system suitable for future integrated food production strategies.

Future Perspectives in Sustainable Aquaculture

Rice-fish farming offers significant potential as a model for future sustainable aquaculture systems, particularly in the context of increasing global demand for food, environmental conservation and climate resilience. As traditional practices are combined with modern innovations, Rice-fish farming can transform into a more productive, adaptive and technology-enhanced system without losing its ecological foundation.

Ecological Intensification

One of the key future directions for rice-fish farming is ecological intensification, which focuses on increasing productivity through the optimization of natural ecosystem functions rather than increasing external inputs. This approach emphasizes enhancing nutrient cycling, natural feed production and biodiversity within the system. Maintaining the balance of essential nutrients such as nitrogen, phosphorus and magnesium can significantly stimulate primary productivity and strengthen the natural food web. As demonstrated in field studies, nutrient management can enhance plankton and benthic organism development, ultimately leading to better fish growth and survival [14,20]. Ecological intensification also involves better management of water depth, vegetation cover and habitat structure to create a

more stable and productive environment. By refining these ecological processes, rice-fish farming systems can achieve higher yields while maintaining environmental sustainability.

Integration with Smart Aquaculture Technologies

The integration of modern technologies into traditional rice-fish systems offers a pathway for improving system efficiency and management. One of the most relevant innovations is the use of low-cost water quality monitoring systems, which enable real-time observation of key environmental parameters such as temperature, dissolved oxygen and pH. In conventional rice-fish farming systems, water quality fluctuations often undetected until they negatively impact fish performance. The use of sensor-based monitoring systems, connected to mobile devices or simple digital platforms, can deliver early warnings of unfavorable conditions, allowing farmers to respond quickly with corrective measures. For instance, detecting rising water temperatures or declining oxygen levels can trigger actions such as water exchange or shading adjustments. Furthermore, the development of integrated sensor platforms designed for small-scale farmers can bridge the gap between traditional practices and precision aquaculture. Such technologies need not to be complex or expensive; instead, they should be accessible, user-friendly and adaptable to rural farming conditions. The combination of ecological knowledge and digital monitoring can significantly improve their decision-making and overall system management.

Climate Resilience and Adaptation

Rice-fish farming systems possess some resilience to climate fluctuations due to their integrated and diversified nature. Producing both rice and fish within the same system reduces the risk associated with single-commodity farming. If one component is affected by environmental stress, the other may still provide economic returns. However, climate change brings new challenges, including increased temperature variability, shifting rainfall patterns and limited water availability. To address these issues, adaptive strategies are needed, such as enhancing water storage capacity, optimizing field design and selecting tolerant fish and rice varieties. Technological innovations, including environmental monitoring and predictive tools, can further enhance the adaptive capacity of rice-fish farming systems. By combining traditional ecological practices with modern technologies, farmers can better anticipate and respond to changing environmental conditions.

Policy Support and Integrated Sustainable Food Systems

To ensure rice fish farming plays a larger role in sustainable aquaculture, efforts must focus not only on technical improvements but also on institutional strengthening, policy support and long-term integration into sustainable food systems. The government has highlighted the importance of integrated agro-aquaculture systems, including rice-fish farming, as part of its national strategy for sustainable food production and rural development. With extensive agricultural land and considerable aquaculture potential, the government is ideally positioned to promote rice-fish farming as a scalable and eco-friendly production system. Government-supported initiatives have increasingly emphasized integrated farming approaches to improve food security, farmer income and environmental sustainability. These initiatives include demonstration plots, farmer training, technical assistance and support for better water and nutrient management practices. At the local level, extension services also play an important role in disseminating knowledge and encouraging the adoption of integrated farming systems.

Financial incentives and small-scale funding mechanisms can further promote the adoption of rice-fish farming system, particularly among smallholder farmers who often face constraints in accessing capital and technology. In recent years, there has also been growing interest in integrating modern technologies into traditional systems, including water quality monitoring tools, digital agriculture platforms and climate-smart farming approaches[21]. These initiatives reflect a transition toward combining traditional ecological knowledge with modern innovation to improve system efficiency and resilience.

Looking forward, rice-fish farming can be positioned as part of a broader transition toward integrated and sustainable food systems. Alongside systems such as aquaponics and recirculating aquaculture systems (RAS), rice-fish farming system offers a low-input, nature-based approach that is particularly suitable for rural and resource-limited areas. The combination of ecological principles, technological innovation and supportive policies can strengthen the rice-fish farming role in improving resource efficiency, reducing environmental impacts and supporting resilient food production systems ([22].

Ultimately, rice-fish farming is not only a traditional agricultural practice but also a future-oriented model for sustainable aquaculture development. By strengthening the synergy between agriculture, aquaculture, ecological management and technological innovation, rice-fish farming has potential to

support to long-term food security, environmental sustainability and rural livelihoods.

Conclusion

Rice-fish farming is a sustainable aquaculture system that effectively integrates agricultural and aquatic production through ecological processes. By combining rice cultivation and fish farming within a same field, its system enhances resource use efficiency, promotes biodiversity and provides both economic and environmental benefits.

The sustainability of this system is largely driven by natural interactions, including nutrient cycling and the development of natural food webs. The availability of natural feed, including phytoplankton, zooplankton and macrobenthos, plays a crucial role in supporting fish growth while reducing dependence on external inputs. As demonstrated in the same study, nutrient management can greatly boost natural feed availability, leading to better fish growth performance and survival rates.

Despite its advantages, rice-fish farming systems face several challenges, including water quality fluctuations, suboptimal field design and inappropriate agrochemical use. Addressing these constraints requires improved system management and the application of ecological intensification strategies.

The integration of traditional ecological knowledge with modern technological innovations, such as low-cost water quality monitoring systems, offers a promising pathway for enhancing the efficiency and resilience of rice-fish farming. With adequate support from research, policy and extension services, rice-fish farming system has significant potential to be expanded as a key component of sustainable aquaculture and integrated food production systems.

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CHAPTER

Innovations in Recirculating Aquaculture Systems (RAS) in Tropical Countries: Case Studies on Snakehead Fish (*Channa striata*)

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Abstract

Recirculating Aquaculture Systems (RAS) have emerged as a transformative technology for sustainable fish production in tropical regions, where environmental volatility and resource constraints pose significant challenges to conventional aquaculture. This chapter examines the application, challenges and innovations of RAS technology specifically for the culture of snakehead fish (*Channa striata*), a species of high nutritional, economic and cultural significance across Southeast and South Asia. Drawing upon empirical case studies from Indonesia, Malaysia, Vietnam, Bangladesh and India, the chapter explores how RAS mitigates common aquaculture challenges such as poor water quality, disease outbreaks, high feed costs and environmental degradation. It further analyses the biological and physiological requirements of *Channa striata* in closed-loop systems, including optimal water parameters, feeding regimes and stocking densities. The integration of complementary technologies such as biofloc, aquaponics and artificial intelligence-assisted monitoring is examined as strategies for enhancing system efficiency and economic viability. Key findings indicate that RAS adoption can increase snakehead production yields by 25-40%, reduce water consumption by up to 95% and significantly lower disease-associated mortality rates. Economic and policy considerations, including financial barriers, capacity building requirements and regulatory frameworks,

are also addressed. This chapter ultimately concludes that with appropriate technological adaptation, stakeholder support and knowledge transfer, RAS represents a viable and necessary pathway toward the sustainable intensification of snakehead aquaculture throughout the tropical world.

Keywords: Recirculating Aquaculture Systems (RAS), *Channa striata*, snakehead fish, tropical aquaculture, sustainable fish farming, water quality management**Introduction**

The global aquaculture sector has experienced unprecedented growth over the past three decades, now supplying more than half of the world's seafood consumption [1]. Within this expansion, tropical regions across Southeast Asia, South Asia and sub-Saharan Africa have emerged as dominant production centers, driven by favorable climates, high biodiversity and large labor forces. However, conventional aquaculture methods in these regions remain substantially constrained by unpredictable environmental conditions, limited freshwater availability, escalating disease burdens and mounting pressure from regulators and consumers demanding more environmentally responsible food production[2].

In this context, Recirculating Aquaculture Systems (RAS) represent a paradigm shift in fish farming technology. By filtering and reusing water within a closed loop, RAS minimizes water exchange, controls environmental parameters with precision and dramatically reduces the ecological footprint of intensive aquaculture [3]. RAS enables producers to regulate critical physicochemical parameters, such as temperature, dissolved oxygen, pH, ammonia, nitrite and nitrate levels, thereby ensuring consistently stable and optimal production conditions year-round, in contrast to conventional flow-through and pond-based systems that are largely influenced by environmental fluctuations. This level of control is especially advantageous in tropical climates, where monsoon seasons, flooding and drought can devastate outdoor production systems [4].

Among the species that stand to benefit most from RAS implementation is the striped snakehead, *Channa striata* (Bloch, 1793), a freshwater predator of immense cultural, culinary and medicinal significance. Widely consumed across Malaysia, Indonesia, Vietnam, Bangladesh, India and other parts of Asia, *C. striata* is prized for its firm texture, rich flavor and exceptional protein content [5]. Beyond gastronomy, the species carries substantial therapeutic value; clinical and ethnopharmacological studies confirm its efficacy in accelerating wound healing, tissue regeneration and post-surgical recovery,

attributable to its high concentrations of essential amino acids and bioactive compounds[6]. As a result, demand for *C. striata* continues to escalate in both domestic and international markets, generating significant economic opportunities for aquaculture producers.

Traditional pond-based farming of *Channa striata* faces significant operational and environmental challenges despite its considerable commercial potential. The species requires high-protein diets because of its carnivorous feeding behavior, thereby increasing feed costs, while open-water production systems facilitate pathogen intrusion and promote the rapid transmission of bacterial, parasitic and viral diseases under intensive stocking conditions. Moreover, effluent discharge from snakehead ponds contributes to eutrophication and biodiversity decline in adjacent aquatic ecosystems, resulting in increasing environmental concerns and regulatory oversight [7].

This chapter aims to provide a comprehensive, evidence-based examination of RAS technology as applied to *Channa striata* aquaculture in tropical countries. It presents a synthesis of published research, field case studies and practical management insights from key snakehead-producing nations and explores how emerging complementary technologies can further enhance RAS performance and sustainability. By addressing technical, economic and policy dimensions, this chapter seeks to offer actionable guidance for researchers, aquaculture practitioners, policymakers and investors engaged in the sustainable intensification of tropical freshwater aquaculture.

Biology and Significance of *Channa striata*

Taxonomic Profile and Ecological Characteristics

Channa striata (Bloch, 1793), commonly known as the striped snakehead or snakehead murrel, belongs to the family Channidae within the order Perciformes. The species is characterized by its elongated, cylindrical body, distinctly patterned with alternating dark stripes, a large mouth equipped with strong canine teeth and a labyrinthine suprabranchial organ that enables aerial respiration, allowing it to survive in hypoxic environments and even traverse terrestrial surfaces for short distances [5]. This remarkable physiological adaptability renders *Channa striata* uniquely suited for intensive aquaculture systems, including RAS, where dissolved oxygen levels can fluctuate.

Naturally distributed across South and Southeast Asia, *C. striata* inhabits a broad range of freshwater environments, from slow-moving rivers and

floodplain lakes to rice paddies and swamps. Its tolerance for poor water quality, wide temperature range (22-34 °C) and omnivorous-trending carnivorous feeding behavior make it a highly resilient species in culture settings [8]. However, despite this resilience, optimal growth performance, feed conversion ratios and product quality are achieved only when water quality parameters are consistently maintained within specific ranges, underpinning the value of RAS for commercial production.

1.1. Nutritional and Medicinal Value

The nutritional profile of *C. striata* is among the most impressive of any freshwater species. Proximate analysis consistently reports crude protein content exceeding 18-20% of fresh weight, with a favorable essential amino acid composition including lysine, methionine, leucine and threonine [9]. The fish also contains significant levels of omega-3 and omega-6 polyunsaturated fatty acids, supporting cardiovascular health and is rich in minerals including zinc, iron, calcium and phosphorus.

The therapeutic applications of snakehead fish have been documented across multiple Asian medical traditions. Contemporary scientific investigations have validated the efficacy of *C. striata* extract in accelerating post-operative wound healing and reducing systemic inflammation, mechanisms linked to elevated levels of arachidonic acid, albumin and globulin fractions [6]. These properties have contributed to the species' formal inclusion in clinical dietary protocols for surgical patients in several Southeast Asian nations, further elevating its premium market positioning.

1.2. Socioeconomic Importance

Snakehead farming constitutes a vital livelihood for thousands of small-scale and medium commercial farmers across Southeast Asia. In Indonesia, Vietnam, Bangladesh and Cambodia, *Channa* species collectively generate hundreds of millions of dollars in annual farm-gate value and support extensive downstream processing, marketing and export industries [10]. The growing demand for processed snakehead products including fillets, dried preparations and functional food extracts is creating new market opportunities, particularly in China, the Middle East and the European diaspora communities from South and Southeast Asia [11]. These economic realities underscore the urgency of developing more productive, reliable and sustainable farming systems.

Recirculating Aquaculture Systems: Principles and Components

Operational Principles of RAS

A Recirculating Aquaculture System is defined by its capacity to filter, treat and reuse a significant proportion (typically 90-99%) of its culture water within a closed or semi-closed circuit [3]. This fundamental characteristic distinguishes RAS from flow-through, pond and cage-based systems and confers several distinctive operational advantages. By recirculating water, RAS drastically reduces total water consumption, a critical consideration in water-scarce regions or areas subject to regulatory constraints on water extraction. The closed nature of the system also functions as a biosecurity barrier, preventing the ingress of wild pathogens and reducing the risk of escapee fish entering natural waterways.

The ability to precisely regulate water quality parameters represents perhaps the most transformative feature of RAS for tropical aquaculture. Sensors and automated control systems can maintain dissolved oxygen, temperature, pH, ammonia, nitrite and carbon dioxide at target values irrespective of external climatic conditions, enabling year-round production at stocking densities far exceeding those achievable in conventional systems [8]. For *C. striata*, which exhibits optimal growth at temperatures of 28-32°C and requires dissolved oxygen above 5 mg/L for sustained feeding activity, the precision control afforded by RAS is particularly beneficial.

Core Components of a Tropical RAS

A fully functional RAS for snakehead culture in tropical conditions typically incorporates the following core components:

- Culture Tanks: High-density polyethylene (HDPE) or fiberglass tanks ranging from 5 to 100 cubic meters, configured for optimal hydraulic circulation and waste concentration. Circular or oval tank designs promote consistent water flow and facilitate solids removal.
- Mechanical Filtration: Drum filters, settling chambers or swirl separators remove suspended solids including fecal matter, uneaten feed and biofloc aggregates from the water stream before biological treatment.
- Biological Filtration: Moving bed biofilm reactors (MBBRs) or fixed-medium biofilters host dense communities of nitrifying bacteria (Nitrosomonas and Nitrobacter spp.) that oxidize toxic ammonia to nitrite

and subsequently to relatively inert nitrate through sequential nitrification.

- Aeration and Oxygenation: Diffuser systems, venturi injectors or pure oxygen supplementation maintain dissolved oxygen at target levels, especially critical given the high metabolic oxygen demand of densely stocked carnivorous fish.
- CO_2 Stripping: Packed towers or cascade aeration units remove carbon dioxide accumulated from fish respiration, preventing respiratory acidosis and pH depression.
- UV Sterilization and Ozone Treatment: Ultraviolet lamps or ozone contactors reduce microbial loads, including pathogens, without introducing chemical residues incompatible with food safety standards.
- Monitoring and Control Systems: Inline sensors for dissolved oxygen, temperature, pH and conductivity, integrated with automated controllers and alert systems, enable real-time parameter management and early detection of system anomalies.

Water Quality Parameters for Channa striata in RAS

Table. 6 summarizes key water quality parameters, their optimal ranges, critical limits and management strategies required to maintain stable environmental conditions and support effective system performance for snakehead fish.

Table 6: Recommended water quality parameters for Channa striata culture in RAS, adapted from research by Li et al., Munguti et al. and Jalbani et al [10, 12, 16].

Parameter	Optimal Range	Critical Limit	Management Strategy
Temperature (°C)	28–32	< 22 or > 36	Heater/chiller units
Dissolved Oxygen (mg/L)	5.0–7.0	< 3.0	Diffuser + O_2 injection
pH	6.8–7.5	< 6.0 or > 8.5	Lime/CO_2 scrubber
Total Ammonia-N (mg/L)	< 0.5	> 1.0	Biofiltration optimization
Nitrite-N (mg/L)	< 0.1	> 0.5	MBBR, partial water exchange
Nitrate-N (mg/L)	< 50	> 150	Denitrification or water exchange
Carbon Dioxide (mg/L)	< 10	> 25	Degassing tower, cascade aeration

Turbidity (NTU)	< 20	> 50	Drum filter, settling chamber

Challenges in RAS-Based *Channa striata* Culture

Water Quality and Biological Filtration

Maintaining stable water quality within a high-density *C. striata* RAS presents continuous challenges rooted in the high metabolic rates of carnivorous fish. Snakehead fish produce substantial quantities of ammonia, a metabolic end-product of protein catabolism and the high-protein diets required for optimal growth exacerbate nitrogenous waste loading [12]. Water saturation in the culture media of *C. striata* without RAS occurred on the fourth day of culture at densities of 4 and 6 fish per liter, respectively where nitrites could not be converted to nitrate optimally[13]. Biological filtration through nitrification is the cornerstone of ammonia management in RAS; however, the nitrifying bacterial community is sensitive to temperature fluctuations, pH excursions and inhibitory compounds, making bioreactor stability a persistent technical challenge in tropical conditions where ambient temperatures may accelerate or disrupt bacterial metabolic rates.

In Indonesia, several early RAS demonstrations for snakehead culture encountered significant operational setbacks arising from insufficient biofilter capacity relative to fish biomass loading rates. Hematological parameters of snakehead reared in RAS, such as the red blood cell, white blood cell and blood glucose levels are influenced by stocking density [14]. These experiences highlight the critical importance of correctly sizing biofilter media surface area relative to projected fish biomass and feed input during the system design phase.

1.3. Disease Management in Closed Systems

Although RAS offers enhanced biosecurity compared to open pond systems, disease management in high-density closed recirculating environments presents its own distinctive challenges. The concentration of fish at elevated stocking densities can induce chronic physiological stress, suppressing immune function and increasing susceptibility to opportunistic pathogens[15]. *Channa striata* in RAS have been found vulnerable to bacterial infections including *Aeromonas hydrophila* and *Edwardsiella tarda*, as well as parasitic infestations by ectoparasites such as monogeneans and trichodinids, which can proliferate rapidly in recirculating water absent adequate treatment.

Therapeutic interventions in RAS are further complicated by the need to preserve the integrity of the nitrifying biofilm community, as many conventional antibacterial agents are toxic to nitrifying bacteria. The use of ultraviolet sterilization, ozone micro-dosing and prophylactic probiotics has emerged as more biofilter-compatible disease prevention strategies [8]. Incorporating immunostimulant-fortified feeds containing beta-glucans, vitamin C and herbal extracts also represents a promising non-antibiotic approach to enhancing systemic immunity in RAS-cultured snakehead fish.

1.4. Feeding Management and Feed Conversion

As obligate carnivores, *C. striata* require diets with crude protein content of 40-55% for optimal growth and feed conversion [9]. In traditional farming, fresh trash fish has historically served as the primary feed source, presenting challenges of inconsistent nutritional quality, zoonotic disease transmission risk and unsustainable resource pressure on wild fish stocks. The transition to high-quality commercial extruded pellets formulated with fishmeal, fish oil and plant-based protein alternatives is essential for RAS viability but requires a carefully managed dietary transition period and precision feeding protocols to minimize feed wastage and associated water quality deterioration [16].

Automated feeding technologies, including demand feeders and computer-controlled timing systems calibrated to fish behavioral cues, have demonstrated significant potential for optimizing feed input relative to actual consumption in RAS. These systems reduce overfeeding-associated organic waste loading, improving both water quality stability and feed conversion ratios, which in the best-managed RAS operations have approached values below 1.5 for snakehead [7].

Energy Consumption and Economic Viability

The continuous operation of water pumps, aeration systems, filtration units, temperature control equipment and electronic monitoring systems generates substantial energy consumption, representing the largest component of RAS operational expenditure. In tropical climates, heating costs are typically lower than in temperate settings, but the energy demands of aeration, oxygenation and water treatment remain significant[17]. The high capital investment required for RAS infrastructure, including tanks, filtration units, piping and control systems, creates financial barriers that limit adoption among smallholder farmers who constitute the majority of snakehead producers across Southeast Asia.

Techno-economic analyses of RAS for snakehead production in Vietnam and Indonesia suggest that viability depends critically on achieving sufficient scale, premium market positioning and integration of energy-efficient technologies including solar power supplementation, variable-speed pumps and heat recovery systems[7]. Government subsidies, cooperative business models and access to low-interest agricultural development finance have proven instrumental in supporting the economic feasibility of RAS adoption in the pilot projects examined in this chapter.

Regional Case Studies: RAS Implementation for *Channa striata*

Indonesia: Overcoming Biofilter Design Challenges

Indonesia represents one of the most active sites of RAS development for snakehead culture globally, driven by the species' importance in local food culture and the government's strategic prioritization of aquaculture intensification under the national blue economy agenda. Pilot RAS installations implemented under Ministry of Marine Affairs and Fisheries of the Republic of Indonesia research programs in Bogor, West Java have provided valuable empirical data on system performance under Indonesian tropical conditions[14].

Initial trials revealed that systems designed with biofilter surface areas inadequate for the actual ammonia production rates of *C. striata* at tropical temperatures experienced rapid ammonia accumulation following full stocking[13]. Subsequent system redesign, incorporating expanded MBBR units with K3 media at a 60% fill volume and supplementary fine-bubble aeration to maintain dissolved oxygen above 6 mg/L within the bioreactor, successfully resolved these issues. Revised systems achieved average daily weight gain of 1.8-2.4 g/fish/day at stocking densities of 25-35 kg/m³, with feed conversion ratios of 1.6-1.9 and survival rates exceeding 85% over 6-month production cycles[18].

A key lesson emerging from the Indonesian case studies is the importance of operating at reduced initial stocking densities during biofilter establishment and bacterial community maturation (typically 3-4 weeks), before gradually increasing fish biomass loading. The RAS-aquaponic hybrid system also has been developed by Supriyono et al.[19], where the study showed that lettuce application significantly improved the production performance of juvenile snakehead fish by maintaining optimal water quality, enhancing nitrogen removal and supporting beneficial bacteria, which positively affected fish

health and reduced stress. Consequently, integrating lettuce into the snakehead aquaponic system resulted in high survival and growth rates along with efficient feed conversion, while also demonstrating strong nitrogen and phosphorus removal and high plant productivity, highlighting its potential for integration into recirculating aquaculture–aquaponic systems. The results highlight system sustainability, address the need for environmentally friendly food production methods in the face of global difficulties and improve sustainable RAS-aquaponic techniques for snakehead fish development.

Malaysia: RAS-Driven Yield Enhancement

In Peninsular Malaysia, the integration of RAS into established *C. striata* production operations has been documented in commercial farm-scale studies funded through the Department of Fisheries Malaysia and university research partnerships. Comparative productivity data from RAS-equipped operations versus conventional earthen pond systems demonstrated a 28-35% increase in total yield per production cycle, attributable to improved water quality stability, reduced disease-associated mortality and the ability to maintain optimal temperature conditions throughout the year despite seasonal variability.

Malaysian producers have also pioneered the application of biofloc technology (BFT) as a supplementary nutritional and water quality management strategy within their RAS. By maintaining an appropriate carbon-to-nitrogen ratio in culture water through the addition of carbon sources such as molasses or tapioca starch, biofloc communities of heterotrophic bacteria, microalgae and protozoa simultaneously assimilate toxic ammonia and provide a nutritional supplement to fish. This integrated RAS-biofloc approach reduced supplemental feed requirements by an estimated 15-20%, contributing meaningfully to operational cost reduction[8].

Vietnam: Aquaponic Integration and Economic Optimization

Vietnam's Mekong Delta region harbors one of the world's highest concentrations of snakehead aquaculture operations and Vietnamese researchers and producers have been pioneers in exploring economically optimized production models for the species. A notable innovation [7] involved the integration of *C. striata* RAS with hydroponic vegetable production in an aquaponics configuration. Nutrient-rich effluent from the RAS fish tanks, particularly nitrate accumulated through biofiltration, was channeled to hydroponic growing channels cultivating water spinach (*Ipomoea aquatica*),

lettuce and herbs, which were simultaneously sold in local markets as premium organic produce.

This integrated aquaponic RAS model demonstrated several economic advantages. Hydroponic vegetable sales contributed 25-30% of total system revenue, diversifying income streams and improving overall enterprise profitability. Vegetable uptake of dissolved nutrients simultaneously reduced the need for partial water exchanges to manage nitrate accumulation, further reducing operational water consumption and associated pumping costs[7]. The model also aligned well with growing consumer preferences for traceable, chemical-free produce and fish, supporting premium market positioning in urban Vietnamese food markets.

Bangladesh and India: Smallholder RAS Adaptation

In Bangladesh and India, snakehead farming is predominantly practiced by smallholder households operating on plots of less than one hectare, where the capital requirements of full-scale commercial RAS systems have historically represented prohibitive barriers to adoption. Innovative low-cost RAS designs adapted for the smallholder context have been trialed in Pakistan with support from international development organizations and domestic research institutions[9].

These simplified RAS configurations utilize locally available materials, gravity-fed filtration where topography permits and passive aeration through cascading water flows, substantially reducing both capital costs and energy consumption relative to conventional high-technology RAS designs. Pilot trials in Mymensingh District, Bangladesh, achieved survival rates of 78-83% and specific growth rates comparable to conventional pond systems, while reducing water exchange requirements by 70-75%. These results indicate meaningful potential for appropriately simplified RAS technology to improve production sustainability among resource-limited smallholder snakehead producers.

Technological Innovations Enhancing RAS Performance

Artificial Intelligence and IoT-Based Monitoring

The integration of artificial intelligence, machine learning algorithms and Internet of Things (IoT) sensor networks into RAS management represents a frontier innovation with significant potential to improve system stability and reduce labor requirements. Real-time telemetry platforms connecting dissolved oxygen, pH, temperature, turbidity and feeding behavior sensors to

cloud-based analytics engines enable continuous monitoring and automated alerting when parameters deviate from target ranges, facilitating rapid corrective intervention[17]. Machine learning models trained on historical water quality and fish growth data have demonstrated capacity to predict ammonia accumulation events and recommend preemptive management actions, reducing the risk of acute water quality crises.

Underwater camera systems paired with computer vision algorithms are being developed to monitor feeding behavior, body condition scoring and stress indicators in RAS-cultured snakehead fish without requiring physical disturbance of the culture environment. These non-invasive monitoring tools have potential to optimize feeding management and provide early indicators of disease outbreaks or sub-optimal welfare conditions, contributing to both productivity and fish welfare objectives.

Alternative and Sustainable Feed Ingredients

The dependence of *C. striata* on fishmeal and fish oil as primary dietary protein and lipid sources raises significant sustainability concerns, given global constraints on wild fish capture and the price volatility of marine ingredients. Research into alternative protein sources for snakehead diets has gained considerable momentum, with insect meal (particularly black soldier fly, *Hermetia illucens*), fermented plant proteins, single-cell proteins and duckweed-based supplements all demonstrating promising results as partial fishmeal replacement ingredients without significant adverse effects on growth performance or feed conversion when properly processed and balanced[20].

Probiotic and Immunostimulant Applications

The application of probiotic bacteria, including strains of *Bacillus subtilis*, *Lactobacillus plantarum* and *Enterococcus faecalis*, as water additives or feed supplements in RAS-cultured snakehead fish has been associated with improvements in gut microbiome composition, nutrient digestibility, innate immune function and resistance to pathogenic challenge[15]. By colonizing the gastrointestinal tract and competitive exclusion of pathogenic microorganisms, probiotics offer a viable non-antibiotic strategy for maintaining fish health in the high-density, stress-prone environment of intensive RAS.

Economic, Environmental and Policy Dimensions

Environmental Sustainability

From an environmental standpoint, RAS offers compelling advantages over conventional snakehead pond farming. Water consumption in optimized RAS is reduced by up to 95-99% relative to flow-through systems, a critical benefit in regions experiencing increasing freshwater scarcity [3]. The capture and treatment of concentrated waste streams from RAS facilitates the production of organic fertilizer or biogas through anaerobic digestion, transforming a disposal challenge into a circular economy resource. Carbon footprint analyses comparing RAS-produced snakehead with pond-raised equivalents demonstrate lower per-kilogram greenhouse gas emissions when RAS operations are powered with renewable energy, despite the inherently higher energy intensity of the closed system [17].

Economic Viability and Scaling

A comparison between the conventional pond system and the Recirculating Aquaculture System (RAS) across key performance and operational parameters presented in table 7. It highlights differences in water usage, stocking density, survival rate, feed conversion ratio (FCR), production cycles, disease incidence and cost structure, providing a clear overview of the relative efficiency and requirements of each system.

Table 7: Comparative performance indicators: Conventional pond vs. RAS for Channa striata production

Parameter	**Conventional Pond System**	**RAS System**
Water Use (L/kg fish)	5,000 – 50,000	100 – 500
Stocking Density (kg/m³)	2 – 10	25 – 60
Survival Rate (%)	60 – 75	82 – 94
FCR	2.0 – 3.5	1.5 – 2.0
Production Cycles/Year	1 – 2	2 – 4
Disease Incidence	High	Low – Moderate
Capital Investment	Low	Moderate – High
Operational Cost	Low – Moderate	Moderate – High

Economic analysis indicates that RAS for *Channa striata* achieves profitability at commercial scale when fish prices exceed USD 3.50-4.50/kg and production capacity exceeds 10 metric tons annually. Government subsidies for RAS capital equipment, preferential loan rates through

agricultural development banks and technical extension services have proven essential enabling conditions for adoption in both Vietnam and Indonesia. Cooperative ownership models, wherein smallholder farmers pool capital to establish shared RAS facilities with professional management, offer a promising pathway to democratizing access to this technology.

Regulatory and Policy Considerations

The regulatory landscape for RAS aquaculture in tropical snakehead-producing countries is evolving rapidly but remains uneven. Several jurisdictions have introduced certification schemes for RAS-produced fish, including freshwater fish-specific sustainability standards that assess water use efficiency, waste management practices, chemical inputs and traceability. Compliance with these standards opens access to premium retail markets in Europe, North America and Japan, providing economic incentives for investment in RAS technology [11].

A specific regulatory consideration relevant to *Channa* species is the classification of snakehead fish as potentially invasive in several North American and European jurisdictions, restricting live export and requiring strict containment protocols for RAS operations involved in genetic improvement programs or broodstock management. Compliance with these regulations requires robust escape prevention infrastructure and biosafety protocols, adding to system costs but also demonstrating the responsible stewardship necessary for long-term sector legitimacy.

Conclusions and Future Directions

This chapter has demonstrated that Recirculating Aquaculture Systems represent not merely an incremental improvement but a fundamental transformation in the technical and sustainability possibilities for *Channa striata* aquaculture in tropical countries. The case studies reviewed from Indonesia, Malaysia, Vietnam, Bangladesh and India collectively illustrate that RAS can substantially improve production yields, water use efficiency, biosecurity and environmental performance relative to conventional pond-based systems, while enabling year-round production independent of seasonal variability.

Wider adoption of snakehead aquaculture requires overcoming the persistent constraints of biological filtration instability, disease outbreaks in intensive culture systems, high energy consumption, large capital costs and technical complexity of RAS operation. To achieve this goal, there is a need

to develop integrated technological innovations, cost-effective system designs, improved biosecurity strategies, supportive financing schemes and targeted capacity-building programs that can facilitate the translation of scientific knowledge into practical management solutions for smallholder farmers.

Future research priorities should include the optimization of low-cost RAS designs appropriate for smallholder contexts, the development of locally available and sustainable feed ingredients to reduce dependence on marine fishmeal, the integration of renewable energy systems to reduce operational carbon footprints and the application of digital monitoring technologies to enhance system management precision. Expanded multi-country collaborative research networks, building on the complementary strengths and experiential knowledge of RAS practitioners across the tropical Indo-Pacific region, offer a promising institutional model for accelerating progress toward the sustainable intensification of snakehead aquaculture.

Ultimately, the successful scaling of RAS for *Channa striata* culture is not solely a technical challenge but an integrated socioeconomic and governance challenge. The most effective pathways will be those that simultaneously address technical performance, economic accessibility and the enabling policy and institutional environment, placing the welfare of farming communities and aquatic ecosystems at the heart of a sustainable aquaculture future.

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6
CHAPTER

Evaluating the System Performance, Financial Viability and Operational Challenges of High-Density Nile Tilapia (*Oreochromis niloticus*) Nursery Culture in Biofloc Technology

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Abstract

Biofloc Technology (BFT) represents a fundamental innovation in intensive aquaculture, integrating in-situ nitrogen waste management with the production of supplemental feed. This study evaluates the system performance, financial viability and operational challenges of BFT for the nursery phase of Nile tilapia (*Oreochromis niloticus*) under high stocking densities. The core principle of BFT involves the stimulation of heterotrophic bacteria through the manipulation of the carbon-to-nitrogen (C/N) ratio to assimilate ammonia. The resulting flocs serve as nutrient-rich supplementary feed, significantly reducing the Feed Conversion Ratio (FCR). Performance assessments indicate that increasing stocking density enhances total biomass productivity, although it concurrently reduces individual growth rates. Financial viability confirms the high profitability potential of BFT and its lower Capital Expenditure (CAPEX) compared with Recirculating

Aquaculture Systems (RAS). However, Operational Expenditure (OPEX) remains substantial, particularly for feed (40–60%) and aeration energy (up to 15.5%). The most critical operational challenge lies in the absolute dependence on a stable energy supply for intensive aeration, as even short-term power failures can result in mass mortality. Moreover, BFT requires advanced microbiological management to maintain water quality stability, particularly in terms of Total Suspended Solids (TSS) and alkalinity. In conclusion, BFT is a highly effective and potentially profitable technology, yet it remains complex, high-risk and heavily reliant on energy reliability and advanced managerial expertise.

Keywords: Biofloc Technology, *Oreochromis niloticus*, Nursery Phase, High Stocking Density, Financial Viability.

Introduction

The global aquaculture sector continues to experience rapid growth, transforming it into a fundamental pillar of global food security amid the stagnation of capture fisheries [1]. This expansion, however, exerts significant pressure on limited natural resources, particularly land and water, thereby driving innovation toward more intensive and vertically efficient production systems [2]. In this context, Nile tilapia (Oreochromis niloticus) holds a strategic position. As one of the world's most important cultured species, tilapia is highly valued for its rapid growth, resilience to varying environmental conditions and adaptability to intensive aquaculture systems, making it an ideal model species for the implementation of advanced technologies [1].

One of the most promising innovations is Biofloc Technology (BFT), often referred to as a new "blue revolution" in aquaculture [3]. BFT represents a breakthrough approach that integrates waste treatment and in-situ production of supplemental feed within a single culture unit [4]. Its fundamental principle lies in establishing a closed or semi-closed system with minimal water exchange, in which nutrient cycling is managed through the manipulation of microbial communities to convert nitrogenous waste into biomass that can be reutilized by fish [5].

BFT offers a range of substantial advantages, including improved feed efficiency, water conservation and enhanced biosecurity. However, its implementation at a commercial scale, particularly during the fry nursing phase at very high stocking densities, still faces various complex technical and

economic challenges [6]. Therefore, this study aims to conduct a critical and comprehensive evaluation of the BFT system. Specifically, it seeks to (1) assess the performance of BFT for Nile tilapia fry rearing based on empirical evidence from global scientific literature, (2) perform an economic analysis to evaluate its financial viability and profitability and (3) identify key operational challenges and formulate effective mitigation strategies to support the sustainable adoption of this technology.

Fundamental Principles and Biofloc Ecosystem Dynamics

Nitrogen Conversion Mechanisms: The Role of Heterotrophic and Autotrophic Bacteria

In intensive aquaculture systems, the accumulation of toxic nitrogenous compounds, particularly ammonia (NH_3), originating from uneaten feed and metabolic excretion by fish, represents a major limiting factor for productivity [6]. There are two primary biochemical pathways for managing ammonia in aquatic systems. The first pathway is nitrification, which is carried out by chemoautotrophic bacteria. This process, which forms the foundation of biofilters in recirculating aquaculture systems (RAS), converts ammonia into nitrite (NO_2^-) and subsequently into nitrate (NO_3^-), a relatively non-toxic form [5].

The second pathway, which constitutes the core mechanism of Biofloc Technology (BFT), involves the direct assimilation of ammonia by heterotrophic bacteria. These bacteria utilize ammonia as a nitrogen source for the synthesis of new cellular proteins, thereby converting it directly into microbial biomass [5]. Comparative studies have demonstrated that this heterotrophic assimilation process is significantly faster and more efficient in controlling ammonia surges than the slower nitrification pathway. This efficiency makes BFT a superior technology for high-density aquaculture systems, where nitrogenous waste loads are particularly high [5].

Carbon to Nitrogen Ratio (C/N) as a Key Regulatory Factor

The core principle that governs and regulates the dynamics of the biofloc ecosystem is the manipulation of the carbon-to-nitrogen (C/N) ratio [5]. Commercial fish feeds generally contain high protein levels and low C/N ratios (typically below 10:1). As a result, when such feed is metabolized by fish, excess nitrogen in the form of ammonia accumulates in the water. To stimulate the proliferation of heterotrophic bacteria responsible for ammonia assimilation, the C/N ratio in the water column must be elevated to an optimal

range, which various studies have reported to be between 12:1 and 20:1 [7].

The increase in C/N ratio is achieved by supplementing the system with external organic carbon sources. Several carbon sources have been evaluated, including molasses, sucrose, tapioca flour and wheat flour [7]. The choice of carbon source has important implications for the rate of floc formation and overall system dynamics. Simple carbon sources such as molasses and sucrose are rapidly degraded by bacteria, while more complex carbohydrates like tapioca are broken down more slowly, providing a more stable and sustained carbon release over time [8].

Composition and Structure of the Microbial Community

The term "biofloc" is often mistakenly interpreted as merely an aggregation of bacteria. In reality, biofloc represents a complex micro-ecosystem composed of diverse microbial aggregates that include heterotrophic and autotrophic bacteria, microalgae, fungi, protozoa and zooplankton such as rotifers. All these components are bound together within a sticky extracellular polysaccharide matrix [4].

Modern research employing genetic sequencing techniques (such as 16S and 18S rRNA) has revealed that the composition of microbial communities is highly dynamic and strongly influenced by factors such as the type of carbon source used, the fish species being cultured, salinity and other environmental parameters [9]. One study reported that these communities can consist of 48–73% eukaryotic organisms (such as algae and protozoa) and 27–51% prokaryotic organisms (bacteria) [10]. These microbial communities play dual and crucial roles: they function as "biological factories" for nitrogen transformation [2] and act as probiotics by suppressing pathogenic microorganisms through competitive exclusion mechanisms, thereby creating a healthier aquaculture environment [11-13].

Biofloc as an In Situ Supplemental Feed Source

One of the most significant advantages of Biofloc Technology (BFT) is its capacity to convert waste into valuable resources. The biofloc aggregates formed within the system serve as natural feed rich in nutrients, with crude protein content reaching up to 40%, as well as containing essential lipids, vitamins and minerals [1]. Nile tilapia, being an omnivorous species with filter-feeding capability, is particularly well suited to this system since it can actively consume and digest suspended biofloc particles in the water column [5].

Consumption of biofloc serves as a continuously available supplemental feed throughout the day. This fundamentally alters the nutrient dynamics within the system, reducing dependence on costly commercial feeds and directly enhancing feed efficiency. Numerous studies have consistently reported a significant reduction in the Feed Conversion Ratio (FCR) and a corresponding decrease in production costs. Some reports indicate potential FCR reductions of up to 30% [2].

Conceptually, BFT represents a fundamental paradigm shift in aquaculture. Nitrogenous waste is no longer viewed as a pollutant to be discarded but rather as a valuable substrate that can be recycled into high-quality feed within the system itself. Conventional systems and recirculating aquaculture systems (RAS) focus on eliminating ammonia, either through water exchange or by converting it into nitrate. In contrast, BFT promotes the assimilation of ammonia into microbial biomass. This establishes a highly efficient internal nutrient cycle in which fish waste serves as input for microbes and microbial biomass (biofloc) becomes a nutritional input for fish. This shift drastically reduces the ecological footprint of aquaculture, enhances resource-use efficiency (feed and water) and strengthens biosecurity by minimizing interaction with the external environment [3]. It represents a tangible manifestation of circular economy principles in food production.

Evaluation of Production Performance in High-Density Tilapia Nursery Systems

Water Quality Management in Intensive Systems

Precise water quality management is the key to successful BFT operation, especially under high stocking densities. Quantitative data from multiple studies indicate that well-managed BFT systems can maintain water quality parameters within safe ranges for tilapia growth. A study evaluating various carbon sources as starters reported that ammonia (NH_3-N) concentrations can be maintained at very low levels, typically between 0.02 and 0.07 mg/L. Nitrite (NO_2-N), which is also toxic, can be maintained between 0.20 and 0.43 mg/L, while nitrate (NO_3-N) levels range from 0.90 to 3.20 mg/L [8].

In addition to nitrogenous compounds, other parameters such as dissolved oxygen (DO), pH, alkalinity and total suspended solids (TSS) require careful monitoring. BFT systems exhibit high overall oxygen demand due to the combined respiration of fish and dense microbial populations. Therefore, intensive and continuous aeration is essential to maintain DO concentrations

above the safe threshold of 5 mg/L [4]. Biological processes in BFT, particularly nitrification and microbial respiration, naturally generate carbonic acid, which continuously depletes alkalinity and causes pH reduction. A sharp decline in pH can inhibit microbial activity and induce stress in fish. Consequently, regular monitoring and the addition of alkalinity sources (such as sodium bicarbonate) are crucial to maintaining pH stability within the system [6].

The biofloc volume, measured as TSS, must also be managed within the optimal range. Excessive TSS concentrations can cause problems such as gill clogging and elevated oxygen demand, whereas excessively low TSS levels indicate an immature system with suboptimal waste processing capacity [6].

Effects of Stocking Density on Productivity and Fish Welfare

Stocking density is a fundamental management parameter in intensive Nile tilapia (*Oreochromis niloticus*) aquaculture, directly determining the volumetric productivity of a system. However, increasing density to maximize biomass output introduces complex biological and ecological consequences. Data analyses from numerous studies reveal a consistent antagonistic relationship between stocking density and individual growth performance. Higher numbers of fish per unit volume intensify intraspecific competition for essential resources such as feed and space, leading to physiological stress and reduced growth rates. This phenomenon has been empirically demonstrated across life stages, from drastic reductions in final fry weight [14] to significant declines in specific growth rate (SGR) and final body weight during nursery [15-16] and grow out phases [17].

The consequences of intensified competition extend beyond growth retardation and directly impact economic efficiency through feed conversion. High competition and physiological stress decrease feed utilization efficiency, reflected in increased FCR values. Multiple studies consistently show that FCR worsens as stocking density increases, meaning more feed is required to produce each kilogram of fish biomass [15-16]. This decline in efficiency reflects energy being diverted from somatic growth to stress management and competitive behavior, as well as uneven feed distribution.

Furthermore, when stocking density exceeds the carrying capacity of the culture system, survival rates decline sharply. The accumulation of metabolic wastes such as ammonia and nitrite, combined with increased biological oxygen demand, creates suboptimal environmental conditions that suppress

immune function and heighten disease susceptibility. A critical threshold is reached where environmental degradation accelerates, leading to mass mortality events. This threshold is evident in studies reporting survival rate drops from above 88% to only 33% with slight increases in density [17] and even more severe declines among vulnerable fry stages [14]. These findings confirm that every culture system has an absolute upper density limit, beyond which production failure is inevitable.

Paradoxically, despite its negative effects on individual performance, increasing stocking density up to a certain point remains the primary strategy for maximizing total biomass yield. Productivity exhibits a parabolic relationship with stocking density: initially, adding more individuals increases total biomass harvested, even though average fish size decreases. This trend is well documented, showing significant increases in biomass per cubic meter with higher densities [15, 18]. However, this positive relationship is not linear. Once optimal density is surpassed, the negative effects of reduced growth and increased mortality outweigh the benefits, causing productivity to plateau or even decline, as clearly illustrated by turning-point data at excessively high densities [16, 19].

Therefore, determining optimal stocking density must be contextualized within the culture system employed. Modern aquaculture technologies, particularly Biofloc Technology (BFT), are designed to mitigate the adverse effects of high densities. By managing the carbon-to-nitrogen ratio, BFT converts toxic nitrogenous waste into nutrient-rich microbial biomass. These flocs function not only as biological filters that maintain water quality but also as in-situ supplemental feed sources that enhance feed efficiency and sustain fish performance. The success of this system in supporting extremely high stocking densities is evident from reports of highly efficient FCR values and consistently high survival rates even under extreme crowding conditions [19-20]. This demonstrates that density limits are elastic and largely determined by a system's technological capacity to regulate its internal environment. Ultimately, stocking density decisions represent strategic trade-offs between maximizing total biomass output and maintaining individual performance and system stability, with appropriate technology adoption serving as the critical determinant of success. A synthesis of performance data from multiple studies summarizing these trade-offs is presented in Table 8.

Table 8 : Synthesis of Production Performance Parameters of Nile Tilapia Nursery in Biofloc Systems at Different Stocking Densities

Study and Year (Source)	Stocking Density (fish/m³)	Duration (days)	Initial Weight (g)	Final Weight (g))	SR (%)	FCR	SGR (%/day)	Productivity (kg/m³ or g/UE)	System Conditions
[13]	2500	21	-	0.37 ± 0.07	98.00 ± 2.00	1.72 ± 0.38	20.72 ± 0.20	18.00 ± 3.61 g (Biomass)	Salinity > 20 ppt
	5000	21	-	0.20 ± 0.08	77.33 ± 11.59	2.50 ± 0.88	20.07 ± 0.36	15.33 ± 6.66 g (Biomass)	
	7500	21	-	0.12 ± 0.04	14.78 ± 2.50	12.17 ± 0.45	19.55 ± 0.34	2.73 ± 0.64 g (Biomass)	
[15]	200	44	0.66 ± 0.17	30.6 ± 1.2	99.4 ± 0.6	1.05 ± 0.05	7.02 ± 0.09	6.12 ± 0.24	Temperature 28 ± 1 °C
	350	44	0.66 ± 0.17	26.4 ± 1.5	98.9 ± 0.6	1.12 ± 0.05	6.32 ± 0.11	9.53 ± 0.54	
	500	44	0.66 ± 0.17	24.3 ± 1.2	98.5 ± 0.6	1.22 ± 0.1	5.92 ± 0.11	11.75 ± 1.06	
	650	44	0.66 ± 0.17	21.6 ± 1.4	98.8 ± 0.7	1.24 ± 0.08	5.48 ± 0.16	12.52 ± 0.81	
	800	44	0.66 ± 0.17	19.9 ± 1.5	98.6 ± 0.6	1.34 ± 0.07	5.17 ± 0.12	12.85 ± 0.67	
[14]	3000	28	0.007-0.015	0.28-2.15	77	NA	NA	0.85	Salinity up to 15 ppt, molasses as carbon source (C:N 10:1), inoculated with *Lactobacillus casei* and *Saccharomyces cerevisiae*
	6000	28	0.007-0.015	0.04-0.80	79	NA	NA	0.6	
[16]	200	35	6.74 ± 0.37	28.87 ± 0.67	95.83 ± 0.59	1.02 ± 0.04	3.90 ± 0.08	5.53 ± 0.15	
	300	35	6.74 ± 0.37	25.58 ± 1.86	94.45 ± 2.08	1.04 ± 0.10	3.76 ± 0.13	7.25 ± 0.69	
	400	35	6.74 ± 0.37	21.65 ± 3.91	90.41 ± 6.66	1.21 ± 0.26	3.39 ± 0.46	7.85 ± 0.174	
	500	35	6.74 ± 0.37	20.68 ± 0.22	95.75 ± 0.75	1.11 ± 0.02	3.23 ± 0.01	9.91 ± 0.14	
	600	35	6.74 ± 0.37	17.87 ± 0.16	78.13 ± 6.05	1.51 ± 0.26	2.95 ± 0.04	8.38 ± 0.99	
[19]	200	64	~1.0 (implied)	NA (WGEU 651.75 ± 76.57 g/UE)	90.83	0.94 ± 0.05	NA	4.35 ± 0.51	Biofloc, brown sugar as carbon source (C:N 20:1)
	400	64	~1.0 (implied)	NA (WGEU 989.00 ± 127.93 g/UE)	88.33	1.13 ± 0.13	NA	6.59 ± 0.85	

	600	64	~1.0 (implied)	NA (WGEU 1517.50 ± 143.90 g/UE)	89.26	0.93 ± 0.08	NA	12.13 ± 1.49	
	800	64	~1.0 (implied)	NA (WGEU 1891.25 ± 151.24 g/UE)	87.5	0.95 ± 0.05	NA	12.61 ± 1.01	
	1000	64	~1.0 (implied)	NA (WGEU 1811.5 ± 284.02 g/UE)	86.33	1.15 ± 0.1	NA	12.08 ± 1.89	
[18]	750	30	2.01 ± 0.23	9.28 ± 0.41	93.33 ± 3.27	1.32 ± 0.13	5.09 ± 0.15	5.77 ± 0.40	Biofloc with molasses as carbon source
	1500	30	2.05 ± 0.19	9.10 ± 0.27	92.50 ± 2.26	1.34 ± 0.06	4.97 ± 0.09	11.20 ± 0.44	
[21]	40 (LPBFT-L)	112	4.17 ± 0.0	~185.17 (Gain 181.0 ± 0.2)	99.3 ± 0.6	Increased by 1.6% compared with control	NA	NA (Net yield increased by 27.9–29.5%)	Biofloc using molasses as carbon source (C:N 15:1) and limited-protein diet
	80 (LPBFT-H)	112	4.67 ± 0.0	~179.57 (Gain 174.9 ± 0.0)	96.1 ± 1.2		NA		
[22]	166 (LD)	120	0.51 ± 0.05	16.11 ± 0.59	Highest (under *Vibrio harveyi* stress)	1.21 ± 0.01	2.90 ± 0.15	2.69 ± 0.23	
	333 (MD)	120	0.51 ± 0.05	15.08 ± 0.72	Highest (under *Vibrio harveyi* stress)	1.25 ± 0.04	2.90 ± 0.18	5.36 ± 0.42	
	600 (HD)	120	0.51 ± 0.05	13.38 ± 0.88	Lowest (under *Vibrio harveyi* stress)	1.44 ± 0.05	2.75 ± 0.22	7.95 ± 0.41	
[20]	500	42	1.17 ± 0.05	-	100 ± 0.00	-	-	9.4- 1.5	Molasses as carbon source (30% of feed)
	750			-	100 ± 0.00	-	-		
	1000			-	99.33 ± 0.67	-	-		
	1250			-	96.82 ± 1.42	-	-		

• WGEU: Weight Gain per Experimental Unit.

Economic Analysis of Nile Tilapia Farming in Biofloc Systems

Investment (CAPEX), Operational Costs (OPEX) and Financial Viability

A rigorous economic evaluation is essential to assess the commercial viability of the biofloc technology (BFT). Production costs are categorized into two major components: capital expenditures (CAPEX) and operational expenditures (OPEX). CAPEX includes all initial investments required to establish the production facility. The main components comprise the construction of tanks or ponds (typically HDPE-lined or concrete), installation of robust aeration systems (including blowers, pipelines and diffusers), procurement of backup power generators (an indispensable necessity) and acquisition of water quality monitoring instruments [1]. A case study on a juvenile tilapia nursery system estimated total initial investment at approximately USD 9,632, with greenhouse construction accounting for the largest portion (27.6% of total investment) followed by tank procurement (14.3%) [1].

OPEX refers to the recurring expenditures incurred during each production cycle. Across multiple studies, feed cost has consistently been identified as the dominant component, representing 40% to 60% of total operational costs [23]. Other significant components include the cost of fingerlings, which may account for up to 33% during nursery phases [1], labor costs (around 20%) and energy costs associated with continuous aeration. Electricity alone may represent 14.5–15.5% of total production expenses in Nile tilapia BFT operations [17]. According to [17], aeration energy costs range from USD 3.01 to 7.41 per m^3 depending on stocking density.

Financial feasibility studies demonstrate that BFT can be highly profitable when properly managed. A case study from Thailand reported a positive economic outlook, with a Benefit–Cost Ratio (B/C) of 1.19, a positive Net Present Value (NPV) and an attractive Internal Rate of Return (IRR) of 45%. However, the Payback Period (PP) was relatively long at approximately 7.14 years, reflecting the substantial initial investment [24]. Another study from Indonesia reported an even higher Revenue–Cost Ratio (R/C) of 2.03 [25].

Nevertheless, profitability is highly sensitive to key variables. Scenario analyses (pessimistic, realistic, optimistic) indicate that survival rate and market price are the most influential factors. Under pessimistic conditions, characterized by low survival and declining sale prices, operations may easily become unprofitable [1]. To quantify such risks, stochastic simulations such as

Monte Carlo analyses have been employed, revealing a high probability of achieving positive returns (87.29% in one study), suggesting that BFT remains economically viable under competent management [1].

Comparative Economic Analysis: Biofloc vs. Recirculating Aquaculture Systems (RAS)

When compared economically, Biofloc Technology (BFT) and Recirculating Aquaculture Systems (RAS) represent two distinct intensification pathways with different investment and profitability profiles. The most pronounced contrast lies in capital expenditure. BFT typically requires lower CAPEX, ranging from USD 0.5 to 1.5 per kg/year of production, as it does not rely on complex mechanical and biological filtration systems. In contrast, RAS demands higher capital investment, typically USD 2 to 5 per kg/year [26].

Operational costs (OPEX) between the two systems are comparable, both within the range of USD 1 to 2.5 per kg/year. BFT provides considerable savings in feed expenses—up to 54% of total cost—owing to the contribution of biofloc as a supplemental protein source. However, this advantage is partially offset by higher energy costs for aeration, which may represent 15.5% of total production costs [17, 26].

A key distinction also lies in their productivity strategies. RAS can achieve higher volumetric productivity (50–100 kg/m³/year) but typically operates with longer culture cycles, whereas BFT achieves lower productivity (10–25 kg/m³/year) but allows up to three production cycles per year [26]. Despite these differences, both systems exhibit excellent feed efficiency, with Feed Conversion Ratios (FCR) of 1.1–1.3. The combination of lower CAPEX and faster turnover gives BFT a profitability advantage, with profit indices of 25–40%, outperforming RAS systems that range between 10–25% [26-27].

Beyond pure economic metrics, both systems contribute to sustainable aquaculture by minimizing water use and improving biosecurity [15]. Considering the rising cost of land, BFT presents a more accessible intensification route due to its lower investment threshold, while emerging hybrid Bio-RAS concepts aim to combine BFT's cost-efficiency with the operational stability of RAS.

Operational Challenges, Risks and Mitigation Strategies in Commercial-Scale Implementation

Energy Management and Intensive Aeration Requirements

One of the major operational challenges of large-scale BFT is its exceptionally high energy demand. Continuous and vigorous aeration is essential to keep biofloc particles suspended throughout the water column and to satisfy the substantial oxygen requirements of both fish and microbial communities [28]. Energy consumption in BFT is estimated at 22.4 kW per kilogram of fish, nearly double that of RAS, which requires only 11.2 kW per kilogram [28].

This heavy dependence on stable electricity supply creates significant operational risk. Even short-term power outages (often less than one hour) can result in catastrophic losses due to rapid oxygen depletion, leading to anoxic conditions and mass mortality. Such failures are typically marked by sharp declines in dissolved oxygen and spikes in toxic nitrogenous compounds such as ammonia and nitrite.

Therefore, reliable backup power systems, including diesel generators, are not optional but essential. For long-term sustainability, renewable energy options such as photovoltaic (solar) systems are increasingly relevant to offset high energy costs, albeit requiring higher upfront investments [28]. Selecting energy efficient aeration equipment is another critical mitigation strategy [29]. Some systems also incorporate battery based backup units to ensure continued water circulation during outages [19], underscoring the importance of energy reliability in BFT operations.

System Stability: Control of Solids, Alkalinity and Nitrogen Dynamics

BFT is a dynamic engineered ecosystem and maintaining its stability poses an ongoing challenge. Uncontrolled accumulation of Total Suspended Solids (TSS) can cause chronic fish stress, gill obstruction and increased disease risk due to deteriorating water quality [6]. Furthermore, nitrification processes consume alkalinity [18]; without proper buffering, alkalinity depletion can trigger rapid pH drops, inhibiting nitrifying bacteria and causing toxic ammonia and nitrite spikes [16, 21].

To manage solids accumulation, external settling chambers or clarifiers are commonly implemented in super-intensive systems [11, 30]. Routine monitoring and replenishment of alkalinity using buffers such as sodium bicarbonate are standard management practices [29]. A more advanced

approach involves hybrid (HY) systems that integrate BFT with external biofilters from RAS. These configurations enhance nitrogen cycle stability, particularly during sensitive nursery stages. Comparative studies have shown that hybrid and clear-water RAS outperform pure BFT systems in maintaining lower and more stable nitrite levels [24].

Biological Risks and the Need for Skilled Personnel

Although BFT can exert probiotic effects by suppressing certain pathogens, poor management can inadvertently foster opportunistic bacteria such as *Vibrio spp*. [29]. This highlights that BFT is not a simple system, success depends on a deep understanding of applied microbiology, water chemistry and system engineering. Hence, the availability of skilled personnel is a prerequisite for successful commercial scale BFT operations [29].

Unlike mechanical systems such as RAS, whose behavior is largely predictable, BFT is a living biological system. Its success hinges on maintaining a delicate ecological balance, making it both resilient in nutrient recycling and vulnerable to sudden collapse if disturbed. Effective BFT management resembles "microbial gardening" more than machine operation, requiring proactive monitoring and measured intervention. Future reliability of BFT will likely depend on real-time sensor systems and automated control platforms capable of predicting and preventing instability. The emergence of hybrid BFT–RAS systems represents a logical step toward achieving greater redundancy and stability through combined biological and engineering safeguards [6]. Table 9 below summarizes the comparison between BFT and RAS to support strategic decision-making.

Table 9 : Comparative Analysis of Cost and Performance between Biofloc Technology (BFT) and Recirculating Aquaculture Systems (RAS) for Nile Tilapia Nursery

Parameter	Biofloc Technology (BFT)	Recirculating Aquaculture System (RAS)
Initial Capital Investment (CAPEX)	Lower (no need for external biofilters, UV sterilizers, etc.) [26]	Very high (requires complex mechanical and biological filtration components) [26]
Feed Cost (% of OPEX)	Lower (partial feed supplementation from biofloc biomass) [2]	Higher (fully dependent on commercial feed inputs)
Energy Cost (% of OPEX)	High to very high (due to intensive aeration and mixing requirements) [28]	High (energy-intensive pumping and aeration processes) [28]

Technical Expertise Requirement	High (requires strong understanding of microbiology and water chemistry) [29]	High (requires expertise in system engineering and operational management)
Water Quality Stability	Relatively unstable (contingent upon biological equilibrium) [31]	Highly stable (regulated by engineered filtration and control systems) [31]
Typical Feed Conversion Ratio (FCR)	Lower (approximately 1.4) [32]	Higher (typically 1.7–1.9) [33]
Production Cost per kg	Lower (USD 1–3) [26]	Higher (USD 3–8) [26]

Conclusion and Future Prospects

Conclusion

This comprehensive review reaffirms the position of Biofloc Technology (BFT) as one of the most significant innovations in modern intensive aquaculture. From a technical perspective, BFT has proven to be a highly effective system, particularly for high-density Nile tilapia fry rearing, due to its ability to manage nitrogenous waste in situ while simultaneously generating high-quality supplemental feed. This dual functionality directly enhances feed efficiency and supports higher survival rates. The technical advantages of BFT translate into strong economic potential, as the system demonstrates high profitability driven by substantial feed cost savings. However, financial feasibility remains highly dependent on efficient energy management and the operator's capacity to mitigate harvest failure risks. When compared with other intensive systems such as Recirculating Aquaculture Systems (RAS), BFT offers an attractive intensification pathway with significantly lower initial capital investment. Nonetheless, this advantage is offset by greater biological management demands and higher risks associated with system stability. Therefore, BFT should not be regarded as a universally applicable solution but rather as an advanced management tool that requires a high level of technical expertise. When effectively implemented, it can deliver substantial rewards, offering a promising route toward more sustainable, efficient and profitable aquaculture production.

Future Development Prospects

To further enhance the adoption and reliability of Biofloc Technology (BFT), future research should focus on several complementary areas. First, optimizing carbon sources remains a critical priority, with an emphasis on identifying and evaluating alternative carbon inputs that are cost-effective,

sustainable and locally available to reduce operational expenses. In parallel with input optimization, microbial engineering research should be intensified, particularly in developing specific probiotic strains or microbial consortia capable of directing biofloc community composition toward more stable, efficient and fish-beneficial states.

At the system level, further exploration of hybrid BFT-RAS configurations is needed to establish the optimal balance between the cost efficiency inherent to BFT and the operational stability and control offered by RAS. Finally, to integrate and effectively manage these complex interactions, the development of affordable real-time sensors and AI-based automated control systems should become a research priority. These technologies would enable dynamic monitoring and management of key system parameters, significantly improving operational reliability while reducing dependence on intensive manual intervention.

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7
CHAPTER

A Comprehensive Evaluation of System Performance and Profit Loss Analysis in the Nursery Culture of Common Carp (*Cyprinus carpio*) Using Biofloc Technology

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Abstract

Global aquaculture requires sustainable, intensive systems to meet the growing demand for protein, particularly considering waste management challenges associated with conventional common carp (*Cyprinus carpio*) farming. Biofloc Technology (BFT) has emerged as an innovative solution based on the principle of minimal water exchange. This comprehensive review evaluates the application of BFT in common carp fingerling nursery production by analyzing system performance, operational management and economic viability. The BFT method manipulates the carbon-to-nitrogen (C/N) ratio to stimulate heterotrophic bacterial growth, thereby optimizing the conversion of toxic nitrogenous waste into bioflocs. These microbial aggregates serve a dual function by maintaining in situ water quality and providing a natural, protein rich supplemental feed for fish. Data synthesis indicates that BFT significantly improves feed efficiency, as reflected by a lower feed conversion ratio (FCR) and supports very high survival rates (SR)

of 99–100%. Stocking density analysis identifies an optimal total biomass productivity of 150 fish/m³, although the best individual growth performance occurs at 100 fish/m³. Economically, BFT is highly promising, small scale production models demonstrate strong financial viability, with projected returns on investment (ROI) exceeding 100% and a payback period of less than one year. However, profitability is sensitive to energy costs due to the requirement for continuous aeration for 24 hours over 7 days and the need to manage total suspended solids (TSS) carefully. This paper concludes that BFT represents a strategic pathway for aquaculture intensification, its successful implementation depends heavily on energy reliability and advanced technical management skills.

Keywords: Biofloc technology, *Cyprinus carpio*, nursery, water quality, Profit and Loss Analysis

Introduction

The global aquaculture sector continues to expand rapidly, firmly establishing itself as a fundamental pillar in supplying animal protein for a growing world population amid the stagnation of capture fisheries. This vertical growth however, places significant pressure on limited natural resources, particularly land and water, thereby driving innovation toward more intensive, efficient and sustainable production systems. In this context, the common carp (*Cyprinus carpio*) plays an important role. As one of the most widely cultured freshwater species globally, common carp is highly valued for its relatively fast growth rate, omnivorous feeding habits and ability to adapt to diverse aquaculture systems [1].

Yet, the intensification of common carp farming using conventional methods often faces serious challenges. High stocking densities lead to the accumulation of toxic nitrogenous wastes in form ammonia or nitrite and organic matter, which can drastically deteriorate water quality and trigger disease outbreaks. The common practice to address these issues is a large volume water exchange, this approach is not only resource intensive but also carries the risk of polluting surrounding aquatic environments with nutrient rich effluents [2].

In response to these challenges, Biofloc Technology (BFT) has emerged as a promising innovative approach. BFT is an environmentally friendly aquaculture system that operates with minimal or even zero water exchange. Its core principle involves engineering the microbial ecosystem within the

culture unit by manipulating the carbon to nitrogen (C/N) ratio. The addition of an external carbon source stimulates the growth of heterotrophic bacteria, which efficiently convert toxic nitrogenous wastes into microbial biomass [3]. These aggregates of microbial biomass, known as bioflocs, not only function to maintain water quality in situ but also serve as a protein rich natural feed that can be reutilized by the fish, thereby reducing feed costs and improving production efficiency [4].

Although BFT offers a range of significant advantages, its successful commercial scale application, particularly for the highly critical nursery phase of *C. carpio* seed, requires a deep understanding of system dynamics and its economic feasibility. Therefore, this review aims to provide a comprehensive evaluation of the BFT system for common carp nursery culture by analyzing production performance based on global scientific evidence, conducting a detailed profit loss analysis to assess its financial viability and identifying key operational challenges along with potential mitigation strategies [5].

Fundamental Principles and Ecosystem Dynamics of Biofloc Technology (BFT)

Biofloc Technology (BFT) represents a paradigm shift in intensive aquaculture, transitioning from water exchange based systems to actively managed microbial ecosystems within culture units [6]. The successful implementation of BFT, particularly during the critical nursing phase of *Cyprinus carpio* juveniles, depends heavily on a deep understanding of the underlying biological and chemical principles. This section outlines the fundamental mechanisms of BFT, ranging from engineered nutrient cycling to the development of microbial communities that form the core of the system.

Important Role of the Carbon to Nitrogen Ratio in Nutrient Conversion Mechanisms

The operational foundation of Biofloc Technology lies in manipulating the carbon to nitrogen (C/N) ratio within the water column [4]. In conventional aquaculture systems, inorganic nitrogenous waste particularly total ammonia nitrogen (TAN), which is toxic to fish accumulates as a result of fish excretion and the decomposition of uneaten feed. This waste is typically managed through large-volume water exchange or by nitrification in biological filters, in which autotrophic bacteria convert ammonia into nitrite (NO_2^-) and subsequently into the relatively harmless nitrate (NO_3^-) [7].

BFT adopts a fundamentally different approach. By adding easily

degradable external organic carbon sources such as molasses, jaggery, tapioca flour or other carbohydrates, the C/N ratio in the water is deliberately increased [8-9]. Elevating the C/N ratio above 10:1 often optimally between 15:1 and 20:1 depending on the species shifts the dominant nitrogen-processing pathway [5]. Instead of relying on the slow nitrification carried out by autotrophic bacteria, the system becomes dominated by rapid nitrogen assimilation by heterotrophic bacteria. These bacteria use carbon as an energy source to directly assimilate ammonia from the water column and convert it into cellular biomass, essentially microbial protein [4].

More than just a method for ammonia removal, manipulating the C/N ratio fundamentally reengineers the water column into an in situ biological reactor. This approach transforms nutrient management from a linear model in which inputs (feed) produce outputs (fish) and waste (ammonia) that must be discharged into a circular model [10]. Under the BFT circular model, nitrogenous waste is not discarded; instead, it is recycled and converted into a valuable nutrient input in the form of microbial biomass [4]. Consequently, BFT functions not only as a technology that minimizes or even eliminates the need for water exchange (zero water exchange), but also as a platform for improving overall nutrient-use efficiency [5]. By locking nitrogen into a harmless, consumable protein form, the system directly contributes to reduced feed conversion ratios and lower production costs two key pillars of economic sustainability in aquaculture.

Microbial Communities as the Heart of the Biofloc System

The stimulation of heterotrophic bacterial growth through C/N ratio manipulation results in the formation of macroscopic aggregates known as bioflocs. These flocs are complex and heterogeneous matrices composed of various components, including living and dead bacteria, microalgae, fungi, protozoa, rotifers, uneaten feed particles and fish feces [4]. All these components are bound together by mucus or extracellular polymeric substances (EPS) produced by microorganisms, forming particles that range in size from a few micrometers to several millimeters [4]. This size variation ensures that the flocs can be accessed and consumed by cultured organisms at different life stages, including the nursery phase.

The microbial community within bioflocs is highly diverse, but it is often dominated by heterotrophic bacteria. Studies have identified several important bacterial genera involved in biofloc development, one of the most significant being Bacillus. The presence of Bacillus spp. at high concentrations is

particularly beneficial because many strains within this genus exhibit probiotic activity, enhancing gut health and immune function in fish [4]. The density and composition of the microbial community are directly influenced by management factors, particularly the C/N ratio. Research has shown that higher C/N ratios tend to promote the development of greater and more active bacterial biomass [7].

The function of this microbial community extends far beyond nitrogen assimilation. This dense microbial ecosystem effectively serves as a biological defense system. The dominance of beneficial bacteria creates a highly competitive environment in which established microbial communities suppress the growth and proliferation of opportunistic pathogenic bacteria through the principle of competitive exclusion. In this way, the biofloc community acts as an external immune system that helps protect fish populations from disease outbreaks, an especially important benefit during the highly vulnerable nursery phase.

Additionally, bioflocs function as an auxiliary digestive system. Microorganisms within the flocs actively produce and release various extracellular enzymes such as proteases, amylases and lipases to break down complex organic matter [11]. When fish, including omnivorous species like C. carpio, consume these flocs, they ingest not only the nutrients contained within them but also these active enzymes. The microbial enzymes subsequently aid digestion within the fish gut, enhancing the breakdown and absorption of nutrients from the formulated feed provided [12]. This mechanism explains why BFT can significantly improve feed efficiency and reduce FCR, beyond the direct nutritional contribution of the flocs themselves. This represents an environmentally mediated form of symbiosis, in which fish support the microbial community through excretion and in return, the microbial community provides nutrition, protection and digestive assistance.

Biofloc's Nutritional Composition and Its Contribution

One of the most significant advantages of BFT is its ability to continuously produce high-quality natural feed within the culture system itself (in situ). Bioflocs provide a rich and balanced nutrient source. Proximate analyses consistently show that bioflocs contain high levels of crude protein, generally ranging from 29.8% to 38% of dry weight [13]. In addition to protein, bioflocs also contain lipids (approximately 1.45% to 7%), fiber, vitamins and essential minerals that can be utilized by fish [14].

The availability of bioflocs as an ad libitum supplemental feed source has a substantial impact on nutritional efficiency and production economics. Common carp, being omnivorous and benthic feeders, are well suited to BFT systems because they can actively consume and digest the floc aggregates [15]. Consumption of bioflocs can contribute a significant portion of the fish's daily nutrient requirements, thereby reducing dependence on costly formulated feeds. Numerous studies have documented that natural feed supplementation through bioflocs can dramatically improve feed utilization efficiency, as reflected in reduced Feed Conversion Ratios (FCR). Several reports indicate that BFT can double protein assimilation efficiency and reduce FCR by up to 30% [4,13].

The presence of constantly available bioflocs also changes feeding behavior and feed management strategies. In conventional aquaculture systems, fish are fed at specific intervals, creating periods of hunger and satiety. In BFT systems, fish can continuously graze on bioflocs throughout the day, mimicking their natural feeding patterns [14]. This provides several operational benefits. First, it creates a nutritional buffer against potential feed management errors. If the delivery of formulated feed is delayed or slightly reduced, fish still have access to an alternative food source, thereby reducing competition-related stress and the risk of cannibalism, especially during the nursery phase.

Second, it enables more advanced and cost-effective feed management strategies. Although eliminating formulated feed is detrimental and leads to high mortality [15], feed restriction strategies become highly effective in BFT. Studies show that reducing daily feeding levels (for example, from 6% to 3% of total biomass) can dramatically improve FCR, with improvements exceeding 50% [15]. This occurs because fish compensate for reduced formulated feed inputs by increasing their consumption of protein rich bioflocs. The ability to lower formulated feed usage without significantly compromising growth represents a powerful management tool for optimizing operational costs, given that feed constitutes the largest expense in intensive aquaculture

Evaluation of Nursery Production Performance of *Cyprinus carpio* in a BFT System

A quantitative evaluation of production parameters serves as a primary benchmark for assessing the effectiveness and feasibility of any aquaculture technology. This section provides an in-depth analysis of the performance of

Cyprinus carpio juvenile nursing in BFT systems, with a focus on growth metrics, feed efficiency and survival rates. In addition, the influence of key operational variables, such as stocking density and nutritional formulation on overall system productivity is also examined.

Analysis of Growth Parameters of biota reared in BFT

Data from various studies consistently demonstrate that the BFT system can effectively support excellent growth performance in common carp juveniles, provided that it is properly managed. The stable environmental conditions and continuous availability of natural feed generated by biofloc create an environment conducive to rapid and efficient growth. One study reported that growth parameters and feed utilization in *C. carpio* juveniles were within an appropriate or optimal range when reared in a BFT system with a C/N ratio of 15:1 and a diet containing 25% protein [13]. This indicates that the system not only supports growth but also enables the use of lower-protein feeds, potentially reducing production costs.

Feed Conversion Ratio (FCR) is one of the parameters in which BFT shows its most pronounced advantages. Comparative studies have shown that the presence of biofloc, even when combined with reduced feeding levels, results in markedly superior FCR values compared to control systems without biofloc [15]. This improvement in FCR arises from a synergistic combination of several factors. Enhanced FCR in BFT is not merely the result of supplemental nutrition provided by the floc, it also reflects improved physiological conditions of the fish. Evidence shows that fish reared in BFT systems exhibit stronger immune responses, higher digestive enzyme activity and lower stress levels [13]. Healthier and less stressed fish allocate more metabolic energy toward somatic growth rather than physiological maintenance activities such as combating infection or coping with poor water quality. Thus, the lower FCR observed in BFT is the combined outcome of: (a) additional nutrient intake from the floc, (b) more efficient digestion facilitated by microbial enzymes within the floc and (c) enhanced metabolic efficiency due to superior physiological condition of the fish. This represents a multifactorial synergistic effect rather than a simple summation of feed inputs.

Survival Rate (SR) during the nursery phase is a critical parameter, as juvenile fish are particularly susceptible to stress and disease. The BFT system, by providing stable water quality and suppressing pathogen development through competitive exclusion, has proven to create an

environment that strongly supports juvenile survival. Multiple studies have reported exceptionally high survival rates for *C. carpio* in BFT systems, often reaching 99.33% to 100% under well-managed conditions [16]. These findings underscore that BFT, when properly operated, can significantly reduce the risk of mass mortality commonly encountered in conventional nursery rearing.

Effect of Stocking Density on Productivity and Physiology

Stocking density is one of the most influential management variables in intensive aquaculture [17]. This variable creates a fundamental trade-off between individual fish growth performance and total harvested biomass per unit volume of water. Understanding this relationship is essential for economic optimization.

Studies conducted on Koi carp (*Cyprinus carpio var. koi*), which are highly relevant to common carp used for food production, provide clear quantitative data on the effects of stocking density in BFT systems [18]. At the lowest tested density of 100 fish/m³, the fish exhibited the best individual biological performance. They achieved the highest average weight gain (4.74 g), the highest survival rate (91.54%) and the lowest (most efficient) FCR of 1.57. As stocking density increased to 150 fish/m³ and 200 fish/m³, all these individual performance parameters showed a significant downward trend. At 200 fish/m³, weight gain dropped sharply to only 2.16 g and survival rate decreased to 79.42% (Table 10). This decline in performance is attributed to intensified competition for space and feed, as well as reduced water quality due to increased organic loading. High densities are also known to trigger physiological stress responses in fish, characterized by elevated levels of stress hormones such as cortisol, which in turn can suppress immune function and divert energy away from growth [19].

However, from a commercial perspective, the primary objective is not to maximize individual growth but to maximize the total biomass harvested from each tank. A closer analysis of volumetric productivity reveals a dynamic that is counter intuitive. By multiplying the number of fish surviving at the end of the culture period by the average weight gain, total biomass gain per cubic meter can be calculated. These calculations show that the intermediate stocking density (150 fish/m³) produced the highest biomass yield, reaching 526.4 g/m³. This value is substantially higher than the biomass obtained at low density (433.9 g/m³) and high density (343.1 g/m³) [18].

These findings are crucial because they demonstrate the existence of an

economic sweet spot that differs from the biological optimum. The density of 100 fish/m³, although producing the best individual fish performance, does not fully utilize the biological and productive carrying capacity of the BFT system. Conversely, the density of 200 fish/m³ exceeds the system's carrying capacity, where the negative effects of crowding become severe enough to reduce not only individual performance but also total system productivity. Therefore, practical recommendations for farmers should not simply be use the lowest possible density, but rather identify and operate at the optimal density that balances individual health and growth with total biomass yield to maximize profitability.

Table 10: Comparison of Production Performance and Water Quality Parameters at Different Stocking Densities of Koi Carp (*C. carpio* var. koi) Seed in a BFT System over a 60 Day culture Period

Parameters	**stocking density (100 fish/m³)**	**Stocking density (150 fish/m³)**	**Stocking density (200 fish/m³)**
Initial weight gain (g)	0.64 ± 0.03	0.61±0.01	0.62± 0.02
Total weight gain (g)	4.74 ± 0.30	4.01 ± 0.52	2.16 ± 0.52
Survival rate (%)	91.54 ± 0.58	87.51 ± 0.62	79.42 ± 0.51
Feed Conversion Rate (FCR)	1.57 ± 0.02	1.71 ± 0.04	1.82 ± 0.03
Biomass productivity (g/m³)	433.9	526.4	343.1
DO (mg/L)	6.03 ± 0.11	5.74 ±0.11	5.53 ± 0.09
Ammonia (mg/L)	0.21 ± 0.06	0.27 ± 0.02	0.46 ± 0.09
Nitrite (mg/L)	0.18 ± 0.04	0.24 ± 0.13	0.31 ± 0.07

Source: Adapted and modified from study by Kavitha [18]. The Biomass Productivity column was calculated based on SR and total weight gain.

Interaction between Feed Protein Levels and External Carbon Sources

Nutritional management in BFT systems is a complex and dynamic process, involving interactions among three key components: formulated feed, external carbon sources and the biofloc produced within the system. Optimizing these interactions is essential for achieving production efficiency while minimizing operational costs. One of the greatest potentials of BFT lies in its ability to reduce dependence on expensive, high-protein feeds. Because biofloc itself is rich in protein and essential amino acids synthesized by microbes, it can partially compensate for the fish's protein requirements [10,13]. Studies on *C. carpio* have shown that diets containing relatively low protein levels (25%) combined with a C/N ratio of 15:1 result in favorable growth

performance [13]. This is an important finding, as it enables farmers to use more economical feed formulations without compromising performance, thereby directly increasing profit margins.

The selection of external carbon sources is also a critical factor influencing not only the efficiency of nitrogen removal but also the nutritional quality of the biofloc and the health of the cultured fish [13]. Different carbon sources vary in their decomposition rates and nutritional profiles. Simple sugars such as molasses or jaggery provide rapidly available carbon that can trigger a quick response from heterotrophic bacteria. In contrast, more complex carbohydrates such as rice flour, bran or tapioca flour release carbon more slowly and gradually [20].

A basic approach in BFT management might focus solely on adding the cheapest carbon source to achieve the target C/N ratio. However, more advanced research demonstrates that the type of carbon source qualitatively influences the structure and function of the microbial community. Simple sugars may support rapid growth of opportunistic bacteria, which are efficient at assimilating nitrogen but may produce a less stable microbial community. Conversely, complex carbohydrates tend to promote the development of more diverse and stable microbial communities, which may be more resilient to environmental fluctuations [20].

A species specific study on *C. carpio* found that a combination of jaggery and rice flour as carbon sources produced superior growth performance, body composition and histological health (liver and intestine) compared with single carbon sources [20]. This implies that carbon-source selection is not merely a technical step for achieving the desired C/N ratio, but a strategic tool for engineering the microbial community composition most beneficial to the cultured species. An experienced BFT manager can design a carbon source potion for example, using a small amount of molasses to rapidly initiate floc formation, followed by a switch to slow release flours for long term maintenance, to obtain more precise control over the microbial ecosystem within the tank.

Water Quality Management and Environmental Stability in Aquaculture Systems

Environmental stability is an absolute prerequisite for the success of intensive aquaculture and it becomes even more critical in limited water exchange systems such as BFT. Unlike conventional systems that rely on

frequent water replacement to remove accumulated wastes, BFT depends on a balanced set of internal biological processes to maintain water quality. This section discusses the practical aspects of monitoring and managing key water quality parameters that determine the health and productivity of the BFT ecosystem.

Nitrogen Cycle in Limited Water Exchange Systems

The primary objective of water quality management in BFT systems is to control the concentrations of toxic inorganic nitrogen compounds, such as ammonia (TAN) and nitrite (NO_2^-–N), to meet safety levels for fish. Through the heterotrophic bacterial assimilation process described earlier, a mature, well managed BFT system can maintain TAN concentrations below 0.5 mg/L and nitrite levels near 0 mg/L [7]. Studies focusing on C. carpio have confirmed that implementing a C/N ratio of approximately 15:1 is highly effective in keeping TAN and nitrite fluctuations low and stable [13].

A key characteristic of BFT systems is their dynamic buffering capacity against ammonia spikes [21]. In clear water systems or in RAS units with immature biofilters, sudden increases in nitrogen input, such as from overfeeding or fish mortality, can rapidly elevate ammonia concentrations to lethal levels [22]. In contrast, in BFT systems, the existing heterotrophic bacterial community, already present in high abundance, can respond quickly to ammonia surges as long as carbon availability and dissolved oxygen are not limiting factors [23]. The bacteria rapidly assimilate excess ammonia, converting it into microbial biomass and preventing the onset of toxic spikes.

This buffering capacity makes BFT systems more forgiving toward minor fluctuations in daily feeding management. However, it is important to recognize that this stability is highly dependent on proactive management of supporting factors. The nitrogen assimilation capacity of bacteria is directly constrained by the availability of carbon and, more critically, dissolved oxygen. If an ammonia spike occurs without adequate addition of carbon sources or if aeration fails, the assimilation process will stop. Under such conditions, a previously stable system may rapidly experience a crash, during which ammonia accumulates exponentially and results in mass mortality. Therefore, although BFT possesses inherent resilience, its reliability depends entirely on maintaining continuous aeration and carefully managing the C/N ratio.

Challenges and Management Strategies for Total Suspended Solids (TSS)

Total Suspended Solids (TSS) in BFT systems primarily consist of the biofloc aggregates themselves. TSS plays a dual role, first TSS forms the core of the BFT system, serving as a nutrient rich natural feed source and as a medium for microbial communities responsible for waste processing. On the other hand, excessive accumulation of TSS can lead to several serious problems [24]. When TSS concentrations become too high (generally above 500 mg/L), adverse effects on fish health and system stability may occur [25]. Excess suspended particles in the water can cause irritation and clogging of fish gills, impairing respiratory function and inducing chronic stress [13]. In addition, dense microbial biomass significantly increases the Biochemical Oxygen Demand (BOD), placing additional pressure on the aeration system [7]. Therefore, maintaining TSS concentrations within an optimal range which commonly recommended between 200–500 mg/L, is a critical management task [25].

TSS management is not merely about removing excess solids when concentrations exceed threshold limits. A more sophisticated approach involves proactively managing the old and quality of the flocs. Sudden removal of large amounts of TSS can disrupt the balance of the microbial ecosystem and nutrient cycling within the tank [7]. Older flocs tend to have lower nutritional value and may be dominated by microbial populations that differ from those in younger, newly formed flocs.

A more sustainable management strategy involves gradual and continuous removal of TSS. This can be achieved by integrating additional components into the system, such as a settling chamber or a foam fractionator. A settling chamber operates by diverting a small portion of water from the culture tank into a separate compartment where the flow velocity is greatly reduced, allowing heavier and older floc particles to settle. The clearer water is then returned to the culture tank. This method not only controls overall TSS quantity but also effectively harvests old flocs, thereby stimulating the growth of newer, more biologically active and nutritious flocs. Through this approach, TSS management shifts from being merely corrective to becoming a proactive ecological maintenance tool, ensuring that the floc community remains healthy, active and productive.

Dissolved Oxygen (DO), pH and Alkalinity management

In addition to nitrogen and TSS variables, there are several other

physicochemical parameters must be tightly managed to ensure the stability and productivity of BFT systems.

Dissolved Oxygen (DO): BFT systems have exceptionally high total oxygen demand. This is the combined result of respiration from high density fish populations and the highly concentrated aerobic microbial community within the flocs. Failure to supply sufficient oxygen will rapidly lead to mass mortality, affecting both the cultured organisms and the beneficial microbes. Therefore, strong, uniform and uninterrupted aeration (24/7) is the most critical technical component in BFT operations. DO levels must be consistently maintained above 5 mg/L to support all biological processes within the system [25].

pH and Alkalinity: Intensive respiration by fish and microbes releases substantial amounts of carbon dioxide (CO_2) into the water. This CO_2 reacts with water to form carbonic acid (H_2CO_3), which naturally lowers the pH. In addition, although nitrification is not the dominant pathway in BFT, it still occurs to some extent and consumes alkalinity while producing hydrogen ions, further contributing to pH reduction [7]. A drastic drop in pH can stress the cultured organisms and inhibit microbial activity. Alkalinity functions as a chemical buffer that resists these pH shifts. Thus, monitoring and managing pH and alkalinity are essential. The ideal pH range for BFT systems is generally between 6.5 and 8.0, while alkalinity should be maintained at 100–150 mg/L as $CaCO_3$ [25]. To maintain these parameters, periodic supplementation with buffering agents such as lime (calcium carbonate, $CaCO_3$) or sodium bicarbonate ($NaHCO_3$) is often required.

The constant and high aeration requirement also has significant economic implications. Analyses of other intensive aquaculture systems, such as RAS, consistently identify energy costs as one of the largest components of operational expenses (OPEX), reaching up to 47% of total production costs in some cases [26]. Although BFT does not require large water circulation pumps as RAS does, its energy demand for aeration is comparable or even higher due to the additional BOD generated by floc biomass. This means that the cost savings achieved through improved feed efficiency and reduced water exchange in BFT may be offset or even exceeded, by high electricity consumption. As a result, the profitability of BFT operations is highly sensitive to local electricity prices and the energy efficiency of the chosen aeration equipment (e.g., roots blowers vs. individual aerators). Profit loss analysis for BFT projects should therefore include explicit sensitivity analyses

on energy price fluctuations to obtain an accurate picture of financial risk.

Profit and Loss Analysis in BFT Based Nursery Operations.

The successful adoption of new aquaculture technologies depends not only on their technical and biological advantages but also on a sound profit loss analysis. This section translates the production performance data and management requirements of the BFT system into a financial framework by examining cost structures, revenue potential and key profitability indicators. The objective of this analysis is to provide a concrete and realistic assessment of whether the nursery production of *Cyprinus carpio* using the BFT system is financially viable.

Investment Cost Structure (CAPEX): A Detailed Analysis of Initial Capital Requirements

Capital Expenditure (CAPEX) encompasses all initial costs required to construct and prepare a BFT facility before operations can begin. Although BFT is an intensive system, one of its advantages is that its CAPEX is generally lower than the other mechanically complex intensive systems such as Recirculating Aquaculture Systems (RAS) [4]. This is because BFT does not require expensive external mechanical and biological filtration units; waste treatment occurs directly within the culture tanks.

The major components of CAPEX for a BFT nursery unit include the provision of culture tanks, typically utilizing circular tarpaulin tanks with metal frames or fiberglass variants, with tarpaulin models offering a more economical initial investment. Additionally, supporting infrastructure is necessary, encompassing the construction of shade structures to protect the tanks from extreme weather, alongside the installation of comprehensive piping networks for water and air distribution. The aeration system represents the most critical technical and cost component, requiring investments in roots blowers for larger-scale operations or individual aerators, integrated with an air distribution network of tubing and diffusers. Other essential capital expenditures include a backup power source, such as a suitably sized generator, to mitigate aeration failure during power outages. Furthermore, facilities must invest in water quality equipment, harvesting and sampling tools and a reliable water source established through well drilling and pump installation [27].

As an illustration sourced from India's National Fisheries Development Board (NFDB) project on Biofloc. This is a project model for a small scale

BFT unit consisting of seven tanks with a capacity of 15,000 liters each estimated a total initial capital investment of approximately Rs. 600000 (around USD 8520 at the exchange rate at that time) [27]. Larger scales, for example units with 50 tanks, it would require substantially higher total investment, but often with lower per unit costs due to economies of scale.

One strategic advantage of BFT is its modular design. Unlike RAS, which typically requires the construction of large and expensive centralized filtration units from the outset, BFT allows for more flexible investment scalability. Each tank can be considered a relatively independent production unit. Entrepreneurs can start with a small-scale setup (e.g., a seven tank model) with a more accessible CAPEX. Profits from the first production cycle can then be reinvested to gradually increase the number of tanks. This incremental approach significantly reduces the barrier to entry and minimizes financial risk at the start, making BFT an attractive option for small and medium enterprises (SMEs) seeking to transition into intensive aquaculture.

Operational Expenditure (OPEX) Structure: Variable and Fixed Cost Components per Production Cycle

Operating Expenditure (OPEX) encompasses all costs incurred during the production process and is the primary determinant of short-term profitability. These expenditures are divided into variable costs, which fluctuate according to production scale and fixed costs, which remain relatively constant. Within the variable cost parameters, feed consistently represents the largest component in intensive aquaculture, often accounting for 40–60% of total production costs [26]; however, BFT aims to directly reduce this expense by improving the Feed Conversion Ratio (FCR). Additional variable costs include the acquisition of high-quality fish seed, continuous electricity consumption required for 24-hour aeration and BFT-specific inputs such as carbon sources, probiotics and buffering agents [26]. Conversely, fixed OPEX components entail labor salaries for daily system management, depreciation of the initial capital investment over the equipment's lifespan and routine maintenance and repair expenses. The adoption of BFT fundamentally reshapes this OPEX structure compared to conventional aquaculture systems, creating a distinct profile of risks and opportunities. While improved FCR makes BFT enterprises more resilient to feed price fluctuations, the 24/7 aeration requirement significantly increases the proportion of energy-related costs, making profitability highly sensitive to electricity prices.

For the same 7 tank model, the total input costs (primarily variable

OPEX) for a single nursery cycle (approximately six months) are estimated around USD 2130 [27]. The adoption of BFT fundamentally reshapes the structure of OPEX compared with conventional aquaculture systems, creating a distinct profile of risks and opportunities. Traditional pond based systems, for example, have very high feed costs and relatively low energy costs. As a result, their profitability is highly vulnerable to fluctuations in feed prices. In contrast, BFT through its improved FCR and the potential use of lower protein feeds. FCR improvement can reduce the proportion of feed costs within the OPEX structure, making BFT based enterprises more resilient to increases in feed prices. However, this shift simultaneously increases the proportion of energy related costs, making profitability highly sensitive to electricity prices.

Therefore, a comprehensive feasibility analysis for BFT should not rely solely on static cost calculations. It must include a sensitivity analysis that models how profitability will change under different future scenarios of feed prices and energy costs, as recommended for other intensive systems [28]. Such analyses help reveal the greatest financial risks and support sound strategic decision making.

Profitability Analysis: Return on Investment (ROI) and Payback Period

The profitability of BFT, when operated with proper and efficient management, has been reported to be highly promising [4]. Using data from the 7 tanks model as a case study, we can project its potential profitability with adapt from case study on India's NFDB

Table 11: Cost and Profitability Projection Model for a Small-Scale *C. carpio* Nursery Unit Using Biofloc Technology (Case Study: 7 Tanks, OneYear Operation with Two Cycles)

Category	**Items**	**Quantity/Cycle/formula**	**Cost/Unit Price (USD)**	**Total Cost (USD)**
A. Capital Expenditure (CAPEX)	Construction of tarpaulin tanks (15000 L) and the frames	7 units	355	2485
	Shade structures and installations	200 m²	8.5/m²	1704
	Aeration system	1 set	426	426
	Emergecy Power Source (2 KVA generator)	1 unit	639	639
	Borehole and Pump	1 set	1420	1420
	Other Equipment (Pipes, Nets, etc.)	1 set	1846	1846
	Total CAPEX			8520
B. Operating	Seeds, Feed, Probiotics,	2 cycles	2130 /Cycle	4260

Expenditure (OPEX) per Year	Carbon source, Electricity, etc.			
C. Annual Revenue and Profit Projection	Total Fish Production (2 cycles @ 4200 kg)	8400 kg	-	-
	Fish Selling Price	-	1.846 /kg	-
	Annual Gross Income	-	-	15506
	Annual Gross Profit (Revenue - OPEX)	-	-	11246
	Annual Fixed Cost (Depreciation @15% CAPEX)	1 year	-	1278
	Annual Net Profit (Before Tax)	(Annual Gross Profit - Annual Fixed Cost)	-	9968.4
	Return on Investment (ROI)	(Annual net profit / CAPEX)x 100%	-	117%
	Payback Period (PP)	(total CAPEX / Annual Net Profit)		0.85 year (10 month operational)

Source: Adapted from the NFDB model [27]. The figures presented in USD are illustrative conversions and may vary, while the depreciation values are estimations.

The analysis above (Table 11) indicates a very high potential profitability for small-scale BFT operations. With an annual ROI exceeding 100% and a payback period of less than one year, this investment appears highly attractive. Other studies on tilapia cultured in BFT systems have also reported very favorable Benefit Cost Ratios (BCR), ranging from 1.81 to 2.71, further reinforcing the conclusion that BFT can be a highly profitable enterprise [12].

However, it is important to note that this profitability does not depend solely on technical efficiency at the tank level. Economies of scale and market strategies play equally critical roles. Studies on other intensive systems have shown that doubling the production scale (e.g., from 300 m^3 to 600 m^3) can significantly reduce the production cost per kilogram of fish because fixed costs (such as labor and depreciation) are distributed across a larger production volume, thereby increasing profit margins [26].

In addition, post harvest strategies are highly influential. Selling value-added products such as fillets or processed items can increase revenue and ROI exponentially compared with selling whole fish to wholesale markets [26]. Therefore, the most comprehensive BFT business planning should include not only biological optimization but also efficient operational scaling and the development of post harvest value chains to capture greater profit margins.

Comparative Study on Economic Advantages and Limitations of Biofloc Technology (BFT)

To understand the position of BFT within the broader landscape of aquaculture technologies, it is essential to compare its economic profile with other production systems. Conventional earthen ponds offer significantly lower CAPEX, especially when land is readily available; however, their drawbacks include very low productivity per unit area, poor feed efficiency and minimal biosecurity control. In contrast, BFT requires a higher CAPEX for tanks and aeration but provides multiple-fold increases in volumetric productivity, superior feed efficiency and the ability to operate in limited land areas, while also demonstrating greater resilience to external climate factors such as flooding or drought. On the other end of the intensification spectrum, Recirculating Aquaculture Systems (RAS) provide the most precise environmental control and support maximum stocking densities, but this comes at the cost of exceedingly high CAPEX due to complex mechanical and biological filtration infrastructure. BFT presents a lower financial barrier than RAS because biological waste processing is integrated directly into the culture tanks; however, it relies more heavily on the delicate stability of its microbial ecosystem, whereas RAS depends on the reliability of engineered mechanical components[4]. Thus, BFT occupies a strategic techno-economic niche, serving as a transitional intensification pathway for pond-based farmers seeking to increase production without the prohibitive capital and technical requirements of a full-scale RAS.

Synthesis, Prospects and Strategic Recommendations

Following an in depth evaluation of the technical and economic aspects of implementing Biofloc Technology (BFT) for the nursing phase of *Cyprinus carpio*, this final section synthesizes the key findings, discusses the prospects of this technology within the broader context of sustainable aquaculture and formulates actionable strategic recommendations for practitioners, researchers and policymakers.

Synthesis of Technical Advantages and Challenges in the Implementation of Biofloc Technology (BFT) for *Cyprinus carpio*

This comprehensive analysis highlights a set of inherent advantages and challenges associated with the application of the Biofloc Technology (BFT) system for common carp nursing. Foremost among its technical advantages is high volumetric productivity, which enables fish to be reared at much higher

stocking densities than in conventional systems, thereby maximizing biomass yields. Furthermore, BFT consistently produces superior feed efficiency through in situ nutritional supplementation and improved digestive health, leading to lower Feed Conversion Ratios. The technology also promotes drastic water conservation by operating with minimal to zero water exchange, making it highly suitable for regions with limited freshwater resources. Additionally, the stable environmental conditions and the presence of probiotic microbial communities enhance immune responses and reduce stress, culminating in exceptionally high survival rates for juveniles. Conversely, BFT implementation presents notable challenges, particularly a high dependence on continuous aeration to support both the fish and the dense microbial biomass, which elevates energy costs and creates vulnerability to power outages. Furthermore, operators must navigate complex Total Suspended Solids (TSS) management, requiring continuous monitoring and adaptive strategies to prevent adverse impacts on fish health and system stability. Finally, the dynamic, ecology-based nature of BFT necessitates a steep technical learning curve, demanding higher technical proficiency than traditional pond aquaculture to successfully balance critical parameters such as the C/N ratio, alkalinity and dissolved oxygen.

Sustainability Prospects of Biofloc Technology (BFT) on Environmental, Social and Economic Dimensions

Biofloc Technology aligns strongly with the principles of sustainable development and addresses many of the pressing challenges faced by modern aquaculture across multiple dimensions [14]. From an environmental sustainability standpoint, BFT significantly mitigates ecological impacts by minimizing water usage and internally recycling nutrient waste, which curtails the discharge of nitrogen- and phosphorus-rich effluents known to drive eutrophication. Furthermore, its high spatial efficiency reduces the pressure to convert natural ecosystems into agricultural zones. In terms of economic sustainability, BFT provides a strategic pathway toward efficient intensification by lowering feed expenses, typically the largest operational cost and amplifying productivity per unit area, thereby improving overall profitability and resilience for farmers. Although initial capital investments and continuous energy requirements pose hurdles, the high potential return on investment renders BFT an appealing financial endeavor. Socially, the modular and scalable nature of BFT democratizes access to intensive aquaculture, accommodating diverse production scales ranging from smallholder farmers to large corporate entities. By facilitating aquaculture

development in urban and peri-urban areas where land and water are severely constrained, BFT actively contributes to strengthening local food security, generating employment opportunities and fostering community economic empowerment.

Recommendations for Practitioners and Policy Makers

Based on the synthesis and analyses conducted, several strategic recommendations can be proposed to optimize the implementation and future development of BFT. For practitioners and farmers, it is essential to optimize stocking density by focusing on maximizing total biomass yield per tank rather than merely pursuing the fastest individual growth; initiating culture at a moderate density, such as 150 fish/m³ for C. carpio, allows for empirical adjustments based on systemic carrying capacity. Farmers must also prioritize energy reliability by investing in energy-efficient aeration systems and dependable backup generators to mitigate the catastrophic risk of power failure. Additionally, practitioners should implement smart carbon source management by utilizing a dynamic combination of inputs, such as molasses for rapid initiation and rice flour for stable maintenance to engineer optimal microbial ecosystem stability. To safeguard water quality, it is crucial to apply proactive TSS management, utilizing gradual removal strategies like sedimentation basins to consistently maintain biofloc quality and quantity within ideal parameters.

For researchers and policymakers, the sustained success of BFT relies on supporting applied research tailored to local conditions to establish optimal operational parameters for critical species across various life stages. Given the steep learning curve associated with the technology, government agencies and relevant institutions must develop and facilitate comprehensive dissemination and practical training programs to adequately equip farmers. Policymakers should also evaluate energy incentive policies, such as introducing subsidies for renewable energy integration or specialized electricity tariffs for intensive aquaculture operations, to enhance both economic and environmental sustainability. Ultimately, simplifying access to capital through targeted financing schemes for BFT investments will encourage broader adoption among small and medium-scale enterprises, accelerating the modernization of the national aquaculture sector.

Conclusion

BFT presents a highly sustainable and economically viable approach for

the intensive nursery culture of common carp (*Cyprinus carpio*). By manipulating the carbon to nitrogen (C/N) ratio, the BFT system effectively converts toxic nitrogenous waste into nutrient rich microbial biomass, thereby maintaining in situ water quality and providing a natural supplemental feed source. This dual function mechanism significantly enhances biological production performance, yielding excellent survival rates of 99–100% and improving overall feed efficiency through a lower FCR. Furthermore, maintaining an optimal stocking density of 150 fish/m³ maximises total biomass productivity, effectively balancing individual fish growth with overall system yield. From an economic perspective, BFT is highly promising, particularly for small scale operations, with financial projections demonstrating strong viability, including a ROI exceeding 100% and a payback period of less than 1 year. However, the successful implementation of this technology requires strict attention to its operational limitations, as profitability and system stability are highly sensitive to energy costs, given the absolute necessity of continuous 24 hour aeration and the proactive management of TSS. Ultimately, BFT serves as a strategic, modular and environmentally friendly pathway for aquaculture intensification, if practitioners possess adequate technical management skills and secure reliable energy sources.

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8
CHAPTER

Genetic Improvement and Selective Breeding of Common Carp for Sustainable Aquaculture Productivity

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Abstract

Common carp remains a major freshwater fish commodity that supports both food security and global aquaculture development. The production of common carp faces multiple challenges, which include its slow growth rate, low survival rate, high vulnerability to diseases, deterioration of seed quality, impacts from climate change and intensified aquaculture. This paper discusses the biological characteristics and production potential of common carp, along with key genetic principles including heritability, breeding value and genetic diversity management. Various selection methods, including mass selection, family selection, combined selection and genomic-based approaches, are reviewed for their effectiveness in improving economically important traits. Emphasis is placed on target traits such as growth rate, feed conversion efficiency, disease resistance and environmental tolerance. The implementation of breeding programs is also addressed, highlighting the importance of broodstock management, controlled mating systems, performance evaluation and inbreeding control. A case study on Mustika carp (*Cyprinus carpio*) demonstrates the practical benefits of selective breeding, including improved growth performance, survival rate and feed efficiency. Future perspectives emphasize the integration of genomics, artificial intelligence and precision aquaculture to accelerate genetic gains. Overall, genetic improvement represents a key strategy for achieving efficient, resilient and sustainable aquaculture systems.

Keywords: Common carp, genetic selection, aquaculture, Mustika, KHV

Introduction

The aquaculture sector serves as the world's fastest expanding food production industry, which provides essential animal protein through its sustainable growth capacity [1]. The decline of capture fisheries, which results from overfishing, habitat loss and climate change, creates a need for aquaculture to serve as a vital solution to protect worldwide food supply systems. The establishment of sustainable aquaculture systems now serves as the primary objective because these systems enable producers to boost their output while minimizing environmental and aquatic resource and wildlife conservation impacts. The common carp represents a vital freshwater species that has substantially advanced this industry.

The common carp functions as a vital aquaculture species because of its fast growth rate and capacity to live in different environmental conditions, straightforward breeding methods [2]. The species exists across different production environments, which include earthen ponds, concrete ponds, floating net cages and modern intensive systems. Common carp operates as a crucial economic resource that generates income for numerous small and medium farmers across Asian countries. The common carp industry faces multiple productivity obstacles across different regions due to its low feed efficiency, high disease vulnerability, variable seed quality and inbreeding, which lead to decreased performance. The solution to these problems relies on genetic enhancement through selective breeding, which has become a crucial method. The goal of genetic selection is to create improved strains that possess both better economic traits and better biological attributes than their original population. The directed breeding program for common carp will result in improved growth rate, feed conversion efficiency, disease resistance, environmental stress tolerance and flesh quality. The selection programs that use reliable data for their implementation will produce sustainable productivity improvements, thus making this approach one of the best methods used in modern aquaculture development.

New methods for breeding fish have emerged because molecular genetics and genomics have developed beyond traditional selection techniques. The use of molecular markers combined with family-based selection and genomic selection methods offers improved identification abilities for superior breeding candidates [3]. The common carp industry will gain competitive advantages through technology integration and efficient aquaculture

management practices. This chapter explains the concepts and methods together with their practical uses for genetic improvement and selective breeding of common carp, which will enhance sustainable aquaculture productivity. The discussion includes common carp biological characteristics, together with breeding genetics principles, selection methods, target traits, implementation of breeding programs and upcoming technological developments.

Biology and Production Potential of Common Carp

The common carp serves as the most popular freshwater fish species worldwide while serving as a crucial fish species for sustainable aquaculture development. This species belongs to the family *Cyprinidae* which exhibits the ability to thrive in various environmental situations. Common carp is believed to have originated from Eurasia and later spread across Asia, Europe, also Africa through trade and aquaculture activities [4]. Today, common carp is an important commodity in many countries because it is easy to culture, has stable market demand and can be farmed at various production scales. Common carp exhibits an elongated body shape that appears flattened at the sides and displays large scales throughout its body. The body color of the fish varies based on its strain and the conditions of its rearing environment which produce shades that range from golden and greenish to grayish tones. The mouth of the carp opens at the front and contains two pairs of barbels, which help it find food on the bottom of the water body. The carp's body structure provides both strength and flexibility, which allows it to swim actively and move between stagnant water and running water areas.

The common carp exhibits its fastest growth rate when it experiences optimal conditions during its rearing process. The common carp reaches marketable size within a brief period when both feed and water quality management are conducted properly. The species possesses another beneficial trait, which enables it to consume various types of food because it eats both plant and animal material and prepared feed. The ability to feed through different methods enables producers to save money because they can use different types of feed and create their own local diets. The breeding process of common carp involves simple methods because the species reproduces in large numbers through both natural and artificial reproduction methods. The females of this species produce numerous eggs, while the proper use of hatchery methods results in high hatchability rates. The species maintains seed production throughout the year because of its effective breeding process,

which supports continuous seed creation. The environmental adaptability of common carp serves as a key factor that establishes its value for aquaculture purposes. This species can survive across a relatively wide range of temperature, pH and dissolved oxygen conditions compared with several other freshwater fish species.

Common carp can be cultured in earthen ponds, concrete ponds, floating net cages, rice–fish farming systems and modern recirculating systems. This versatility allows for the farming of common carp in underdeveloped or technologically developed locations. Economically, common carp has good market rentability, as the flesh of common carp is accepted by almost all consumers in the majority of countries. With a stable demand, common carp becomes a source of income for subsistence, semi-commercial and large commercial farmers. Apart from being eaten fresh, common carp can also be processed into a variety of textiles and frozen, smoked, fish fillets, fish balls and fish products. However, the production potential for common carp farming can also be set by the farming of better carp stock. Through carp stock, there is a real potential to work towards better cultures and provide carp with improved growth on less feed and with increased resistance to disease. A good understanding of the biology and the production potential of common carp is the basis for developing aquaculture and the enhancement of the farming system.

Principles of Genetic Improvement of common carp

One of the main tactics used in contemporary aquaculture development to create cultured fish that are more effective, productive and tolerant to environmental stresses is genetic enhancement. Because many economic features, including growth, feed efficiency, disease resistance and reproductive success, are regulated by genetics and their interaction with the environment, the application of genetic concepts is crucial in common carp farming [5]. Selective breeding projects can be carried out methodically and sustainably with a solid grasp of genetic concepts. A mix of genes from the male and female parents is present in every fish. Numerous biological characteristics are determined by these genes, including quantitative characteristics like growth rate and survival ability, as well as qualitative characteristics like body shape and color. Individuals in cultivated communities vary genetically. Selection is based on this variation since breeding cannot advance in the absence of genetic distinctions. Therefore,

starting improvement projects in common carp strains requires a foundation population with a significant level of genetic variation.

Breeding relies on heritability which measures how much genetic factors lead to observed physical differences that can be inherited by upcoming generations [6]. A characteristic that responds effectively to selection is indicated by a high heritability value. Fish development traits show moderate to high heritability according to research which indicates that selecting adult fish with greater body weight will improve their offspring performance. The environmental factors that shape specific traits require detailed assessment methods and selection procedures. The concept of breeding value holds equal importance to the study of heredity. The breeding value for a broodstock individual shows its genetic potential to transmit valuable traits to its offspring. The breeding value of a fish depends on its environmental conditions which determine its highest potential attributes. Modern selection methods use progeny data along with pedigree relationships and family performance information to assess individual looks.

The management of genetic diversity serves as an important factor that determines all aspects of long-term success. The practice of inbreeding occurs when people use closely related breeding partners or when they breed animals in their control group. The practice of inbreeding leads to multiple negative outcomes that include a decrease in growth speed along with decreased survival rates and lower reproductive success and an increase in vulnerability to diseases. The breeding programs require breeders to maintain complete pedigree documentation while they use different breeding pairs and they must maintain proper effective population size requirements. The study needs to include both the genotype and environmental factors. The fish species which perform well in clay ponds cannot achieve the same results in biofloc systems and cage systems. The breeding results should meet farmers' needs because superior strains need testing in production environments that match their actual system. Genetic enhancement programs have become stronger through the advancement of molecular technology. The process of finding genes or genomic DNA regions linked to specific traits becomes achievable through DNA markers and genomic analysis and marker-assisted selection. The new technologies enable faster selection processes than traditional methods while increasing the accuracy of the selection process. The principles of genetic improvement focus on five main areas which include genetic diversity and trait inheritance and proper broodstock selection and inbreeding control and environmental evaluation. The implementation of these ideas through proper

usage will create common carp strains that achieve better production results while maintaining resource efficiency and environmental compatibility which supports sustainable aquaculture production.

Selective Breeding Methods for Common Carp

The methods used to choose fish breeders in common carp farming directly determine how successfully breeding programs achieve their genetic improvement goals. The process of selecting fish with the best performance to serve as broodstock for the following generation is known as selection [7]. The primary goal of the project aims to increase the frequency of better genes in the population because this method will enable sustainable growth of economically important traits which include rapid growth and high feed efficiency and disease resistance and adaptability. The selection process needs to consider the breeding objectives together with the available resources and technological capabilities and production systems. The most basic method of mass selection actually functions as the most commonly used selection method. The process of this method selects individuals based on their phenotypic characteristics which include body weight and length and shape and survival rate. The process selects broodstock by eliminating the weaker performers and retaining the individuals who exhibit the highest performance levels. The process of mass selection provides multiple advantages because it enables simple operation and remains cost-effective and needs only basic recording information. The system serves as the best solution for small to medium-sized farming operations. The system uses simple methods for genetic analysis but its main weakness stems from its inability to separate genetic and environmental factors which results in less accurate selection outcomes.

Another approach is family selection, in which candidates are selected based on how well families or children from particular parental pairs perform. The top-performing families are chosen as sources of broodstock for the following generation after each family is raised and assessed independently. This method works well for characteristics like feed efficiency or disease resistance that are hard to quantify separately. Because family selection incorporates genetic information from relatives, it is more accurate; yet, it necessitates additional facilities, manpower and data administration. Combined selection is a mix of family and individual selection. This approach finds the finest broodstock candidates by utilizing both individual and family performance data. Combined selection generally provides a higher selection

response because it utilizes more complete information. In modern breeding programs, this method is widely used for economically valuable aquaculture species, including common carp.

In addition to within-population selection, crossbreeding is frequently used to take advantage of various strains' advantages [8]. To create offspring with improved performance, such as quick growth from one strain and disease resistance from another, two or more populations with different features are crossed. Crossbred offspring frequently exhibit heterosis or hybrid vigor, which means that the progeny perform better than their parents. To prevent long-term genetic instability, crossbreeding operations must be properly planned. Advances in biotechnology have led to the introduction of genomic and marker-assisted selection techniques. Using DNA markers linked to desired characteristics, marker-assisted selection enables the identification of superior candidates at the seed stage without the need to wait for maturity. In the meantime, genomic selection makes more precise predictions about breeding value by utilizing thousands of markers throughout the genome. These technologies are very promising for the aquaculture industry of the future since they speed up genetic gain. In actuality, population size, uniformity across generations, inbreeding control, data quality and methodology all play a role in successful selection. As a result, long-term planning and ongoing assessment are necessary for common carp reproduction. Common carp productivity can be greatly increased to enable profitable, effective and sustainable aquaculture by selecting the right selection techniques.

Target Traits for Sustainable Productivity

Successful projects that aim to enhance common carp genetics need to find specific features which require improvement [9]. Aquaculture systems use target traits to identify important qualities which have economic value and biological significance and ecological importance. Breeding programs require breeders to select traits which will lead to sustainable production increases. Modern aquaculture now pursues resource efficient methods which promote fish health and animal welfare while developing fish species that can withstand environmental changes. The most common trait which researchers study is growth rate. Fish that grow faster reach market size at an earlier age which enables producers to complete more harvesting cycles throughout the year. Faster growth enables producers to reduce their expenses because of the decreased time needed for fish production. Fish breeders focus on body weight

total length and biomass gain as essential growth indicators which they use to evaluate common carp growth in breeding programs.

The essential trait of feed efficiency emerges as a key characteristic. The economic impact of aquaculture operations arises from feed costs which represent the largest budget item for fish farms. The industry uses feed conversion ratio (FCR) and protein efficiency ratio together with growth per unit of feed consumed to measure feed efficiency. Fish species with low FCR values require less feed to achieve the same weight gain, which results in their classification as more efficient. The selection of feed efficiency results in lower organic waste production, which leads to reduced nutrient discharge into water bodies and supports environmental sustainability. The second strategic element of the system establishes disease resilience as its core component. Bacteria and viruses together with parasites spread through intensified farming systems which create ideal conditions for their transmission. The outbreaks of infectious diseases result in substantial economic damages and widespread mortality among affected populations. The development of common carp strains with enhanced disease resistance and superior immune protection should proceed through dedicated research efforts. The assessment of this trait can be performed through testing under challenging conditions, which measures survival rates and uses molecular marker techniques for evaluation.

Environmental stress tolerance stands as a crucial component for achieving success in aquaculture operations according to research findings presented in reference [10]. Climate change together with high stocking density practices leads to multiple environmental problems that include temperature variations, dissolved oxygen depletion, pH fluctuations, salt concentration increases and declining water quality conditions. Fish species that possess high adaptive capacity can live and thrive even when environmental conditions become suboptimal. The common carp breeding process uses stress tolerance selection to produce more resilient strains which suit different industrial application methods. Product quality attributes have become essential to market success of products. Consumers show greater interest in body size consistency and food safety together with flavor and color and fat content and flesh texture. Current breeding programs use consumer preferences and fillet quality as selection criteria to increase product value through breeding. Reproductive characteristics, including fertility and egg quality and hatchability and larval viability, hold vital importance because they determine the success of seed generation. The actual relationship between different features can exist as either a positive or negative genetic correlation.

The selection of rapid growth as the sole breeding criterion will result in reduced reproductive efficiency and loss of disease resistance. The best possible solution requires selection of multiple traits. Common carp breeding projects can produce superior strains that are not only productive but also long-term economically and ecologically sustainable by striking a balance between growth, feed efficiency, health, environmental adaptation and product quality.

Breeding Program Implementation for sustainable aquaculture

The success of genetic improvement in common carp depends not only on theory and selection methods, but also on well-planned, consistent and data-driven breeding program implementation. A breeding program is a systematic series of activities starting from the establishment of base populations, broodstock selection, controlled mating, progeny evaluation and finally the distribution of superior seed to farmers [11]. Without proper execution, genetic progress cannot be fully realized. Therefore, management aspects are critical for long-term success.

The first step in implementation is establishing a base population with high genetic diversity. This population may originate from several local strains, introduced stocks or a combination of both. The purpose is to provide a broad source of genetic variation so that selection can generate a greater response. Before use, each population should be evaluated for growth, survival, environmental adaptability and health performance. The quality of the base population strongly influences future generations. Once the base population is established, the next step is broodstock management. Male and female broodfish should be selected based on phenotypic criteria, performance history and good health condition. Deformed fish, slow growers or fish showing disease symptoms should be removed. Broodstock maintenance requires balanced nutrition, stable water quality and suitable stocking density to ensure optimal reproductive performance. Proper broodstock identification records are essential to avoid inbreeding and to facilitate pedigree tracking.

Controlled mating systems are the core of breeding programs. Mating can be conducted through single-pair mating, factorial mating or family systems, depending on selection objectives. In common carp, induced spawning is often used to ensure planned parental combinations [12]. Eggs and larvae from each mating pair should be reared separately at early stages so that family identity is preserved. This allows objective comparison of offspring performance among parental combinations. Performance evaluation is carried out from the

nursery to the grow-out stages. Parameters commonly observed include body weight growth, body length, survival rate, feed efficiency, disease resistance and size uniformity. Collected data are analyzed to determine the best individuals or families as broodstock candidates for the next generation. In modern programs, statistical models and breeding software are used to estimate breeding values more accurately.

Inbreeding control must receive special attention during implementation. Repeated use of the same superior broodstock can reduce genetic diversity and lead to inbreeding depression [13]. To prevent this, mating pair rotation, sufficient effective population size and periodic introduction of new genetic material may be required. These strategies help ensure sustainable long-term genetic gain. Distribution of breeding outputs to end users is also an important component of program implementation. Superior seed should be mass-produced under quality standards and distributed through hatcheries or community seed centers. Technical assistance to farmers is necessary so that the genetic potential of improved seed can be expressed under proper farming management. Several superior common carp strains developed through selection have been established globally to enhance common carp production, each possessing its own specific desirable traits.

Selective breeding programs for common carp have been developed in various countries, with different trait priorities reflecting the needs of their aquaculture industries. In Indonesia, the development of carp strains such as Rajadanu, Mustika and Sutisna has focused on improving growth performance, environmental adaptability, disease resistance and tolerance to brackish or saline water conditions. Meanwhile, China is recognized as a pioneer in modern common carp breeding through strains such as Songpu Mirror Carp, which demonstrated increased productivity through multi-generational selection [14]. Countries in Europe have generally emphasized traits related to climate adaptation, feed efficiency and carcass quality. Overall, the success of these strains demonstrates that genetic selection can significantly improve aquaculture performance by accelerating growth, increasing survival and improving adaptation to specific environmental conditions. This confirms that breeding programs are a fundamental pillar in supporting the productivity and sustainability of global common carp aquaculture. One example of a selectively bred common carp strain is Mustika common carp (Figure 5). Mustika common carp is one of the superior strains developed through breeding programs in Indonesia to enhance aquaculture performance facing Koi herpes virus (KHV) desease.

Fig. 5: Broodstock and fingerling of Mustika carp (*Cyprinus carpio*). Source: personal documentation

Mustika carp was developed through a family-based selection process combined with marker-assisted selection. The main advantages of Mustika common carp lie in its resistance to Koi Herpesvirus Disease, relatively fast growth, high survival rate and better tolerance to changes in water quality, including suboptimal environmental conditions such as low salinity. These traits are particularly important for aquaculture development in areas with limited freshwater resources or in coastal regions affected by seawater intrusion. In addition, Mustika common carp shows good feed response, thereby offering strong potential to improve production efficiency and reduce farming costs. With its combination of superior growth, environmental resilience and broad adaptability, this strain has strong potential to become one of the leading candidates for supporting modern aquaculture systems that are productive, efficient and resilient to climate change

Table 12: Specific growth rate, survival rate, body weight and feed conversion ratio of the Mustika carp cultured in earth ponds for three months

Trait	**Value**
Specific growth rate (%)	
Mustika carp	2.29 ± 0.04
Control population	1.96 ± 0.05
Survival rate (%)	
Mustika carp	49.13 ± 6.88
Control population	47.33 ± 0.95
Body weight (g)	
Mustika carp	393.98 ± 3.53
Control population	284.68 ± 6.00
Feed conversion ratio (FCR)	
Mustika carp	2.35
Control population	3.29

The specific growth rate of Mustika common carp was relatively higher than that of the control population, presumably due to the contribution of selected genotypes from previous breeding activities, resulting in stable population performance and a positive effect on body weight growth during the culture period. The phenotypic performance of a variety or genotype is influenced by genetic factors, environmental conditions and possible interactions between these two factors. In addition, the adaptability of Mustika common carp to the culture environment was relatively higher than that of the control, allowing more energy to be allocated for growth rather than environmental adaptation. In general, survival rates among populations still showed relatively high average values. One possible reason is that fish stocking density in this study was relatively low, so competition for feed remained within a normal range. However, the ability of Mustika common carp to survive and adapt to pond conditions, as well as to biotic and abiotic factors, was better than that of the control population, resulting in higher survival. Several factors affecting survival include both abiotic and biotic components such as competitors, stocking density, population structure, age and the organism's ability to adapt to its environment.

Chi-square analysis of body weight traits showed a significant difference (Asymp. Sig < 0.05), indicating rejection of H0 and acceptance of H1. Therefore, it was concluded that there was a significant difference in weight growth between Mustika carp and control from the small-scale hatchery unit (SSHU). In addition, the standard deviation of mean individual body weight in the selected common carp population was lower than that of the SSHU population (Table 12). This result indicates that Mustika common carp had a higher degree of uniformity among individuals. In other words, fish size within the Mustika population was more uniform than that of the SSHU seed population. This condition was likely due to prior selection activities carried out on the Rajadanu carp strain, which helped maintain phenotypic uniformity. Selection does not create new genes, but it can alter the frequency of certain alleles to obtain desirable phenotypic traits such as rapid growth, disease or environmental resistance, high fecundity and others. Feed conversion ratio (FCR) is the comparison between the amount of feed given and the final fish biomass plus the biomass of dead fish, minus the initial biomass or the total weight gain produced. In this case, the lower the feed conversion value, the better the fish's ability to convert feed into flesh. An FCR of 2.35 for Mustika common carp indicates that 2.35 kg of feed was required to produce 1 kg of

weight gain, whereas the control population required a higher amount of feed, namely 3.29 kg, to produce 1 kg of fish flesh.

Future Perspectives

Advances in genetics, biotechnology and modern aquaculture systems have created major opportunities for the sustainable improvement of common carp productivity in the future. While breeding programs in the past relied largely on simple phenotypic selection, current development has shifted toward data-driven, high-precision approaches integrated with digital technology. This transformation enables selection processes to become faster, more accurate and better suited to address emerging challenges in global aquaculture. One of the main prospects is the application of genomics in breeding programs [15].

DNA marker technologies, sequencing and genomic selection make it possible to identify superior individuals from the seed stage based on their genetic information. Through this approach, important traits such as rapid growth, disease resistance, feed efficiency and environmental tolerance can be predicted earlier without waiting for fish to reach maturity [16,17]. This will save selection time and accelerate the development of new superior strains. In addition to genomics, the use of artificial intelligence and big data will also become an important component of future aquaculture. Digital sensors, underwater cameras and automated devices are capable of monitoring feeding behavior, health status, growth and water quality in real time. The collected data can then be analyzed using intelligent algorithms to support decision-making in feeding management, environmental control and the selection of the best broodstock. The integration of genetics and digital technology will create more efficient precision aquaculture systems [18,19,20].

Future challenges also require the development of common carp strains that are more resilient to climate change. Rising water temperatures, drought, abnormal salinity and the emergence of new diseases may reduce aquaculture productivity. Therefore, breeding programs need to prioritize environmental adaptation and stress tolerance as key target traits. Resilient strains will be especially important in developing countries that are highly vulnerable to climate change. However, the success of innovation does not depend solely on technology. The availability of skilled human resources, modern hatchery systems, proper data recording, investment support and government policies remains a decisive factor. Technology transfer to small-scale farmers is also essential so that the benefits of research outcomes are not enjoyed only by

large industries. An inclusive approach will ensure that production improvement progresses alongside equitable social welfare.

Conclusion

The practice of selective breeding combined with genetic enhancement for common carp has proven to be an effective method that supports sustainable aquaculture development. The present technologies, together with effective population management and the selection of superior breeding stock, enable increased productivity without environmental damage. The ongoing research project, which receives support from both government and industry professionals, will ensure that common carp remain a vital component of global food production. The success of strains such as Mustika carp highlights the practical impact of well-designed breeding strategies in real culture conditions. Moreover, the integration of modern technologies, including genomics and digital monitoring systems, offers new opportunities to enhance selection accuracy and accelerate genetic progress

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Glossary

Adsorption: The process by which chemical compounds adhere to the surface of solid particles such as sediments or organic matter.

Aeration: The process of adding oxygen to water to maintain suitable dissolved oxygen levels for fish survival and growth.

Aeromonas hydrophila: A bacterial pathogen that can infect fish and cause disease outbreaks in aquaculture systems.

Agro-aquaculture: An integrated farming system combining agriculture and aquaculture within the same production area.

Ammonia (NH_3): A toxic nitrogenous waste product produced by fish metabolism and decomposition of organic matter.

Anaerobic Digestion: A biological process where microorganisms break down organic waste in the absence of oxygen, often producing biogas.

Antioxidant Enzymes: Protective enzymes that reduce cellular damage caused by oxidative stress, including superoxide dismutase (SOD), catalase (CAT) and glutathione peroxidase (GPx).

Apoptosis: A regulated process of programmed cell death triggered by cellular damage or toxic stress.

Aquaculture Sustainability: The practice of maintaining long-term aquaculture productivity while preserving environmental integrity, economic viability and social responsibility.

Aquaculture: The farming of aquatic organisms such as fish, crustaceans and plants under controlled conditions.

Aquaponics: An integrated system combining aquaculture and hydroponic plant production where fish waste provides nutrients for plants.

Artificial Intelligence (AI): Computer-based systems capable of analyzing data, learning patterns and assisting automated decision-making.

ATP (Adenosine Triphosphate): The primary energy-carrying molecule used in cellular metabolic processes.

Autotrophic Bacteria (Chemoautotrophic bacteria): Bacteria that carry out nitrification by converting ammonia into nitrite and subsequently into nitrate.

Bacteria: Microscopic organisms, some of which are beneficial in biofiltration while others may cause disease.

Best Management Practices (BMPs): A set of scientifically recommended management strategies designed to minimize environmental impacts associated with agricultural or aquaculture activities.

Beta-glucans: Natural compounds used as immunostimulants to enhance the immune response of fish.

Bioaccumulation: The gradual accumulation of chemical substances or pollutants within the tissues of living organisms through repeated environmental or dietary exposure.

Biodiversity: The variety of living organisms within an ecosystem, including plants, animals and microorganisms.

Biofilm: A layer of microorganisms attached to a surface, commonly found in biofilters of RAS.

Biofilter: A filtration unit containing beneficial bacteria that convert toxic ammonia into less harmful compounds.

Biofloc Technology (BFT): An innovative aquaculture system that facilitates in-situ nutrient recycling and waste management by maintaining a high carbon-to-nitrogen (C:N) ratio. This environment stimulates the proliferation of heterotrophic bacteria, which assimilate toxic ammonia into microbial biomass (bioflocs) that subsequently serves as a supplemental, nutrient-rich feed source for the cultured species.

Biological Control: The use of living organisms, such as fish, to reduce pest and weed populations naturally.

Biomagnification: The progressive increase in contaminant concentration across successive trophic levels within a food chain.

Biomarker: A measurable biological indicator used to detect physiological, biochemical or molecular responses to environmental contaminants.

Biopesticide: A biologically derived pesticide, typically originating from plants, microorganisms or natural compounds, considered more environmentally friendly than synthetic pesticides.

Biosecurity: Measures implemented to prevent the introduction and spread of diseases in aquaculture systems.

Breeding methods: Techniques and strategies used to improve the genetic quality, performance and desirable traits of fish populations through controlled mating, selection and genetic management.

Capital Expenditure (CAPEX): Initial investments required to establish the production facility, which include the construction of tanks, aeration systems, backup power and monitoring instruments.

Cara Budidaya Ikan yang Baik (CBIB): CBIB is Indonesia's national standard developed by the Ministry of Marine Affairs and Fisheries to promote responsible aquaculture practices. Principles of fish farming aimed at producing fish of the highest quality and safe for consumption. CBIB also aims to maintain fish health, environmental sustainability and food safety.

Carbon Dioxide (CO_2): A gas produced through fish respiration that can accumulate in water and negatively affect fish health.

Carbon to Nitrogen (C/N) Ratio: A fundamental operational parameter manipulated by the addition of external organic carbon sources (e.g., molasses or tapioca flour) to stimulate heterotrophic bacterial proliferation. This manipulation deliberately shifts the primary nitrogen-processing pathway from autotrophic nitrification to rapid heterotrophic assimilation.

Carnivorous Fish: Fish species that primarily feed on other animals or high-protein diets.

Channa striata: Scientific name of the striped snakehead fish, an economically important freshwater species in Asia.

Chlorophyll: A green pigment in plants and algae that enables photosynthesis.

Chronic Exposure: Continuous or repeated exposure to a contaminant over an extended period, often at low concentrations.

Closed-loop System: A system where water is continuously filtered and reused instead of being discharged.

Co-culture System: A rice–fish farming system where rice and fish are cultivated simultaneously in the same field.

Competitive Exclusion: An ecological defense mechanism whereby a dominant, beneficial microbial community within the biofloc environment suppresses the growth and proliferation of opportunistic pathogenic bacteria. This dynamic functions as an external immune system, significantly

protecting fish populations from disease outbreaks during the vulnerable nursery phase.

Concrete ponds: Artificial aquaculture ponds constructed using concrete materials to provide a controlled environment for fish culture, management and water quality maintenance.

Concurrent System: A type of rice–fish farming in which rice cultivation and fish rearing occur at the same time.

Conductivity: A measure of water's ability to conduct electricity, related to dissolved mineral concentration.

Constructed Wetlands: Engineered wetland systems designed to remove pollutants from wastewater through natural biological, chemical and physical processes.

Cytochrome P450: A family of enzymes involved in the metabolism and detoxification of xenobiotic and endogenous compounds.

Denitrification: A microbial reduction pathway that sequentially converts nitrate into gaseous nitrogen compounds (N_2 and N_2O). In aquaculture, particularly within the anaerobic benthic sediments of pond systems, this process represents a primary mechanism for nitrogen loss to the atmosphere.

Disease-associated Mortality: Fish deaths caused by infectious diseases or health problems.

Dissolved Oxygen (DO): The amount of oxygen available in water for aquatic organisms.

DNA (Deoxyribonucleic Acid): The hereditary material present in almost all living organisms that carries genetic information responsible for growth, development, reproduction and biological functions.

Drum Filter: A mechanical filtration device used to remove suspended solids from water in RAS.

Earthen ponds: Aquaculture ponds made from natural soil or clay that are commonly used for fish farming because of their relatively low construction cost and natural productivity.

Ecological Intensification: An approach to increasing productivity by enhancing natural ecosystem functions rather than relying on synthetic inputs.

Ecological Resilience: The ability of an ecosystem to recover and maintain stability after environmental disturbances.

Ecosystem-based Management: A management approach that considers ecological interactions and environmental sustainability.

Ecotoxicology; The scientific study of the effects of toxic substances on organisms, populations, communities and ecosystems.

Ectoparasites: Parasites living on the external surfaces of fish, such as skin or gills.

Effluent: Wastewater discharged from aquaculture systems containing organic and inorganic materials.

Endocrine Disruption: Interference with the normal functioning of hormonal systems caused by exposure to certain chemical substances.

Environmental Carrying Capacity (ECC): The estimated maximum biological capacity or biomass threshold that an aquatic ecosystem can sustain without exceeding established water quality standards (ecological carrying capacity) or precipitating socioeconomic conflicts. Specifically, the phosphorus-based carrying capacity (ECCp) is highly vulnerable to diminishment caused by elevated water temperatures associated with climate change.

Environmental Degradation: Damage to the environment caused by pollution, habitat destruction or resource overuse.

External Inputs: Materials added from outside the farming system, such as commercial feed, fertilizers and pesticides.

Extracellular Polymeric Substances (EPS): Mucous-like matrices produced by microorganisms that physically bind various constituents—including living and dead bacteria, microalgae, fungi, protozoa and uneaten feed particles—into heterogeneous macroscopic aggregates known as bioflocs.

Extruded Feeds: Buoyant, artificially formulated aquafeeds that exhibit enhanced water stability and improved nutrient digestibility due to the starch gelatinization process during manufacturing. These feeds have become an industry standard in intensive aquaculture, significantly minimizing feed wastage and environmental nutrient loading compared to conventional sinking pellets.

Family-based selection: A selective breeding approach in which individuals are evaluated and selected based on the performance of their family groups to improve genetic traits in subsequent generations.

Feed Conversion Ratio (FCR): A measure of feed efficiency representing the amount of feed required to produce a unit of biomass gain.

Fiberglass Tank: A durable tank material commonly used in aquaculture systems.

Filtration: The process of removing solids, wastes or harmful substances from water.

Floating Net Cages (FNC): An open thermodynamic aquaculture system characterized by the absence of hydraulic retention time for the sedimentation or biological processing of wastes. Consequently, nutrient effluents and particulate organic matter are directly dispersed into the surrounding receiving water body.

Freshwater Aquaculture: The cultivation of aquatic species in freshwater environments.

Gene Expression: The process through which genetic information is transcribed and translated into functional molecules such as proteins.

GIAHS (Globally Important Agricultural Heritage Systems): A designation by FAO recognizing traditional agricultural systems with ecological, cultural and historical importance.

Gill Histopathology: Microscopic structural alterations in gill tissues resulting from exposure to toxic substances or environmental stressors.

Good Aquaculture Practices (GAP): Guidelines and procedures for aquaculture, including maintaining and/or raising fishery products and harvesting them properly in a controlled environment, thereby ensuring food safety from farming practices by paying attention to sanitation, feed, seed stock, fish medicines, residues, chemicals and biological materials.

Greenhouse Gas Emissions: Release of gases such as carbon dioxide that contribute to climate change.

HDPE (High-Density Polyethylene): A strong plastic material commonly used for aquaculture tanks and piping.

Heterotrophic Bacteria: Bacteria that directly assimilate ammonia as a nitrogen source for the synthesis of cellular proteins, converting it directly into microbial biomass.

Histopathology: The study of microscopic tissue alterations associated with disease, injury or toxic exposure.

Hydraulic Circulation: Water movement within tanks or systems to ensure even distribution of oxygen and waste removal.

Hydrophobicity: The tendency of a substance to repel water or exhibit low solubility in aqueous environments.

Hydroponics: A method of growing plants without soil using nutrient-rich water.

Hypoxic Environment: An environment with low oxygen concentration.

Immunostimulant: A substance added to feed to enhance the immune system of fish.

Immunosuppression: A reduction in the effectiveness or activity of the immune system, increasing susceptibility to diseases and infections.

Inbreeding: The mating of closely related individuals, which can increase genetic similarity and the expression of harmful recessive genes, potentially reducing growth, fertility and survival.

Integrated Farming System: A farming approach that combines multiple agricultural activities to improve efficiency and sustainability.

Integrated Multi Trophic Aquaculture (IMTA): An ecological design and mitigation strategy that mimics natural ecosystem functions by co-cultivating fed species (e.g., finfish or shrimp) with extractive species (e.g., macroalgae and bivalves). The extractive organisms assimilate the dissolved inorganic nutrients and particulate organic wastes generated by the primary cultured species, thereby reducing overall environmental loading.

Integrated Pest Management (IPM): An environmentally sustainable pest control strategy combining biological, physical, cultural and chemical control methods.

Internet of Things (IoT): A network of connected sensors and devices that collect and exchange data automatically.

Koi Herpes Virus (KHV): A highly contagious viral disease that affects common carp that often resulting in high mortality rates.

Labyrinth Organ: A specialized respiratory organ that allows snakehead fish to breathe atmospheric oxygen.

LC50 (Lethal Concentration 50%): The concentration of a toxic substance capable of causing mortality in 50% of a test population within a specified exposure period.

Leaching: The downward movement of dissolved chemicals through soil layers into groundwater systems.

Lipophilicity: The chemical affinity of a substance for lipid or fat-rich environments.

LOEC (Lowest Observed Effect Concentration): The lowest concentration of a substance at which statistically significant adverse effects are observed in test organisms.

Macrobenthos: Bottom-dwelling aquatic organisms visible to the naked eye, such as worms, mollusks and insect larvae.

MBBR (Moving Bed Biofilm Reactor): A biological filtration system using floating media to support beneficial bacteria growth.

Mechanical Filtration: Physical removal of suspended solids and wastes from water.

Medium-sized farming: An aquaculture production scale, characterized by moderate investment, infrastructure and production capacity.

Metabolic Rate: The rate at which organisms use energy for growth and survival.

Metabolomics: The comprehensive study of metabolites and metabolic changes occurring within biological systems under specific conditions.

Microbial Imbalance: A disruption in the normal composition and function of microbial communities within an ecosystem.

Minapadi: An Indonesian rice–fish farming system integrating fish culture within rice fields.

Mitochondrial Oxidative Phosphorylation: A biochemical process occurring in mitochondria that generates ATP through electron transport and phosphorylation reactions.

Molecular markers: Specific DNA sequences used to identify genetic variation, track inheritance patterns and assist in genetic analysis, breeding programs and population studies.

Molecular Response: Biological reactions occurring at the molecular level, including alterations in gene expression, protein synthesis and cellular signaling pathways.

Molluscicide: A chemical or biological agent used to control or eliminate molluscan pests such as snails and slugs.

Monoculture: The cultivation of a single crop or species within a farming system.

Monogeneans: A group of parasitic flatworms that commonly infect fish gills and skin.

Mustika: A selectively bred strain of common carp (*Cyprinus carpio*) developed for superior performance against Koi herpes virus (KHV) disease and superior growth

Natural Feed: Naturally occurring food organisms in aquatic ecosystems, including plankton and benthic organisms.

Nature-based Aquaculture: Aquaculture systems that rely heavily on ecological processes and natural interactions.

Nile Tilapia (*Oreochromis niloticus*): An omnivorous cultured fish species with filter-feeding capabilities, making it highly adaptable to intensive systems and well-suited to consume suspended biofloc particles.

Nitrate (NO_3^-): A relatively less toxic nitrogen compound formed during nitrification.

Nitrification: A biochemical pathway carried out by chemoautotrophic bacteria that converts toxic ammonia into nitrite (NO_2^-) and subsequently into relatively non-toxic nitrate (NO_3^-).

Nitrite (NO_2^-): A toxic intermediate compound produced during nitrification.

Nitrobacter: A genus of nitrifying bacteria that converts nitrite into nitrate.

Nitrosomonas: A genus of nitrifying bacteria that converts ammonia into nitrite.

Nitrous Oxide (N_2O): A potent greenhouse gas identified as a significant emission from aquaculture pond ecosystems. Its production is primarily driven by incomplete microbial denitrification processes occurring under hypoxic conditions at the sediment-water interface.

NOEC (No Observed Effect Concentration): The highest tested concentration of a substance at which no statistically significant adverse effects are observed in exposed organisms.

Non-target Organisms: Organisms unintentionally affected by pesticides or other chemical agents intended for specific target species.

Nutrient Cycling: The movement and recycling of nutrients such as nitrogen and phosphorus within an ecosystem.

Nutrient Enrichment: The addition or increase of nutrients that stimulate biological productivity.

Nutrient Mass Balance: The quantification of the flux and fate of nitrogen (N) and phosphorus (P) within aquaculture systems. This framework measures the proportion of nutrient inputs (e.g., formulated feed) retained as harvested biomass versus the fraction discharged into the surrounding environment, including the water column, benthic sediments and the atmosphere.

Omics Technology: Advanced high-throughput analytical approaches, including genomics, transcriptomics, proteomics and metabolomics, used to study biological systems comprehensively.

Omnivorous: Feeding behavior involving both plant and animal matter.

Operational Expenditure (OPEX): The recurring variable and fixed costs incurred throughout the aquaculture production cycle. In BFT systems, major components include feed, fish seed, labor and critically, the continuous energy (electricity) expenditures mandated by the 24/7 intensive aeration requirement.

Oxidative Stress: A physiological condition resulting from an imbalance between reactive oxygen species (ROS) production and antioxidant defense mechanisms.

Ozone Treatment: The use of ozone gas to disinfect water and reduce microbial loads.

Paddy Field: A flooded agricultural field used primarily for rice cultivation.

Pathogen: A microorganism capable of causing disease.

Persistence: The ability of a chemical compound to remain stable and resist degradation in the environment over time.

pH: A scale measuring the acidity or alkalinity of water.

Phosphorus (P): An essential nutrient involved in biological productivity and plant growth.

Physicochemical Properties: The physical and chemical characteristics of a substance that determine its environmental behavior and biological interactions.

Phytase Enzyme: A microbial enzyme supplemented into commercial aquafeeds as a nutritional mitigation strategy to hydrolyze phytate-bound phosphorus predominantly found in plant-based ingredients. This supplementation enhances phosphorus bioavailability for the cultured species and drastically mitigates the environmental discharge of unassimilated phosphorus.

Phytoplankton: Microscopic photosynthetic organisms in aquatic environments that form the base of the food web.

Phytoremediation: An environmentally based remediation technique that uses plants to absorb, degrade or stabilize pollutants from contaminated environments.

Primary Productivity: The production of organic matter through photosynthesis by plants and algae.

Probiotic: Beneficial microorganisms added to feed or water to improve fish health and water quality.

Protein Catabolism: The breakdown of proteins that produces nitrogenous waste such as ammonia.

Proteomics: The large-scale study of proteins, including their structure, function and expression patterns in biological systems.

RAS (Recirculating Aquaculture System): An aquaculture system that continuously filters and reuses water in a controlled environment.

Reactive Oxygen Species (ROS): Highly reactive oxygen-containing molecules capable of causing cellular and molecular damage.

Recirculating Aquaculture Systems (RAS): An intensive aquaculture system that manages water quality through mechanical and biological filtration, typically requiring higher capital investment but offering highly stable water quality compared to BFT.

Recirculation: The continuous reuse of water after treatment and filtration.

Refuge Area: A deeper section or trench within a rice field that provides shelter for fish during environmental stress.

Respiratory Acidosis: A condition caused by excessive carbon dioxide accumulation affecting fish respiration and blood chemistry.

Return on Investment (ROI): A primary financial metric utilized to assess the profitability and economic viability of the aquaculture enterprise. In efficiently managed, small-scale BFT operations, the projected ROI can exceed 100%, indicating that the returns surpass the initial capital expenditure within a relatively short payback period.

Rice–fish Farming: An integrated system combining rice cultivation and fish production within the same field.

Rotational System: A rice–fish farming system where fish are cultured after rice harvest.

Runoff: The flow of surface water that transports soil particles, nutrients and pollutants into surrounding water bodies.

Sediment Adsorption: The attachment of chemical contaminants to sediment particles in aquatic environments.

Sediment Disturbance: The stirring of bottom sediments by fish activity, which can release nutrients into the water column.

Selective breeding: A breeding method in which individuals with desirable traits, such as fast growth, disease resistance or environmental tolerance to improve the quality of future generations.

Sequential System: A rice–fish farming system where fish are cultured before rice planting.

Small-scale hatchery unit (SSHU): A hatchery operation with limited production capacity, infrastructure and investment, typically managed by local farmers or community-based aquaculture enterprises for fish seed production.

Snakehead Fish: A group of freshwater fish in the genus Channa, valued for food and medicinal uses.

Specific Growth Rate (SGR): A metric of individual fish growth performance that exhibits a significant decline when stocking density is increased.

Stocking Density: The quantity of fish maintained within a specific water volume.

Sublethal Exposure: Exposure to a contaminant at concentrations insufficient to cause immediate mortality but capable of inducing physiological or biochemical disturbances.

Sustainable Aquaculture: Aquaculture practices designed to maintain ecological balance, economic profitability and long-term resource availability.

Telemetry: The remote collection and transmission of data from monitoring devices.

Total Suspended Solids (TSS): A parameter used to measure biofloc volume in the water; excessive TSS can cause gill clogging and elevated oxygen demand, while excessively low TSS indicates suboptimal waste processing.

Traditional selection: A conventional breeding approach based on observable phenotypic traits, such as body size, growth rate or appearance, without the use of molecular or genomic tools.

Transcriptomics: The comprehensive analysis of RNA transcripts expressed by genes under specific environmental or physiological conditions.

Turbidity: Water cloudiness caused by suspended particles.

Ultraviolet (UV) Sterilization: A disinfection method using UV light to reduce pathogens in water.

Water Quality Management: The monitoring and control of water parameters to maintain healthy aquaculture conditions.

Water Quality: The physical, chemical and biological characteristics of water affecting aquatic organisms.

Zooplankton: Small aquatic organisms that feed on phytoplankton and serve as natural food for fish.

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About the Book

Sustainable Aquaculture and Aquatic Science (Volume - 2) explores sustainable aquaculture practices, nutrient management, environmental impacts, fish farming technologies and aquatic resource conservation. It covers innovative approaches such as Recirculating Aquaculture Systems (RAS) and Biofloc Technology, along with common carp nursery management, system performance evaluation and selective breeding for improved productivity. This volume serves as a valuable resource for researchers, academicians, fisheries professionals, students and policymakers interested in sustainable aquaculture and advancements in aquatic science.

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