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Advancing Aquaculture Integrating Microbiome Modulation, Immunomodulatory Approaches, and Mitigating Environmental Stressors in Nile Tilapia Farming

Adeeba Naseer[1], Nadish Mustafa[2], Sara Iftikhar[2], Zeeshan Ul Hassan Fareed[3], Waqas Bashir[3], Kamran Khan[4], Iqra Batool[2], Iram Zafar[5], Usman Ali[6], Nimra Ather[2]

[1]College of Fisheries, Southwest University, Chongqing, China.
[2]Department of Zoology, Wildlife and Fisheries, University of Agriculture, Faisalabad, Punjab, Pakistan.
[3]Department of Zoology, Government College University, Faisalabad, Punjab, Pakistan.
[4]School of Life Sciences, Southwest University, Chongqing, China.
[5]Department of Biochemistry, Superior University Lahore, Punjab, Pakistan
[6]Department of Zoology, Government College University, Lahore, Punjab, Pakistan.

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Corresponding Author: Adeeba Naseer, College of Fisheries, Southwest University, Chongqing, China.
Email: adeebanaserr44@gmail.com

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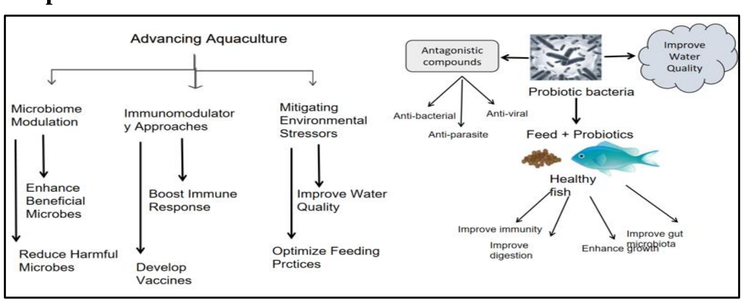
ABSTRACT

Sustainable aquaculture methods must be advanced to meet the problems presented by environmental stresses and the expanding worldwide need for food. This study examines cutting-edge methods for raising Nile tilapia (Oreochromis niloticus), emphasizing immunomodulatory techniques, microbiome modification, and the crucial task of reducing environmental stresses to increase resilience and production. Probiotics, prebiotics, and synbiotics are important in enhancing nutrition absorption, promoting disease resistance, and optimizing gut health, making microbiome modification an essential strategy. The use of functional feeds enhanced with bioactive chemicals and the creation of tailored vaccinations are two examples of advances in immunomodulatory approaches that have demonstrated promise in bolstering tilapia's immune systems against pathogenic threats. A holistic strategy to guarantee sustainable production is provided by simultaneously reducing environmental stresses, such as hypoxia, variable water temperatures, and pollutant exposure, through enhanced aquaculture systems, water quality control, and stress-resilient fish strains. The importance of addressing these environmental stressors is underscored, as they pose significant threats to the industry. Emerging technologies like genomics, transcriptomics, and precision aquaculture tools, which allow for the monitoring and adjusting of farming operations to suit the unique requirements of Nile tilapia, further facilitate the integration of these tactics. This review highlights the potential of comprehensive, science-driven methods in converting Nile tilapia farming into a resilient, sustainable, and fruitful enterprise and emphasizes the importance of addressing environmental stressors in this transformation.

Graphical Abstract



INTRODUCTION

The aquaculture of Nile tilapia (Oreochromis niloticus) has become a major component of fish farming worldwide because of its versatility, quick growth rates, and resistance to various environmental factors (Prabu et al., 2019). Nile tilapia, one of the most extensively cultivated fish species, makes a substantial contribution to nutrition and food security, especially in underdeveloped nations where fish is the main source of protein. Current aquaculture trends include the adoption of genetically improved strains, such as the Genetically Improved Farmed Tilapia (GIFT), to increase productivity, the growth of intensive and semi-intensive farming systems, and the incorporation of sustainable practices like biofloc technology and recirculating aquaculture systems (Arumugam et al., 2023). However, the industry faces several obstacles, such as environmental issues, habitat degradation, and eutrophication from agricultural effluents. Production is seriously threatened by disease outbreaks, worsened by high stocking numbers and climate change (Abbas et al., 2024). Additionally, a move toward alternate protein sources like insect meal and plant-based components has been spurred by the growing costs of feed, a significant operating expenditure. The industry's expansion is further hampered by regulatory concerns, such as complex permitting processes and compliance requirements, market access obstacles, trade barriers and competition from other protein sources, and socioeconomic difficulties, including the need to guarantee fair rewards for small-scale producers. Addressing these issues through innovation, legislative changes, and stakeholder cooperation is essential to maintain and increase the significance of Nile tilapia farming worldwide (Jolly et al., 2023).

There has never been a more pressing need for integrated methods in contemporary healthcare, especially as we discover the complex relationships between immunomodulation, environmental stress management, and microbiome modulation in fostering resilience and general health (Saqlain et al., 2024). A varied community of bacteria that live in and on our bodies, the human microbiome is essential for immune system function, gut-brain axis modulation, and homeostasis maintenance. Numerous chronic illnesses, including autoimmune diseases, metabolic problems, and mental health ailments like anxiety and depression, have been connected to dysbiosis or the imbalance in microbial communities (Alam et al., 2017). Restoring microbial balance and promoting physical and mental well-being may be possible through microbiome modification via probiotics, prebiotics, dietary changes, and even fecal microbiota transplantation. At the same time, immunomodulation techniques are becoming more popular as the immune system's function broadens to control inflammation, tissue healing, general systemic health, and infection management. Recalibrating the immune system's reactions is the goal of therapies like immunotherapy, customized vaccinations, and cytokine modulation, which provide novel treatments for ailments including cancer and autoimmune illnesses (Kumar et al., 2017). However, environmental stress, a ubiquitous element affecting the immune system and microbiota, must be addressed if these biological techniques are to reach their full potential. A vicious cycle of bad health is created when chronic stress modifies the hypothalamic-pituitary-adrenal (HPA) axis, upsets the balance of the microbiota, and sets off chronic inflammatory reactions. Good stress-reduction techniques, such as mindfulness exercises, exercise, and time spent in nature, enhance immunomodulatory and microbiome therapies to provide a comprehensive framework for better health (DePace et al., 2019).

Additionally, real-time monitoring of stress indicators, immune system activity, and microbiome composition is made possible by integrating cutting-edge technology like artificial intelligence (AI) and wearable health devices, allowing customized and flexible treatment programs. These multidisciplinary approaches highlight the importance of seeing health from an interconnected perspective, acknowledging that addressing the underlying causes of disease rather than just its symptoms requires a synergy between immune optimization, stress management, and microbiome modulation (Obeagu et al., 2024). In addition to improving individual outcomes, implementing integrated healthcare approaches will help achieve larger public health objectives by lowering the burden of chronic diseases and promoting resilience in an increasingly difficult environmental landscape as research continues to reveal the complex interactions between these systems. This study seeks to investigate and promote sustainable aquaculture practices by integrating immunomodulatory techniques, microbiome modification, and methods to reduce environmental stresses in Nile tilapia farming (Elgendy et al., 2024). Some goals include examining how microbiome manipulation can improve fish health and growth performance, assessing how well immunomodulatory treatments can increase disease resistance, and finding workable ways to lessen environmental stressors like temperature swings and declining water quality. By encouraging ecological balance and reducing the sector's environmental impact, this all-encompassing strategy aims to increase the resilience and productivity of Nile tilapia aquaculture.

A Revolution Underwater: The Nile Tilapia Farming Renaissance

As the "aquatic chicken" because of its adaptability, quick development, and capacity to flourish in a variety of habitats, the Nile tilapia (Oreochromis niloticus) has become a revolutionary force in aquaculture (Gephart et al., 2020). This fish has gained international recognition as a cost-effective and sustainable source of protein, especially in areas struggling with food insecurity and population growth. Nile tilapia, which bridges the gap between conventional traditions and cutting-edge innovation, has emerged as the aquaculture industry's crown gem due to its mild taste, strong adaptability, and effective feed-to-protein conversion. Recent developments in integrated aquaculture systems, genetic selection, and water quality control have transformed tilapia farming into a model for environmental stewardship and a means of producing food. The revolution in Nile tilapia farming highlights the industry's commitment to efficiency and sustainability, from creating recirculating aquaculture systems (RAS) to using biofloc technology and precision aquaculture technologies like AI-powered monitoring systems. By reducing ecological footprints, enhancing disease resistance, and increasing production yields, these methods have established a standard for aquaculture worldwide. Nile tilapia, which is still at the forefront of aquaculture's comeback, is a prime example of how innovation and tradition may be combined to meet the world's changing ecological and nutritional needs (Odende et al., 2022).

Microbial Alchemy Engineering the Tilapia Gut Microbiome

An essential component of aquaculture practice optimization, the gut microbiome of Nile tilapia is a dynamic ecosystem that serves as a command center for growth, immunity, and resilience (Ogello et al., 2024). This microbial consortium strengthens the fish against infections through innate and adaptive immunological regulation, improves metabolic efficiency, and controls nutritional intake. Next-generation probiotics are a ground-breaking method of microbiome engineering in which custom-made microorganisms address human health issues. These specialized probiotics promote strong development and feed conversion efficiency, which also increase the activity of digestive enzymes and outcompete dangerous bacteria. The bioactive substances and metabolites that helpful microorganisms make, known as postbiotics, are becoming the next big thing in the field of probiotics. These compounds, which include antimicrobial peptides and short-chain fatty acids, have shown promise in enhancing gut health, lowering inflammation, and increasing immunity (Mann et al., 2024). A sizable amount of the microbiome comprises "microbial dark matter," unknown microbial species with unrealized potential, which contributes to the incomplete understanding of the microbiome. These mysterious actors are unraveled by cutting-edge metagenomics and bioinformatics, which may reveal new microorganisms and compounds that revolutionize aquaculture. By utilizing these developments, tilapia farming may shift to more robust, efficient, and sustainable methods, highlighting the revolutionary potential of microbial alchemy (Al-Kodmany et al., 2018).

Figure 1
Microbial Alchemy Engineering the Tilapia Gut Microbiome

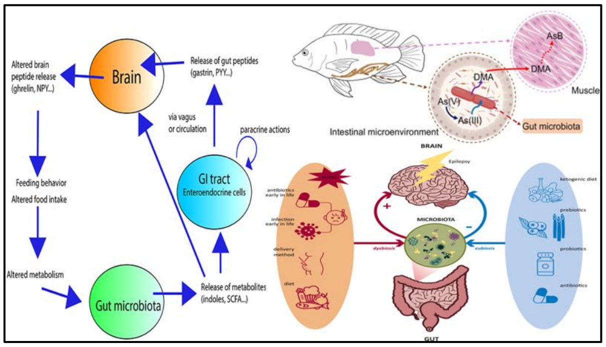
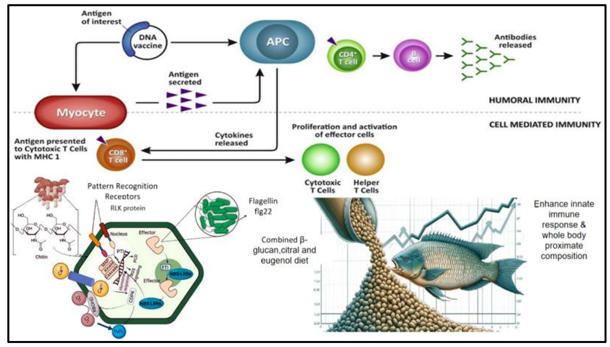


Figure 2
Immunity Unleashed: Supercharging Disease Resistance



Immunity Unleashed: Supercharging Disease Resistance

Enhancing immunity has become a key component of sustainable fish health management in aquaculture, with cutting-edge tactics like "smart immunity" taking center stage. Using sophisticated immunological insights and precision-targeting techniques, "smart immunity" in tilapia refers to adjusting immune responses to certain pathogens, guaranteeing strong disease resistance without overstimulating the immune system. The emergence of plant-based immunostimulants, which provide affordable and environmentally friendly substitutes for pharmaceutical medications, complements this (Olayem et al., 2024). In addition to enhancing immunological function, these natural compounds from herbs, algae, and other plant sources reduce environmental impact and satisfy customer desire for more environmentally friendly aquaculture methods. The age of nano vaccines, which transform immune defense with precise delivery methods, has been brought about by nanotechnology. These vaccines provide targeted administration, controlled release, and increased effectiveness against aquatic infections by encapsulating nanoparticle antigens. By fusing nanotechnology's accuracy, plant-based remedies' sustainability, and smart immunity's specificity, these developments collectively usher in a new era of disease resistance in tilapia (Newell-McGloughlin et al., 2006). These methods protect fish health and support aquaculture's economic and ecological resilience as it expands to satisfy the world's food needs.

Survival in Chaos: Mastering Environmental Stress

Rapid variations in temperature, water quality, and other variables can endanger fish health and production, making environmental stress a major problem in aquaculture (Mugwanya et al., 2024). Aquaculture stress management is changing due to new technology and approaches, especially for species like tilapia. Stress whisperers continually measure cortisol levels, oxygen consumption, and other stress indicators using biofeedback and real-time sensors, offering crucial insights into fish physiology. By implementing timely treatments, aquaculturists can improve growth performance and survival rates thanks to these advancements. Another frontier is epigenetic resilience, in which tilapia are trained generation after generation to withstand environmental stress. By subjecting parent populations to regulated stresses, this strategy successfully instills resilience in their children through epigenetic memory (Matheson et al., 2020). The outcome is a genetically more resilient fish that can survive in less-than-ideal circumstances. Eco-acupuncture, a systematic optimization of aquaculture habitats to balance water parameters, biodiversity, and nutrient cycles, is a complementary approach to these tactics. By optimizing these microenvironments, tilapia show better behavioral stability and health, reducing mortality and increasing output. These methods represent a comprehensive framework combining ecological principles, genetic insights, and technology to transform aquaculture stress management and ensure robust and sustainable production systems (Houston et al., 2020).

Table 1
Innovations in Environmental Stress Management for Tilapia Aquaculture

Category	Approach	Key Features	Benefits	Challenges	References
Stress Monitoring	Biofeedback and Real-Time Sensors	Continuous monitoring of stress biomarkers like cortisol levels, oxygen consumption, and heart rates	Early detection of stress, reduced mortality, and optimized feed conversion ratios	High initial investment and maintenance costs	Vavrinsky et al., 2021
	Water Quality Sensors	Monitoring pH, ammonia, dissolved oxygen, and temperature in real-time	Helps maintain optimal water conditions and prevent stress caused by rapid environmental changes	Calibration and potential sensor failure	Luo et al., 2015
Epigenetic Resilience	Generational issue condition	Exposing parent populations to controlled stressors to induce genetic and epigenetic adaptations	Creates stress-resilient offspring capable of thriving in suboptimal conditions	Ethical considerations and unpredictable genetic responses	Lehrner et al., 2018
	Genetic Mapping and Editing	Identifying and modifying genes associated with stress tolerance	Targeted enhancement of stress resistance traits	Regulatory hurdles and potential Ecological Impacts	Zafar et al., 2020
Eco-Acupuncture	Biodiversity Enhancement	Introducing beneficial species to stabilize ecosystems and reduce competition	Promotes ecological balance, reduces disease outbreaks, and improves tilapia health	Managing interspecies interactions	Roggema et al., 2016
	Habitat Structuring	Creating artificial reefs or hiding spaces to mimic natural habitats	Reduces aggressive behavior and stress caused by overcrowding	Additional space and resource requirements	Baine et al., 2003
Integrated Techniques	Automated Feeding Systems	Optimized feed delivery based on fish activity and stress levels	Improves growth rates and minimizes stress related to underfeeding or overfeeding	Dependence on technology and power	Zhou et al., 2018
	AI-Based Environmental Control	Use of AI for predictive analysis and real-time adjustments to environmental conditions	Increases efficiency in maintaining optimal aquaculture environments	High complexity and need for skilled operators	Ramadan et al., 2024
Health Interventions	Probiotic and Prebiotic Additives	Enhancing gut health and immunity through dietary supplementation	Reduces vulnerability to stress-induced diseases	Requires regular monitoring to assess efficacy	Marasco et al., 2020
	Vaccination Against Stress-Related Diseases	Development and application of vaccines targeting pathogens common in stressed populations	Minimizes losses from disease outbreaks	Time-intensive development and variable effectiveness	Birhane et al., 2020
Behavioral Strategies	Low-Density Stocking	Reducing fish density to decrease competition and aggression	Promotes better growth and reduces stress-related behaviors	Limits total production capacity	Ellis et al., 2002

	Light and Sound Management	Adjusting lighting schedules and minimizing noise pollution in aquaculture facilities	Improves fish circadian rhythms and reduces behavioral stress	Requires careful calibration and potential energy costs	Arechavala-Lopez et al., 2022
Technological Integration	Mobile Aquaculture Apps	Apps for real-time tracking and management of stress metrics	Empowers aquaculturists with accessible data for quick decision-making	Dependence on reliable Internet connectivity	Mandal et al., 2024
	Remote Monitoring and Automation	IoT-enabled systems for remote monitoring and automatic adjustments	Reduces human intervention and ensures continuous operation	Expensive setup and reliance on advanced technology	Alshamrani et al., 2022
Sustainability	Circular Aquaculture Systems	Recycling nutrients and water within the system	Reduces waste, enhances water quality, and minimizes environmental footprint	Requires advanced engineering and maintenance	Campanati et al., 2022
	Renewable Energy Integration	Using solar or wind energy for system operations	Reduces operational costs and aligns with sustainable aquaculture practices	Initial investment and site-specific feasibility	Talaat et al., 2020

Turbocharging Sustainability Environmental and Ethical Aquaculture

Sustainability is revolutionizing aquaculture, and tilapia farming is at the forefront of this change by implementing environmentally friendly methods (Ahmed et al., 2019). Combining biofloc technology, renewable energy-powered operations, and fertilizer recycling, carbon-negative farming redefines aquaculture's environmental impact and captures more carbon than is released during production. This method sets a standard for moral aquaculture while lowering greenhouse gas emissions and supporting global climate objectives. The Aquaculture Blockchain makes the real-time recording of product origin, farming practices, and sustainability measures possible, which promotes previously unheard-of openness and accountability (Obasi et al., 2024). By guaranteeing moral behavior across the supply chain, this digital ledger allows customers to make knowledgeable decisions and encourages fair commerce in the sector. Another ground-breaking development is in the feed industry, where the protein loop is being closed by switching from conventional fishmeal to sustainable substitutes like algae and insect-based protein. These innovative feed sources provide high nutritional value, improve resource efficiency, and lessen the strain on wild fish stocks, all contributing to aquaculture's circular economy. By redefining the moral parameters of fish production and supporting environmental conservation, these developments collectively establish tilapia farming as a paradigm for sustainable food systems (Adam et al., 2024).

Table 2

Turbocharging Sustainability Environmental and Ethical Aquaculture

Category	**Sustainability Innovation**	**Description**	**Environmental Impact**	**Ethical Benefits**	**Challenges**
Carbon-Negative Farming	Renewable Energy Integration	Use of solar, wind, and bioenergy for powering aquaculture operations.	Reduces reliance on fossil fuels and lowers carbon footprint.	Encourages eco-conscious practices and aligns with global sustainability goals.	High initial costs for renewable installations, dependence on climatic conditions.

	Biofloc Technology	Cultivating beneficial bacteria to convert organic waste into nutrients for fish.	Enhances water quality and reduces waste discharge.	Promotes resource efficiency and minimizes ecological disruption.	Requires technical expertise for setup and maintenance.
	Carbon Sequestration via Aquatic Plants	Utilizing plants like seagrass in farming systems to absorb CO_2.	Mitigates greenhouse gas emissions and improve water ecosystems.	Supports biodiversity and enhances farm sustainability.	Limited scalability, need for optimized plant-aquaculture integration.
Aquaculture Blockchain	Real-time Product Tracking	Blockchain-based systems for tracing aquaculture products' origin, farming methods, and supply chain.	Builds consumer trust and reduces food waste by ensuring quality.	Enhances transparency, supports fair trade, and combats fraudulent practices.	High costs for implementation require digital literacy among stakeholders.
	Certification Transparency	Provides digital proof of adherence to sustainability standards.	Promotes global sustainability benchmarks and encourages eco-certification.	Boosts ethical branding and ensures compliance with sustainability policies.	Dependence on regulatory bodies, potential technological barriers
Revolutionizing Feed	Insect-based Feed	Replacing traditional fishmeal with protein derived from black soldier flies, mealworms, etc.	Reduces reliance on wild fish stocks and minimizes land and water usage.	Offers a sustainable protein source and promotes ethical aquaculture.	Scaling up production, ensuring consumer acceptance.
	Algae-based Feed	Incorporating microalgae as a high-protein alternative in aquaculture feed.	Enhances feed sustainability and reduces pressure on terrestrial and marine resources.	Encourages circular economy and improves the nutritional quality of farmed fish.	High production costs, potential barriers in mainstream adoption.
Circular Economy Practices	Waste-to-Resource Systems	Recycling fish waste into fertilizers or biogas.	Lowers environmental pollution and supports regenerative farming practices.	Promotes zero-waste operations and benefits multiple industries.	Logistic challenges in waste collection and conversion.
	Integrated Multi-Trophic Aquaculture (IMTA)	Combining fish farming with seaweed and shellfish to recycle nutrients.	Improves ecosystem health and enhances biodiversity.	Creates diversified income streams for farmers and supports resilient aquaculture.	Complexity in system management requires technical knowledge.
Eco-friendly Practices	Precision Aquaculture	Using IoT devices and AI to monitor and optimize water quality, feeding, and overall farm operations.	Improves resource efficiency and reduces environmental impact.	Ensures ethical resource usage and enhances productivity sustainably.	High setup costs are needed for continuous training and updates.
	Use of Biodegradable	Adoption of biodegradable	Reduces plastic pollution in aquatic ecosystems.	Promotes eco-conscious farming and	Limited availability and higher costs

	Nets and Materials	materials in farm infrastructure.		aligns with global environmental goals.	compared to traditional materials.
Consumer-focused Strategies	Sustainable Branding and Marketing	Promoting eco-friendly tilapia products with certifications like ASC (Aquaculture Stewardship Council).	Encourages demand for sustainable seafood.	Raises consumer awareness about ethical aquaculture practices.	Marketing costs, potential resistance to premium pricing.
	Educational Campaigns	Informing consumers about the environmental and ethical impact of their seafood choices.	Increases public engagement in sustainability initiatives.	Empower consumers to support sustainable aquaculture.	Requires collaborative efforts and long-term commitment for impactful results.
Regulatory Frameworks	Policy Support and Subsidies	Government incentives for adopting sustainable aquaculture technologies	Accelerates the transition to carbon-negative practices.	Encourages farmer participation in sustainability programs.	Dependency on political will, slow adoption in regions with less-developed policies.
	International Collaboration	Joint efforts between countries for knowledge-sharing and establishing global sustainability standards	Promotes innovation and implementation of best practices worldwide.	Builds ethical consensus for environmental stewardship	Complexity in harmonizing regulations across nations.

The Crystal Ball

Future Trends in Nile Tilapia Farming

Innovation abounds in the future of Nile tilapia farming, which will revolutionize aquaculture by combining biotechnology and cutting-edge technology (Xia et al., 2024). AI-assisted farming leads the way with "fishbots" and "cyber-tilapia" improving feeding, monitoring, and disease detection. These clever technologies use sensors and machine intelligence to maximize fish health and water quality, allowing farmers to make real-time decisions that increase sustainability and production. Additionally, the idea of "banking" the microbiome, storing and deploying precisely tailored microbial communities to improve tilapia immunity, digestion, and growth rates while lowering antibiotic dependence, is gaining popularity. A jump from the lab to the pond is anticipated with the next generation of tilapia, which will have improved disease resistance, quicker development, and greater nutritional profiles because of biotechnological advancements, especially CRISPR gene editing (Martinell et al., 2024). Researchers and space agencies are taking a daring step into the unknown by investigating aquaculture in alien environments, preparing Nile tilapia for life beyond Earth. This entails developing closed-loop ecosystems and tilapia adaptation to microgravity to provide space colonies with sustainable protein supplies. Combined, these cutting-edge ideas can completely transform tilapia farming and make it more robust, effective, and responsive to the demands of a world that is changing quickly (Allioui et al., 2023).

CONCLUSION

A revolutionary method where ecological balance and economic viability smoothly match, sustainable aquaculture is embodied by health, environment, and profit harmony. Growing tilapia, especially red tilapia, provides a special chance to show how aquaculture can satisfy the rising need for premium protein without sacrificing environmental integrity. However, achieving this trifecta calls for a steadfast dedication to crossdisciplinary cooperation and innovation. Important steps in achieving this aim include incorporating eco-friendly feed formulas, cutting-edge monitoring technology, and bio-remediation techniques to combat pollutants like cadmium. Furthermore, overcoming obstacles and building a robust aquaculture system depends heavily on collaborating with scientists, farmers, legislators, and technology developers. Aquaculture can reduce its environmental effect and increase stakeholder profitability by funding research and innovation that prioritize sustainability. Aquaculture's future depends on innovative concepts such as combining AI-driven farm management, the ideals of the circular economy, and international cooperation to establish standards that balance ecological responsibility and production. As a model species, tilapia is an excellent example of how aquaculture may spur economic expansion while tackling urgent environmental and food security concerns. The roadmap for aquaculture's next frontier is in this trinity of profit, health, and the environment. Ambition and action will come together to create a sustainable and just future.

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