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The Tilapia Industry—Challenges, Prospects, and Research Initiatives Worldwide and in the Philippines: A Review

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ABSTRACT

Tilapia is a globally significant aquaculture species, ranking third in total production volume worldwide and second among cultured species in the Philippines. Cultivated in over 150 countries, its wide adaptability and economic importance are underscored in diverse production systems. Commonly referred to as the "aquatic chicken", tilapia is characterized by rapid growth, broad environmental tolerance, relative disease resistance, high reproductive capacity, and efficient utilization of both natural and formulated feeds. This paper reviews and assesses the industry's challenges, prospects, and research initiatives essential for its sustainable development. The review analysis shows that tilapia aquaculture is expanding in response to rising global demand and market diversification, driven by technological innovations in genetics, water management, digital monitoring, and disease control that enhance production efficiency and system resilience. Nevertheless, productivity is still limited by low survival rates of fry and fingerlings, genetic deterioration of broodstock, disease outbreaks, increasing production costs, and environmental stressors, with disproportionate impacts on small- and medium-scale producers. Recent scientific developments, including improved and salt-tolerant strains, sex-control and gene-editing technologies, recirculating and biofloc production systems, vaccine development, rapid diagnostic tools, and alternative feed formulations, offer substantial potential to address these constraints and advance the sustainability of tilapia aquaculture systems. Overall, rising global demand, expanding markets, and continued technological and research-driven innovations position tilapia aquaculture for sustained growth, provided that persistent production, disease, and environmental challenges are addressed through integrated and sustainable approaches. Accordingly, integrated and coordinated investments in genetic improvement, resource-efficient production systems, disease prevention and health management, alternative feed development, and capacity building are critical to improving productivity, resilience, and long-term sustainability of the tilapia aquaculture sector.

Keywords: Nile tilapia, aquaculture, genetics, disease, recirculating aquaculture system, climate change

Abbreviations: AI, Artificial Intelligence; AMR, Antimicrobial Resistance; ASC, Aquaculture Stewardship Council; AuNPS, Gold nanoparticles; BAFS, Bureau of Agriculture and Fisheries Standards; BAP, Best Aquaculture Practices; BAR, Bureau of Agricultural Research; BEST, Brackishwater Enhanced Selected Tilapia; BFAR, Bureau of Fisheries and Aquatic Resources; BFT, Biofloc Technology; BIOTECH, National Institute of Molecular Biology and Biotechnology; BSF, Black Soldier Fly; CLSU, Central Luzon State University; CRISPR, Clustered Regularly Interspaced Short Palindromic Repeats; DA, Department of Agriculture; DFR, Diseased Fish Rizal; DNA, Deoxyribonucleic Acid; DOST, Department of Science and Technology; FAO, Food and Agriculture Organization; FaST, FAC Selected Tilapia; FBC, Fisheries Biotechnology Center; FCM, Fermented Copra Meal; GIFT, Genetically Improved Farmed Tilapia; GMT, Genetically Male Tilapia; HDPE, High-density polyethylene; ICSI, Intracytoplasmic sperm injection; IoT, Internet of Things; LGU, Local Government Unit; MAS, Marker-Assisted Selection; MAS, Motile Aeromonad Septicemia; MSTN, Myostatin; NBC, National Breeding Nucleus; NFRDI, National Fisheries Research and Development Institute; NFTC, National Fisheries Technology Center; PCAARRD, Philippine Council for Agriculture, Aquatic and Natural Resources Research and Development; PCEM, Protein Enriched Copra Meal; PCR, Polymerase Chain Reaction; RAS, Recirculating Aquaculture Systems; RDK, Rapid Detection Kit; SEAFDEC, Southeast Asian Fisheries Development Center; SPIN, Saline-tolerant Population of Improved Nilotica; TALEN, Transcription activator-like effector nucleases; TiLV, Tilapia Lake Virus; UPLB, University of the Philippines Los Baños; UPV, University of the Philippines Visayas

1. Introduction

Tilapia is a major aquaculture species, ranking third worldwide, with about 6.7 million MT valued at USD 14.1 billion in 2023. Asia produces 91% of global output, led by China at 1.4 million MT or 46% (Figure 1) (Jory 2023; FAO 2024). In the Philippines, tilapia is second to milkfish, yielding 261,000 MT worth PHP 25.4 billion, with Region III as the top producer at 172,000 MT valued at PHP 16.2 billion (PSA 2024). Native to Africa and the Middle East, tilapia belongs to the Cichlidae family—Oreochromis, Tilapia, and Sarotherodon (Philippart and Ruwet 1982; El-Sayed 2016). Nile tilapia (*Oreochromis niloticus*) remains the most widely-farmed species due to its high economic value (FAO 2021). Tilapia culture, introduced in the mid-20th century, has expanded to 150 countries (El-Sayed 2006; Gupta and Acosta 2004; FAO 2024). Known as the "aquatic chicken," tilapia is favored for aquaculture because of its rapid growth, environmental tolerance, disease resistance, prolific reproduction, and ability to utilize diverse feeds (Romana-Eguia et al. 2014; El-Sayed 2006; Guerrero 2019). It also contributes to rural development, poverty reduction, and food security, supporting the UN Sustainable Development Goals (Abdel 2023).

The tilapia industry faces major challenges that hinder its growth and sustainability, including disease outbreaks, high feed costs, and environmental pressures. Key diseases such as TiLV, *Streptococcus* spp., and *Aeromonas* spp., along with limited diagnostics, lack of vaccines, and rising antimicrobial resistance, continue to constrain production (Surachetpong et al. 2020; Puneeth et al. 2022). High feed prices further reduce profitability due to reliance on costly protein ingredients (Ng and Romano 2013). Farm-level issues—low fry and fingerling survival, poor broodstock management, and inconsistent good aquaculture practices—also limit productivity, especially among small and medium producers (Alam et al. 2021). Environmental stressors include water pollution, agricultural runoff, climate change, and increasing salinization from seawater

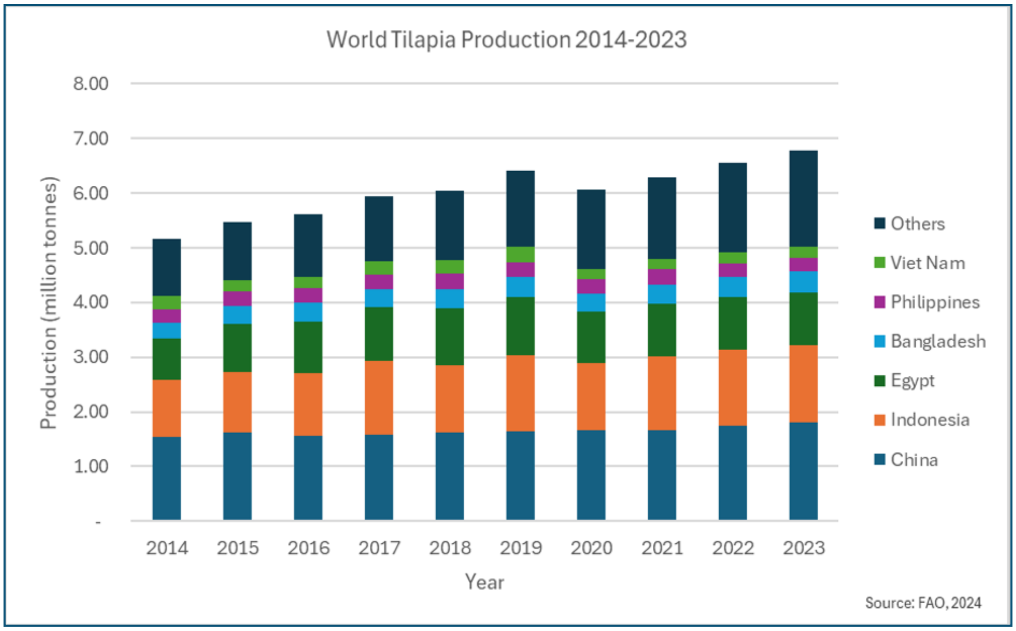

Figure 1. World tilapia production from 2014 to 2023, showing five major producing countries (FAO 2024).

intrusion and groundwater depletion, and further threaten farm viability (Alam et al. 2021; Pine and Boyd 2011).

Despite these challenges, the tilapia industry shows strong potential driven by rising demand for affordable protein, technological advancements, and expanding markets. According to Gupta and Acosta (2004), tilapia farming worldwide has seen significant developments since the 1970s. Tilapia was described as the most important aquaculture species of the 21st century due to its increasing commercialization and continuing growth (Shelton 2002). However, tilapia farming worldwide needs further support for research and development, market diversification, and the adoption of responsible practices for sustaining its phenomenal progress in the 21st century (Guerrero 2008). Given the rising global demand and challenges, Prabu et al. (2019) described that tilapia farming will persist to be an important source of animal protein.

This review assesses the current state of the industry worldwide, with a focus on the Philippine situation, covering trends, challenges, prospects, and research efforts, through an extensive review of reports, studies, books, and articles, and offers recommendations for its sustainable development.

2. Prospects of Tilapia Aquaculture

The increasing market demand and emerging markets are the major prospects of tilapia aquaculture (Figure 1) (FAO 2024). As global demand for affordable, nutritious, and sustainably produced protein continues to rise, tilapia is gaining increasing attention in both traditional and emerging markets (Steffens 2024). One of the most notable trends is the growing demand for tilapia in non-traditional importing countries such as Eastern Europe, the Middle East, and Latin America, seeking cost-effective sources of white fish to supplement local supplies and meet rising consumer needs (Roderick 2025; FAO 2001a). In Russia, Ukraine, Saudi Arabia, and the UAE, tilapia imports are increasing due to the fish's affordability, mild taste, and versatility in local cuisines (IndexBox 2025). At the same time, Africa is both an expanding market and a production base. South America is another region where tilapia consumption is on the rise, not only through domestic production in countries like Brazil, Colombia, and Ecuador, but also through exports and imports within the region. As the aquaculture industry matures, more countries are establishing intra-regional trade in tilapia products, particularly frozen fillets and value-added items (Proaño 2024; Roderick 2025).

Emerging consumer markets such as India, Bangladesh, and parts of Southeast Asia are developing a stronger appetite for farmed fish like tilapia, due to its affordability compared to traditional fish such as carp or marine species. This shift is supported by growing supermarket penetration and changing food preferences, especially among urban populations (IMARC 2024; Alam et al. 2024).

Meanwhile, premium and health-conscious markets in North America and Western Europe are beginning to rediscover tilapia, especially when it is certified as sustainably farmed, antibiotic-free, or traceable. Certified tilapia—such as those with ASC, GlobalG.A.P., or BAP labels—is gaining a foothold in high-end retail, catering to consumers who prioritize food safety and sustainability. In the U.S., tilapia remains one of the top imported seafood items, with increasing emphasis on responsibly sourced products (Ferreira et al. 2022; Easyfish 2025).

Another promising avenue lies in institutional and food service sectors, including schools, hospitals, and quick-service restaurants, where tilapia's low cost, easy preparation, and mild flavor make it an ideal protein. As plant-based trends slow and attention returns to lean animal protein, tilapia is seen as a practical and scalable solution (Painter 2024; More 2025).

Furthermore, processed and value-added tilapia products—such as smoked tilapia, tilapia burgers, and ready-to-cook meals—are entering convenience-driven markets. This trend opens up new opportunities in urban areas, especially among younger consumers and dual-income households (PBI 2024).

3. Challenges in Tilapia Production

Despite significant technological advancements, tilapia farming continues to face several pressing challenges that limit its full potential. These obstacles affect not only productivity and profitability but also the long-term sustainability of the industry.

One of the most persistent issues is the low production levels due to the low survival rate of fry and fingerlings (Frimpong 2018; Moyo and Rapatsa 2021). The early life stages of fish are vulnerable to environmental stress, poor nutrition, and disease outbreaks. Without proper nursery management and care, a significant portion of young fish fail to reach maturity, directly impacting the overall harvest (Hu et al. 2024; Santiago et al. 1987; Fabio et al. 2025). Many tilapia farms, particularly small- to medium-scale operations, struggle to achieve optimal output due to inefficiencies in management, limited access to quality inputs, and substandard infrastructure

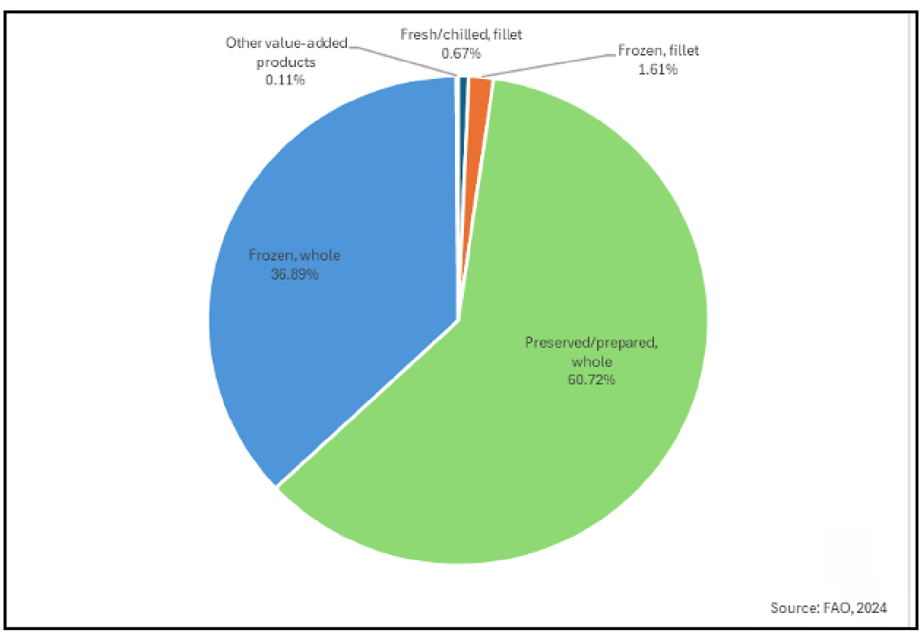

Figure 2. Global tilapia product forms in trade and market in 2023 (FAO 2024).

(Mengistu et al. 2020; Sumon et al. 2025). As a result, yields often fall below the industry's potential, limiting income and market competitiveness (Rayos and Macaraeg 2024).

The genetic health and performance of broodstock are also crucial in producing strong, fast-growing offspring (Bentsen et al. 2017; Thodesen et al. 2011; Gjedrem and Rye 2016). Broodstock in many farms are not regularly replenished or selectively bred, resulting in inbreeding, declining stock quality, weaker fish with lower growth rates, reduced disease resistance, and inconsistent performance over time (Hussain 2025; Mohamad et al. 2021). Research on genetically resilient and fast-growing strains is needed to expand tilapia farming across diverse Philippine environments (Tayamen et al. 2002; Yue et al. 2024).

Fish diseases remain one of the most unpredictable and damaging threats in tilapia farming. Pathogens such as Tilapia Lake Virus (TiLV) (Aich et al. 2022; Machimbirike et al. 2019) and *Streptococcus* (Mishra et al. 2018) can cause rapid mortality, especially in densely stocked or poorly managed systems. In many areas, access to timely diagnostics, vaccines, or effective treatment is limited, leaving farmers vulnerable to devastating losses. Antimicrobial resistance (AMR) has also become a growing concern, leading to risks of increased disease spread and high mortality in tilapia (Pakingking et al. 2022; Legario et al. 2023).

High cost of production is another major challenge to farmers (Rayos and Macaraeg 2024; Cala-Delgado et al. 2024). Fish feed represents the major operational cost, accounting for 50–70% of total production expenses in tilapia farming (FAO 1997; FAO 2001b; Borski et al. 2011; Aya 2017; SEAFDEC 2021; Roa 2023).

The lack of awareness or adherence to good aquaculture practices causes problems in tilapia farm operations (DA BAFS 2020). Many farmers do not follow standardized procedures for water management, feeding, stocking density, and biosecurity (Haque et al. 2025). This can lead to inefficient operations, increased disease risk, and environmental harm—ultimately reducing productivity and marketability (Porthinho et al. 2021).

Lastly, environmental concerns such as pollution further complicate tilapia production (Abd El-Hack et al. 2022). Discharges from nearby agricultural or industrial activities can contaminate water sources, introducing toxins or harmful pathogens (Metwally et al. 2023; Osman and El-Khateeb 2016). In turn, polluted water can lead to poor fish health, stunted growth, and higher mortality rates (Satkar et al. 2024; Hossain et al. 2021). The impacts of climate change—including shifts in temperature, rainfall patterns, and seasonal cycles—are becoming increasingly evident (Siddique et al. 2022; Jiang and Wang, 2024). Tilapia are sensitive to temperature changes, and extreme weather events such as droughts or floods can disrupt breeding, reduce oxygen levels, and damage infrastructure. These environmental stressors add unpredictability to farming operations and demand greater resilience and adaptability from producers (Sumon et al. 2025).

4. Technological Advancements in Tilapia Aquaculture

Tilapia farming is undergoing a remarkable transformation due to a wave of technological innovations and advancements in critical areas such as genetics, water management, disease control, feeding systems, and digital decision-making tilapia production more efficient, sustainable, and profitable than ever before.

One of the most significant breakthroughs lies in genetic improvement and breeding. The development of Genetically Improved Farmed Tilapia (GIFT) (Bentsen et al. 2017), as well as other genetically improved Tilapia strains in China (Thodesen et al. 2011) (Figure 3), has revolutionized productivity by selecting strains that grow faster, utilize feed more efficiently, and have higher survival rates. These improved breeds are now widely used across Asia and Africa. Furthermore, producers are increasingly adopting all-male tilapia production, as male fish grow more rapidly and avoid the complications of uncontrolled reproduction (Abo-Al-Ela 2018). Hormonal and hybrid techniques are employed to ensure uniform, high-performing stocks.

Recirculating Aquaculture Systems (RAS) represent a cutting-edge approach that reuses filtered water in closed-loop systems, minimizing waste and environmental impact (Ahmed and Turchini, 2021; Ende et al. 2024). In parallel, Biofloc technology is gaining traction for its ability to improve both water quality and feed efficiency (Khanjani et al. 2022; Ogello et al. 2021). By cultivating beneficial microbial communities that

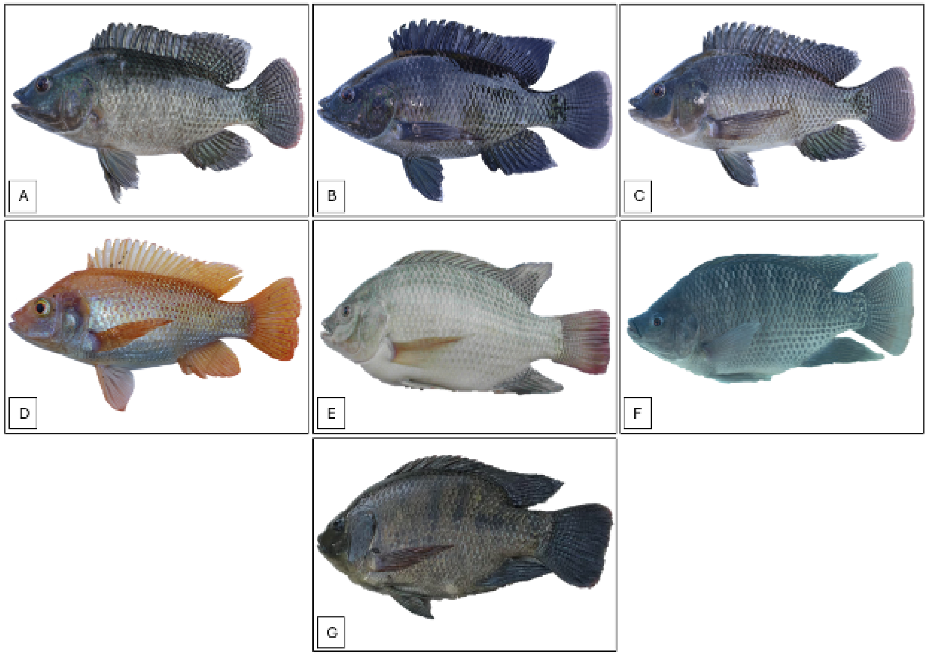

Figure 3. Different commercially available tilapia strains: A) Improved Excel Strain Tilapia (iEXCEL); B) Improved Brackishwater Enhanced Selected Tilapia (iBEST); C) Cold-tolerant Tilapia (COLD); and D) Developed Adaptable Red Tilapia (DART) (Source: Dr. Jodecel C. Danting, BFAR-NFTC); E) Genetically Improved Farmed Tilapia (GIFT) (Source: FAO 2022); F) GenoMar Strain (Source: Genomar); and G) Molobicus Strain (Source: Aquatech ni Doc Westly).

convert waste into protein-rich biomass, biofloc systems reduce the need for frequent water exchange and offer an additional food source for the fish, ultimately lowering production costs (Cala-Delgado et. al. 2024).

Digital transformation is becoming a cornerstone of modern tilapia farming. Aquaculture management software now allows farmers to track stock levels, growth, health metrics, feed usage, and water quality—all in one platform (Chandran et al. 2025; Fernandes and DMello 2025, Hossam et al. 2024). Automated feeding systems now ensure consistent, precise feeding schedules, reducing both labor and feed waste. Meanwhile, real-time sensor technologies track critical water parameters such as pH, temperature, dissolved oxygen, and ammonia levels. These systems are often integrated with the Internet of Things (IoT) and mobile applications, allowing farmers to remotely monitor and control farm operations with ease (Chandran et al. 2025; Abdullah et al. 2024; Bernal-Higuita et al. 2023). Advanced tools powered by artificial intelligence (AI) and machine learning provide predictive insights on growth trends, disease risk, and harvest timing (Yang et al. 2025; Rather et al. 2024). Furthermore, blockchain technology is being adopted to ensure traceability and food safety, especially in premium export markets (Chandran et al. 2025).

In addressing disease threats, producers are embracing improved biosecurity and disease detection methods. Rapid diagnostic tools, such as PCR-based tests, enable early identification of pathogens like Tilapia Lake Virus (TiLV) and *Streptococcus* spp. (Chakraborty and Krishnani 2022). Vaccines are also being developed to protect fish health, while biosecure hatchery practices and quarantine protocols help prevent disease outbreaks (Priya and Kappalli 2022).

Another area of progress is the development of sustainable and alternative feeds (El-Sayed 1999). In an effort to reduce reliance on traditional fishmeal, many farms are turning to plant-based (Hussain et al. 2024; Dasari et al. 2025), insect-based (Rossi et al. 2025; Hossain et al. 2021; Zou et al. 2024; Zhou et al. 2023;

Mohan et al. 2022), or microbial protein sources (Tao et al. 2024; Sobhi et al. 2023). Enzymes and probiotics are added to enhance nutrient absorption and gut health (Mohammed et al. 2025), while researchers continue exploring fermented feeds (Li et al. 2025) and locally available ingredients to cut costs and improve sustainability.

On the hatchery side, innovations are improving both survival rates and fry quality. Modern hatchery and larval rearing technologies include temperature and light manipulation to optimize breeding cycles and ensure a consistent supply of fingerlings (Al-Emran et al. 2024).

Finally, structural advancements are optimizing farming environments. High-density polyethylene (HDPE) floating cages provide durability and enhanced water circulation (Cardia and Lovatelli 2015), while aeration systems in ponds help maintain optimal oxygen levels for high-density culture (Yaparatne et al. 2024). Together, these technologies are not only enhancing the productivity and resilience of tilapia farming but also paving the way for a more sustainable and data-driven aquaculture industry. Table 1 summarizes the technological advancements in tilapia aquaculture, addressing the different challenges in tilapia production.

5. Current Research and Development Initiatives

Key research and development initiatives for tilapia are presented in Table 2, showing scientific works on genetics and breeding, aquaculture, fish diseases, and feed development and sustainable aquaculture in the Philippines.

5.1 Genetics and Breeding

The Genetic Improvement of Farmed Tilapia (GIFT) was a breeding program for *Oreochromis niloticus*, which marked a global milestone in tropical fish genetic enhancement. GIFT and other improved strains have played a key role in significantly increasing tilapia production in the Philippines and worldwide (Ordoñez et al. 2014). Genetic manipulation techniques such as YY-male tilapia (genetically male tilapia or GMT) have

Table 1. Technological advancements in tilapia aquaculture addressing challenges in tilapia production.

Challenges in Tilapia Production	Technological Advances Addressing the Challenges
Low survival rate of fry and fingerlings; poor nursery management; substandard infrastructure	Genetic improvement (GIFT, improved strains); modern hatchery technologies; temperature/light manipulation; RAS and Biofloc improving water quality and survival
Poor broodstock quality, inbreeding, weak growth and disease resistance	Selective breeding; genetically improved strains; all-male tilapia production for uniform performance
Disease outbreaks: TiLV, Streptococcus; limited diagnostics and treatment; AMR	PCR-based rapid diagnostics; vaccines; strict biosecurity; quarantine protocols; AI-based disease prediction
High feed cost (50–70% of expenses)	Alternative feeds (plant-, insect-, microbial-based); probiotics, enzymes; improved feed efficiency via biofloc and automated precision feeding
Lack of adherence to Good Aquaculture Practices; poor water, feeding, stocking management	Digital monitoring systems; IoT water sensors; automated feeding; aquaculture management software; blockchain for traceability
Environmental issues: pollution, climate change, water contamination	RAS (reduced water use), biofloc; HDPE cages for better circulation; aeration systems; climate-adaptive farm monitoring tools

Table 2. Summary table of key research and development for tilapia.

Thematic Area	Problem Addressed	R&D Initiatives	References
Genetics and Breeding	Declining broodstock quality; inbreeding; limited growth performance; lack of sex-control options	GIFT and improved strain breeding programs	Ordoñez et al. 2014
		YY-male/GMT non-hormonal sex-control technology	Mair et al. 1995; Chen et al. 2019
		Marker-Assisted Selection (MAS), sex-linked DNA markers, genotyping	Chen et al. 2019
		Gene editing: MSTN knockout, TALEN/CRISPR	Chen et al. 2019; Wu et al. 2023
		Germ cell transplantation, cryopreservation	Lacerda et al. 2010
		Development of clonal lines via gynogenesis	Hussain et al. 1998
		ICSI for precise fertilization	Poleo et al. 2005
Aquaculture	Low survival; poor water quality; limited space; high operational costs; vulnerability to climate change	RAS improvements—design, filtration, energy efficiency	Helfrich and Libey 1991; upta et al. 2024; Rodríguez-Hernández 2025
		Biofloc Technology (BFT) for water recycling & feed conversion	Lima et al. 2019; Khanjani et al. 2022; Blatt et al. 2025
		Aquaponics integration for circular resource use	Mullins et al. 2017; Silva et al. 2025
		Technology verification: large fingerlings, saline tilapia expansion, polyculture, large-size tilapia production	NFRDI 2021; BFAR 2022a and 2022b
		Digital tools: real-time sensors, automated feeders, mobile apps	NFRDI 2021; DOST 2022; BAR 2023

Thematic Area	Problem Addressed	R&D Initiatives	References
Fish Diseases	Disease outbreaks; limited vaccines; lack of rapid diagnostics; AMR concerns	Oral vaccines (Fishvax Aero; Aeromonas veronii vaccines)	Ramoran 2024; Argayosa et al. 2024
		Hydrogen peroxide–inactivated Streptococcus vaccine	Saturno et al. 2025
		pH-inactivated Aeromonas vaccine (CLSU)	de Guzman et al. 2025
		Nanogold-based Rapid Detection Kits (RDKs) for Aeromonas & Streptococcus (CLSU)	Ramoran 2023
		Development of TiLV vaccine and detection kit (NFRDI)	Roy 2023, Logronio et al. 2022
Food Development	High cost of commercial feeds; fishmeal dependence; limited local protein alternatives	Protein Enriched Copra Meal (PECM) by UPLB-BIOTECH	UPLB-BIOTECH 2025
		Fermented Copra Meal (FCM) as soybean meal replacement	Flores et al. 2024
		NFRDI verification of SEAFDEC low-cost feed formulations	Mutia et al. in-press
		Insect-based feeds using BSF larvae meal (NFRDI)	Santos 2024
		PCAARRD S&T Program for aquafeeds (microalgae, alternative proteins)	DOST-PCAARRD 2025
Sustainable Aquaculture	Environmental stress, climate change, resource degradation; limited availability of high-quality seed; low adoption of improved technologies	National Breeding Nucleus (BFAR-NFTC); broodstock enhancement	BFAR 2022a
		Strengthening satellite nucleus farms (FaST program, CLSU)	Fabros 2025
		Development of value-added tilapia products (ice cream, cookies, tilading)	Coballes 2022; CLSU 2023; Ramos et al. 2024; CLSU 2024
		Pilot-scale aquashade systems	Mazo and Vera Cruz 2024; DOST 2022
		Sex reversal using phytoandrogens	Gahon and Fernandez 2018

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also been successfully developed to improve growth performance (Mair et al. 1995). YY-male or Genetically Male Tilapia (GMT) technology provides a non-hormonal alternative to the widely used practice of producing hormone-treated fry. This approach generates all-male progeny through conventional breeding techniques, rather than chemical sex reversal, thereby addressing long-standing concerns regarding environmental contamination and negative consumer perceptions associated with hormonal treatments. The technology was originally pioneered, developed, and field-tested at Central Luzon State University (CLSU), which established robust protocols for producing YY "supermales" and rigorously validated their performance under farm conditions (Mair et al. 1995; Chen et al. 2019).

In support of these breeding strategies, advanced tools like sex-linked DNA markers and marker-assisted selection (MAS) systems have improved the identification of sex genotypes in Nile and blue tilapia, reducing reliance on progeny testing. Combined with gene-editing technologies such as TALEN and CRISPR/Cas9, these innovations offer precise methods for sex control and genetic enhancement in tilapia aquaculture (Chen et al. 2019).

Recent developments also include targeted gene mutation, such as myostatin (MSTN) gene knockout in Nile tilapia, which significantly improved growth traits, including weight gain, feed efficiency, and condition factor (Wu et al. 2023). A major breakthrough in tilapia reproductive biotechnology is the successful non-surgical transplantation of spermatogonia into mature tilapia testes, enabling the production of functional sperm and donor-derived progeny within two months. When integrated with cryopreservation and gene-editing of spermatogonial stem cells, this approach offers a scalable solution for seed production, conservation of genetic resources, and development of transgenic lines in commercial aquaculture (Lacerda et al. 2010). Also, heterozygous and homozygous clonal lines of Nile tilapia were successfully produced using gynogenesis and marker-based validation. These clones offer potential applications in genetic research and large-scale aquaculture production (Hussain et al. 1998). Another study successfully applied intracytoplasmic sperm injection (ICSI) to Nile tilapia by using a controlled spawning system and preserving egg viability for precise sperm injection. Out of 113 eggs, one developed normally and reached adulthood, proving ICSI's potential for tilapia fertilization, cryopreservation, and reproductive research (Poleo et al. 2005).

The NFRDI-Fisheries Biotech Program takes the lead in advancing genetics and genomics research in tilapia (Ordoñez et al. 2014). The Tilapia Industry Roadmap of the DA prioritized in 2021-2025 the selective breeding and broodstock enhancement programs and genotyping towards Marker Assisted Selection (MAS), and importation of other strains or species of tilapia (*Oreochromis* spp.) to improve resilient tilapia strain. For the long-term plan (2022-2040), research will focus on the enhancement of fish immunity, isolation and cryo-conservation of somatic cells, and application of genomics and Marker Assisted Selection (MAS) in tilapia and breeding production (BFAR 2022). Sustaining the long-term performance of improved tilapia strains requires comprehensive genetic monitoring and marker-based strain management implemented at the national level (Ponzoni et al. 2011; Joshi et al. 2018). Conducting regular genetic audits across government and private hatcheries is essential to maintaining strain integrity and ensuring that farmers consistently receive high-quality seed (Gjedrem & Baranski, 2009). This form of marker-assisted stock management is increasingly recognized as a national priority, particularly as tilapia supply chains expand and broodstock sources become more diverse across regions (FAO 2020; Nguyen et al. 2021).

5.2 Aquaculture

Research on RAS concentrates on improving system design together with water treatment systems and energy efficiency, and conducting cost-benefit analyses of production costs against growth performance to establish economic feasibility (Helfrich and Libey 1991; Rodríguez-Hernández 2025). The adoption of RAS systems leads aquaculture towards highly regulated and intense operations, but requires major financial resources together with specialized technical skills for proper management (Gupta et al. 2024).

The filter-feeding nature of tilapia, combined with their ability to thrive in high-density environments, makes Biofloc Technology (BFT) an ideal intensive system for their culture (Lima et al. 2019) (Figure 4).. The maintenance of water quality in BFT systems depends on precise carbon-to-nitrogen ratio management, which

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promotes heterotrophic bacterial growth (Khanjani et al. 2022). The heterotrophic bacteria convert dangerous nitrogenous waste substances into bioflocs, which become a valuable protein-rich food supplement for cultured tilapia. BFT provides double benefits through its capability to produce high yields with no wastewater discharge, which minimizes environmental impact (Blatt et al. 2025).

Studies on tilapia-based aquaponics investigate how variables such as fish stocking density and plant species impact water quality, overall system productivity, and the growth responses of both fish and plants under different feeding or fasting conditions (Mullins et al. 2017). Aligned with circular economy principles, aquaponics promotes the simultaneous cultivation of fish and plants while maximizing water reuse and resource efficiency (Silva et al. 2025).

Technology verification of tilapia culture technologies, such as the use of larger fingerlings in grow-out, outscaling of saline tilapia (Molobicus) culture through backyard satellite hatcheries, polyculture systems, and production of larger tilapia (>500g), are being undertaken by NFRDI and BFAR in collaboration with LGUs to support livelihood in the community (NFRDI 2021; DA BFAR 2022a and 2022b). As a response to climate change and resource degradation, tilapia research and development plans are focused on the development of smart aquaculture technologies such as real-time sensors, automated feeders, and mobile applications to improve production (NFRDI 2021; DOST 2022; DA BAR 2023).

5.3 Fish diseases

Research on oral vaccines and diagnostic kits for tilapia aims to combat diseases like *Aeromonas*, *Streptococcus*, and Tilapia Lake Virus (TiLV).

The Fishvax Aero oral vaccine, when integrated into fish feeds, has been shown to protect Nile tilapia against Motile Aeromonad Septicemia (MAS) and significantly improve fingerling survival (Ramoran 2024). MAS, caused by *Aeromonas* species, remains a major challenge in fish health management. Argayosa et al. (2024) successfully isolated and characterized *Aeromonas veronii* DFR01 from diseased tilapia in Binangonan, Rizal, which served as the basis for developing the Fishvax Aero oral vaccine. Tank trials demonstrated that Fishvax Aero-vaccinated fingerlings exhibited higher survival rates, elevated IgM

Figure 4. Indoor view of one of the 766-cubic-meter BFT tilapia grow-out tanks at Chambo Fisheries, Malawi (Source of figure: Global Seafood Alliance).

levels, and substantially lower cumulative mortality (25–35%) compared with unvaccinated fish, which showed mortality rates of up to 75% (Argayosa et al. 2024).

CLSU and Maejo University in Thailand have developed an inactivated vaccine with hydrogen peroxide to protect red Nile tilapia from *Streptococcus agalactiae*. Experimental trials of the vaccine showed promising results in protecting fish from bacterial infections (Saturno et al. 2025). Furthermore, CLSU research on pH-inactivated Aeromonas *hydrophila* vaccine development demonstrates local expertise in making effective inactivated vaccines. A 100% relative percent survival was reported through the use of pH manipulation together with formaldehyde for inactivation (de Guzman et al. 2025).

Immunoassay kits utilizing colloidal gold nanoparticles (AuNPs) to detect key bacterial pathogens, including *Aeromonas* and *Streptococcus* in freshwater tilapia aquaculture, have been developed at CLSU (Ramoran 2023). The newly developed Rapid Detection Kits (RDKs) are more affordable than traditional plate culture or molecular methods and easier to operate without the need for specialized instruments or expert knowledge, and have undergone pilot testing. The sensitivity of the nanogold-based RDK for *Aeromonas hydrophila* detection has been enhanced in preparation for its eventual commercialization (Ramoran 2023).

The National Fisheries Research and Development Institute-Fisheries Biotechnology Center (NFRDI-FBC) has developed diagnostic detection methods for tilapia lake virus (TiLV) and has initiated the development of a detection kit and vaccine for TiLV (Roy 2023; Logronio et al. 2022).

5.4 Feed development

The National Institute of Molecular Biology and Biotechnology (BIOTECH) at the University of the Philippines Los Baños successfully developed Protein Enriched Copra Meal (PECM) as a major breakthrough of a cost-effective feed ingredient replacing soybean meal protein in tilapia aquafeeds while maintaining optimal growth outcomes (UPLB-BIOTECH 2025). On the other hand, fermented copra meal (FCM) fed to saline-tolerant tilapia juveniles was shown to be effective in replacing soybean meal by 50% in weight terms without negatively affecting the growth outcomes, protein efficiency ratio, survival, or specific growth rate of the fish (Flores et al. 2024).

The DA-NFRDI has verified the effectivity of SEAFDEC-AQD low-cost feed formulations to milkfish and tilapia farms in the country. The use of corn by-products, PECM, and poultry by-products produced tilapia with good growth and survival and has reduced the feed cost by P8 to P10 per kilogram (Mutia et al. in-press). Currently, NFRDI is developing an insect-based feed using black soldier fly (BSF) larvae meal as a protein substitute to create cost-efficient diets that improve the health and immunity of Nile tilapia fingerlings (Santos 2024).

DOST-PCAARRD also implements the Aquafeeds Industry Strategic Science and Technology Program, which addresses the problems faced by the Philippine aquafeeds industry, including low algal paste yield and the high cost of fish meal and soybean meal-based protein source for aquafeed, which increases the cost of aquafeeds (DOST-PCAARRD 2025).

5.5 Sustainable aquaculture

In the National Tilapia Industry Roadmap, BFAR-National Fisheries Technology Center (BFAR-NFTC) serves as the National Breeding Nucleus (NBC) of tilapia that provides foundation stocks and parent lines to Central and Satellite Hatcheries of the country. Together with NFRDI-FBC and other research institutions, studies on broodstock enhancement, selective breeding, and genotyping towards Marker Assisted Selection will be continued to improve and increase tilapia production in the country by 3% annually (DA BFAR 2022a).

The tilapia R&D program of DOST-PCAARRD aims to create technological advancements to boost tilapia farming systems, focusing on the genetic improvement, broodstock quality development, and strengthening satellite nucleus facilities that will multiply FaST Strain fingerlings (Fabros 2025). CLSU, as the main implementer of DOST-PCAARRD's National Tilapia R&D Program, serves as the main breeding facility that produces top-quality FasT broodstock and fingerlings (Fabros 2025). The university also expanded its research to develop innovative value-added products from tilapia, such as the "Daerrys Tilapia Ice Cream" and "Tilapia Cookies"

(Coballes 2022; CLSU 2023) and improved the quality standards of traditional processed products like "tilading" (dried tilapia) (Ramos et al. 2024; CLSU 2024). PCAARRD also supported the research initiatives on the pilot-scale application of aquashade to enhance production of tilapia and on-farm trials of phytoandrogen for sex reversion of tilapia (Mazo and Vera Cruz 2024; Gahon and Fernandez 2018; DOST 2022).

SEAFDEC/AQD implements the development of a responsible and sustainable aquaculture technologies program, which aims to build efficient farming systems and develop feed alternatives that decrease fishmeal dependency (SEAFDEC 2016).

6. Conclusions

Tilapia aquaculture demonstrates strong potential for sustained growth as global demand for affordable, nutritious protein continues to rise across both traditional and emerging markets. Expanding consumption in Eastern Europe, the Middle East, South America, and parts of Asia is opening new trade opportunities, while premium markets in North America and Europe increasingly favor sustainably certified products. Technological advancements—such as improved genetics, advanced water management systems, digital monitoring tools, and enhanced disease-control strategies—are reshaping tilapia production into a more efficient and resilient industry. The development of value-added products and increasing interest from institutional buyers further strengthen market prospects.

Despite these positive trends, the industry continues to face significant challenges. Low survival rates of fry and fingerlings, suboptimal farm management, limited access to resources, genetic deterioration of broodstock, disease outbreaks, rising production costs, and environmental stressors all constrain productivity and profitability, particularly for small- and medium-scale producers. Climate variability, pollution, and extreme weather events further intensify these constraints. Ongoing research and development efforts in genetics, aquaculture systems, fish health, and feed innovation—supported by government and academic institutions—are addressing these challenges through improved strains, sustainable production systems, disease mitigation strategies, and cost-efficient feeds. Collectively, these developments position tilapia aquaculture for continued growth, provided that innovation and sustainability remain central to industry advancement.

7. Recommendations

To enhance tilapia production and ensure long-term sustainability, strategic and coordinated actions are required. Increased investment in genomics, selective breeding, and cryopreservation should be prioritized to accelerate the development and dissemination of high-quality, resilient strains while preserving genetic diversity. The wider adoption of intensive and resource-efficient culture systems such as recirculating aquaculture systems, biofloc technology, and aquaponics, integrated with digital monitoring tools and renewable energy sources, can significantly improve production efficiency and environmental performance.

Disease prevention and management should be strengthened through the rapid deployment of locally developed oral vaccines, affordable diagnostic tools, and enhanced disease surveillance systems to mitigate emerging pathogens and reduce antimicrobial resistance. Expanding the use of alternative and cost-effective feed ingredients, including plant-based proteins, insect meals, and microbial protein sources, will help lower production costs and reduce dependence on conventional feed inputs. Capacity-building programs for fisherfolk and producers, coupled with the development and scaling of salt-tolerant and climate-resilient strains such as UPV SPIN, BFAR-BEST, and Molobicus, should be intensified to support industry expansion in brackishwater and estuarine environments increasingly affected by salinization and climate-related stressors. Together, these measures will strengthen productivity, resilience, and sustainability across the tilapia aquaculture value chain.

Contribution of Authors:

All authors contributed substantially to the preparation of this review article.

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The authors declare that artificial intelligence (AI)–assisted tools were used in the preparation of this manuscript titled exclusively for language editing, grammar checking, and improvement of clarity and readability. No AI tools were used to generate scientific content, interpret data, draw conclusions, or make scholarly judgments. All concepts, analyses, interpretations, and conclusions presented in this review are the sole work and responsibility of the authors.

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