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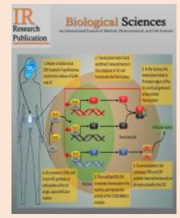

Tilapia Aquaculture: A Review

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ABSTRACT

The tilapia aquaculture has developed into a vital component in the global food security and rural livelihoods, with its value of around 6.9million metric tonnes worth of $12.5 billion in 2023. This review brings together the current literature that is related to the biological traits, farming systems, nutrition, disease management, environmental impacts, socioeconomic benefits, and technological innovations in tilapia aquaculture. It is centered on the main cultured species, i.e. *Oreochromis niloticus*, *O. mossambicus*, *O. aureus*, etc. The narrative review method was adopted based on the recent peer-reviewed publications, FAO reports, and industry data. The key gaps identified include poor adoption of climate-resilient and precision technologies by small-scale producers, an underlying gender inequality, lack of scalable biosecurity and vaccination solutions, and environmental threat in the form of nutrient runoffs and invasive escapes. The research recommends giving priority to affordable innovations, inclusive policy frameworks that serve the interests of the small holders particularly women, climate-adaptive strains and systems, strengthened biosecurity systems and enhanced application of certified sustainable practices including the ASC and the BAP, which will balance the productivity, environmental stewardship and social equity.

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Introduction

The aquaculture of tilapia is faced by challenges that are interconnected with increasing global population, rising demand of animal protein, rising feed costs, outbreaks of diseases, global warming and environmental issues associated with nutrient discharge and biodiversity loss. Despite being among the most extensively cultivated fish species, there are still low productivity, high levels of disease-related losses, limited marketability, and susceptibility to climate extremities among a large number of small-scale producers in the developing economies (1).

Tilapia farming is now a mainstay in the world of fish farming which is made possible by its versatility, profitability and more people wanting cheaper protein options (1). The Nile tilapia which is native to Africa and the Middle East, is now a mainstay in aquaculture because it can thrive in many habitats, grow quickly and is eaten in many places worldwide (2). The increase in tilapia fish farms around the world is because they support access to food, economic growth and sustainable agriculture in various developing countries (1).

Three of the most frequently grown tilapia species are *Oreochromis niloticus*, *Oreochromis mossambicus* and *Oreochromis aureus* which are belonging to the family Cichlidae. These features are fast development time (being market-ready in 6 to 8 months), frequent reproduction by females and being able to adjust to several environmental conditions such as temperatures between 20 to 30°C, a variety of salt levels and low oxygen concentration. Tilapia is suitable for areas with limited food resources because, unlike carnivores such as salmon, it is omnivorous which is cheaper for farmers (3).

People in ancient Egypt started farming tilapia in ponds by the Nile more than four thousand years ago (4). With the introduction of new generations in the 1980s, for example, Genetically Improved Farmed Tilapia (GIFT) by the WorldFish Center, modern tilapia farming grow significantly. Tilapia farming in Asia and Africa has been improved by the GIFT strain because it allows fish to grow up to 50% faster and uses feed better. Tilapia being able to adapt to many different ways of farming has made it popular in more than 120 countries for small-scale and commercial farming (5). Because tilapia is mild-flavored, has white flesh and can be prepared as fillets or whole fish, it attracts customers worldwide, competing with popular fishes such as cod and haddock in the international market (3).

Lately, tilapia aquaculture has benefited from precision farming like real-time water testing and automatic feeding machines that have helped lower the impact on nature (6). Working in a polyculture environment with shrimp and carp helps tilapia use resources efficiently and keeps farms strong (7). Other difficulties such as the tendency of non-native tilapia strains to carry diseases and the impact of escapes on nature still exist, so it is necessary to keep investigating and monitoring these fish (4).

This review was done with the aim of offering a synthesis of available information on the systems of aquaculture, biology, nutrition, health management, environmental sustainability, socioeconomic contributions and emerging technologies of tilapia ponds. The aim of the study is to find out the bottlenecks that have persisted through the recent scientific discoveries and industry trends, and to bring out the actionable pathways to more productive, resilient, equitable, and environmentally responsible tilapia farming across the world. This paper adopts the narrative review approach, which entails the methodical collection and analysis of data in the form of peer-reviewed journal articles, FAO documents, market reports, and published literature. No formal meta-analysis protocol or systematic review was applied; rather, the selection emphasized breadth, recency and relevance to key producing areas and contemporary global issues.

Global importance and economic significance

Global tilapia production was 6.8 million metric tons in 2022, making up roughly 9.8% of all fish produced by aquaculture (8), making it second only to carp among farmed fish (8). Nearly three-quarters of the world's aquatic products come from China, Indonesia, Egypt, Bangladesh and the Philippines every year and China is the single largest producer with 1.85 million tons annually (9). According to the Market Research Future (2024), forecasts point to the global tilapia market expanding from USD 12.3 billion in 2023 to USD 16 billion in 2030 because more people are seeking affordable, protein-rich seafood. Tilapia is attractive to both farmers and consumers because its efficient feed conversion ratio is lower than that of carnivorous fish (7).

Tilapia aquaculture is an important source of income and work for more than 10 million people around the world who are involved in farming, processing and exporting tilapia (10). Tilapia farming is important for rural communities in sub-Saharan Africa and Aquaculture programs from the African Development Bank help many small farmers reduce poverty and malnutrition (10). About 200,000 tons of tilapia were imported by the U.S. in 2023 and the majority of this fish was consumed as frozen fillets delivered from Asia and Latin America (11).

Accessible protein which in many regions includes tilapia, is especially important for food security in low-income areas (3). Even so, aquaculture industries deal with problems such as feed cost changes, limitations on trade and concerns over pollution from water use and waste (12). Viruses such as tilapia lake virus (TiLV) cause harm to the economies of many countries in Asia and Africa, suggesting that better disease management is necessary (13). In spite of all these difficulties, tilapia is still famous all over the globe because of its adaptable and thriving economy.

Biology and Ecology of Tilapia

Figure 1. Global tilapia production, major producers, and market growth trends.

Tilapia is important in aquaculture worldwide because of its unique biology and ecology that make it adaptable to many types of aquaculture and different environments. Because of their ability to adapt quickly, their swift development and efficient reproduction, tilapia species are used widely both in small-small-scale and large-scale farming (14).

Taxonomy and species diversity

Most people refer to Tilapia as a group of freshwater fish that are members of the family Cichlidae and mostly from the genera Oreochromis, Sarotherodon and Tilapia. Because there is so much diversity and mixing among tilapia species, their taxonomy is not simple. More than 70 species have been described, but only a handful are used in aquaculture for their outstanding qualities (14). Most tilapia on the planet comes from *Oreochromis niloticus* (Nile tilapia) which accounts for around 70% of all tilapia produced, with *Oreochromis mossambicus* (Mozambique tilapia) and *Oreochromis aureus* (blue tilapia) coming in second and third, respectively, according to FAO (8). Creating hybrids such as *O. niloticus* × *O. aureus* is also frequent and these are bred to grow faster and withstand lower temperatures (7).

Found in Africa and the Middle East, tilapia fish can be found in many different areas such as rivers, lakes or even in the coastal waters where the salt concentration is lower. Because *O. mossambicus* lives in estuaries in nature, it becomes tolerant to salt, while *O. niloticus* prefers rivers like the Nile without much salt (14). Because of the genetic diversity in tilapia, scientists have breed selectively to make the GIFT line which grows 30 to 50% faster than wild ones (12). Connections between species may also become blurred by hybridization and the addition of foreign species which can negatively affect the environment in places like Asia and Latin America (15). Being able to classify closely is still key for managing and breeding marine organisms in aquaculture.

Physiological adaptations for aquaculture

Tilapia's physiological adaptations are key to their success in aquaculture. Because they eat different things, they can get the nutrition they need from algae, plants and formulated foods which saves them from having to depend on pricier fishmeal (7). The digestive system of tilapia is also efficient, and the feed conversion ratio (FCR) is 1.5 to 1.8, which is much lower than that of carnivorous fish such as salmon (2.0 to 2.5), and it is also inexpensive to culture (3). They have high reproductive potential with mouth-brooding species, such as those of the Oreochromis, spawning hundreds of eggs per spawning event which makes their stock replenishment high (14).

The tilapia are also very strong in terms of physiological tolerance. The efficient gill structures and hemoglobin adaptations enable them to tolerate low dissolved oxygen (down to 1 to 2 mg/L) and, thereby, survive in high-density culture systems (5). They can osmoregulate over a salinity of 0-20 ppt, making them be cultivated in brackish water, especially in the case of species such as *O. mossambicus* (16). Also, tilapia has a fast growth rate, and under excellent conditions, market size (500 to 800 g) can be reached in 6 to 8 months, which helps to keep the intensive systems productive (8). Recent studies also emphasize stress response genes that increase the tolerance of tilapia to environmental changes, which further solidify their adaptability to a variety of aquaculture environment (6). But the adaptations also provoke questions regarding their invasiveness in case of escapes, so they must be managed (15).

Environmental requirements and tolerance

One reason that Tilapia is so successful in aquaculture across the world is their environmental tolerances. They prefer warm waters, and the optimum temperature range is between 25 and 30oC, although some, such as *O. aureus*, may endure lower temperatures down to 10oC but briefly (7). Growth and reproduction drastically reduce below 15oC, hindering their production in temperate zones without heat structures (4). Tilapia can also endure low water quality and thrives in waters containing high levels of ammonia (up to 2 mg/L) and low oxygen concentration, which makes them suitable for low-cost, extensive farming systems in resource-limited settings (5).

The degree of salinity tolerance is species-specific. *O. mossambicus* and its hybrids can adapt to salinities as high as 20 ppt, making them suitable to use in coastal aquaculture, whereas *O. niloticus* feels best in freshwater but can adjust to 10 ppt (16). pH tolerance is between 6 and 9, with 7 to 8 being the optimum growth range, and the extreme pH values can cause stress to the fish, slowing down the growth rates (8). The toleration of high stocking densities (up to 20 to 30 kg/m3 in RAS) makes Tilapia well-suited to intensive production, whereas overcrowding may predispose fish to disease, including Streptococcus infections (13).

Site selection and system design are also affected by environmental requirements. As an example, systems placed in ponds in tropical locations take advantage of the tilapia species ability to tolerate variable conditions, whereas RAS in controlled conditions can maximize growth by keeping the parameters constant (6). Nevertheless, due to its adaptive advantages, tilapia has also created ecological issues, since the escaped populations may colonize non-native environments and outcompete the native species (15). According to recent research, site-specific environmental management practices are necessary to strike the right balance between productivity and ecological sustainability (3).

Aquaculture Systems and Practices

The aquaculture of tilapia is highly variable in the systems and practices used to suit different environmental, economic and social conditions that graduates from low cost and traditional to high technology and intensive procedures. These systems utilize the biological flexibility of tilapia to maximize production, increase sustainability and to provide affordable protein to the ever-increasing global population (17).

Pond-based aquaculture

The most common and widely used system of tilapia farming in most parts of the world especially in the tropics and subtropics is pond-based aquaculture because it is cheap and easy and falls within the ecological tolerance of tilapia. Earthen ponds (mostly between 0.1 and 2 hectares) use natural ecosystem processes, including photosynthesis and microbial activity to grow tilapia, with or without the addition of commercial feeds or organic matter (18). Semi-intensive pond systems, practiced in Africa and Southeast Asia, produce 5 to 15 tons per hectare per year, and intensive ponds, with aeration and high-quality feeds, can give up to 20 tons per hectare (19). Smallholder farmers prefer ponds due to their cheap infrastructure requirements and capacity to fit into agricultural systems like rice-fish culture that promotes food security and income diversification at the rural levels (20).

Other new developments in the pond culture of fish have been the introduction of biofloc-enhanced systems, which reuse nutrients, leading to a 15 to 25 % increase in feed efficiency and cutting the water exchange requirement (18). Organic plankton fertilizing using manure or farm wastes results in a 20-40% reduction in the cost of feed produced in low-input systems, especially in sub-Saharan Africa (19). Nevertheless, there are still issues, namely the development of water quality due to excessive nutrient loading that might lead to eutrophication and algal blooms and the risks associated with diseases, the most typical of which, in intensely stocked ponds, is the Aeromonas infection (21). Additional challenges to management of ponds include environmental susceptibility to flood, or drought in cases of climatic sensitive areas. To increase resilience and productivity, they are investigating different advances in pond management like water quality monitoring by utilizing drones and polyculture using species such as catfish (20). Environmental mitigation of the impacts should be an essential consideration and this can be achieved through sustainable activities such as sediment removal and treating effluents to make the operation viable in the long run (19).

Cage and tank systems

Cage and tank systems offer diversified options of tilapia aquaculture especially in areas where land is scarce, or water bodies are numerous. Cage culture entails placing net pens in lakes, rivers or reservoirs and using the natural water current to oxygenate the water and carry away waste products with production of up to 50 to 120 kg per cubic meter in properly managed systems (22). In land-based activities, tanks (built with materials such as concrete, fiberglass, or polyethylene) can be utilized, where fine control of water quality, stocking density, and biosecurity are desired, and hence are well-suited to urban or peri-urban aquaculture. Cage systems are prevalent in such countries as the Philippines, Brazil, and Thailand whereas tank systems are getting popular in regions where land prices are high or environmental policies are strict (23).

Cage systems have low set up requirements, and high productivity, but have issues regarding their environmental impacts, including nutrient pollution due to uneaten feed and fish waste, which can cause eutrophication and disturb other water users, including tourism or fishing industries (22). Although tank systems allow more control, they are costly to implement (USD 10,000 to 100,000 to install small-scale systems) and operate (aeration, filtration, and energy) and thereby are not affordable to smallholder farmers (23). More recent developments are the implementation of biofloc technology in tank systems, allowing to recycle nutrients and decrease waste by 20-30%, and the usage of solar-powered aerators in cages, which decreases the energy expenses (21). On another note, more cage designs using finer mesh and waste-capture systems are being innovated in order to reduce environmental impacts (24). The advantage of both systems is that tilapia can tolerate high stocking densities, although both systems need close attention to avoid diseases associated with stress, including tilapia lake virus (22).

Recirculating aquaculture systems (RAS)

Recirculating Aquaculture Systems (RAS) are an advanced recirculation and filtration of water used in tilapia aquaculture to establish controlled high-density production systems. RAS use 90 to 95% less water than conventional systems, which makes them viable in water-stressed areas, and allows production throughout the year in a wide range of climates, even temperate regions (25). The tolerance of Tilapia to stocking density (20 to 40 kg per cubic meter) and low oxygen enable RAS to obtain yield of 100 to 200 kg per cubic meter, which is much higher than pond or cage systems (26). RAS are being used more in developed nations, including the Netherlands and the United States, and in cities where land and water are scarce.

RAS benefits are associated with improved biosecurity, low environmental effluent, and the possibility to culture tilapia in non-tropical locations using heated systems. Nonetheless, the cost of capital (USD 50,000 to 1 million to commercially set up) and energy to power pumps, filters, and aeration are severe impediments, especially to the small-scale producers in the developing world (25). A technical understanding and solid backup systems are needed in case of system failure that can cause a rapid decline in water quality and mass mortalities, including filter clogging or power outages (26). More recent advances have been the addition of Internet of Things (IoT) sensors and machine learning algorithms to optimize water quality parameters which can decrease operational costs by 10 to 20% and increase fish growth rates (24). There is also the emergence of hybrid RAS systems that integrate biofloc and hydroponics to maximize nutrient recycling and provide diversity in revenue by producing crops (21). The issue of scaling RAS to be adopted by smallholders is still problematic, and it requires affordable designs and training courses.

Integrated multi-trophic aquaculture (IMTA)

The latest technology is Integrated Multi-Trophic Aquaculture (IMTA) where tilapia is co-cultured with other organisms, e.g., shrimp, shellfish, algae or aquatic plants, to establish a synergetic ecosystem, where nutrients are recycled and environmental impacts are reduced to a minimum. In IMTA, tilapia waste can feed lower-trophic-level organisms that will enhance water quality and produce extra products, e.g., seaweed as food or bioenergy (27). As an illustration, tilapia-shrimp IMTA systems have shown to cut 15 to 20% of nitrogen and phosphorus release over monoculture, but yield two saleable species (28). IMTA is becoming popular in Asia, especially in China and Vietnam, and experimental projects in Africa and Latin America, where it aids sustainable intensification.

IMTA possesses several advantages, such as the enhancement of resource use, decreasing an ecological footprint, and the diversification of farmer income. It is, however, complex and needs cautious species-selection and system-design to achieve compatibility and balance nutrient flows, which makes management 10-15% more expensive than monoculture systems (27). Tilapia due to its omnivorous diet and environmental tolerance is a good candidate to be used in IMTA, however the market demand of co-cultured products, like seaweed or bivalves, may restrict the economic feasibility in certain areas (28). New studies consider advanced IMTA systems design, including tilapia with hydroponic vegetables or biofloc, which can enhance the overall system output by 25% and lessen water consumption (24). There is also pilot IMTA implementation in salty coastal environments, taking advantage of the fact that tilapia can tolerate some salinity to broaden its use (27). Scalability and knowledge barriers are the main obstacles to overcome towards wider adoption.

Nutrition and Feed Management

Management of nutrition and feed is very crucial in maximizing the growth, health and cost-effectiveness of tilapia in aquaculture since feed constitutes 50 to 70% of the production cost. The omnivorous nature of tilapia species enables them to have feeding strategies that are more flexible and cost effective, thus, enabling it to be a very versatile species in different aquaculture systems (17).

Nutritional requirements of tilapia

To achieve fast growth, reproduction and maintenance of the immune system Tilapia needs a balanced diet but the specific requirements differ depending on the life stage, species and the culture system. The main macronutrients are expressed as%ages of diet: proteins (25 to 35% of diet, juveniles; 20 to 25% of diet, adults), carbohydrates (30 to 40%), and lipids (6 to 12%), and *Oreochromis niloticus* exhibits best growth at 28 to 32% protein in intensive systems (29). The protein synthesis essential amino acids (lysine and methionine) and the cost-effective carbohydrate source (starches grain amylase activity) are also beneficial to tilapia (17). Lipids provide energy and essential fatty acids, with omega-3 and omega-6 requirements met through plant-based oils, reducing reliance on fish oil (30).

Micronutrients (such as vitamins (e.g., vitamin C and immune health) and minerals (e.g., phosphorus and calcium and bone development) play an important role in metabolic processes, and their deficiency results in stunted growth or predisposition to disease (29). Tilapia is an omnivorous fish, which can use diverse feedstuffs, such as algae and water plants in large systems or formulated pellets in the intensive systems. Nevertheless, the environmental conditions differ depending on the nutritional requirements; that is, in high-density recirculating aquaculture systems (RAS), the metabolic rates necessitate the inclusion of higher protein levels (up to 35%) in the diet (17). New research focuses on the optimization of nutrient proportions to enhance feed conversion ratios (FCR), which are 1.5 to 1.8 in tilapia, and to decrease the production of wastes, which can diminish environmental impacts by 10 to 15% (30).

Advances in feed formulations

Developments in feeds formulations have assisted in enhancing tilapia aquaculture efficiency with emphasis on maximum nutrient delivery, minimalization of costs, and maximization of sustainability. Commercial tilapia diets are designed to balance the protein, energy, and micronutrient levels and pelletized feeds are used instead of the traditional mash feed to enhance digestibility and minimize wastage by 20 to 30% (22). High-temperature processing technology (extrusion technology) to improve nutrient bioavailability has become the norm in commercial feed production with FCRs as low as 1.4 in optimized systems (31). Floating pellets enable the farmers to observe the feeding behavior to reduce overfeeding and water quality challenges, especially in pond and cage systems (32).

More recently, precision nutrition has been used, in which the composition of feeds is optimized to the particular strain of tilapia, life-stage, and culture conditions, with growth rates increased by 10 to 15% (22). As an illustration, the genetically enhanced farmed tilapia (GIFT) strains must be fed on feeds that are richer in lysine in order to promote growth potential. Functional feeds (additives such as probiotics, prebiotics, and immunostimulants e.g., β-glucans) can help increase disease resistance and gut health, decreasing mortality rates by 1020% in intensive systems (31). The use of specialized feeds, which might raise the production cost by 10 to 20%, is challenging because it requires region-specific formulation as it considers local availability of ingredients (32). New technological developments in feed testing (near-infrared spectroscopy) allow analyzing nutrients in real-time, which is relevant to guarantee feed quality and minimize nutrient deficiencies (22).

Alternative and sustainable feed sources

Dependence on fishmeal and fish oil, which have been conventionally employed in aquaculture diets, is unsustainable because of over fishing and excessive prices. There has been a focus on alternative and sustainable feed sources of tilapia with an aim of mitigating on the environmental impacts and enhancing cost-effectiveness. Fishmeal has been substituted by plant-based proteins, including soybean meal, corn gluten, and canola meal, which make up 50 to 70% of tilapia diet in commercial diets, with no inevitable effects on growth when well balanced (33). Single-cell proteins Single-cell proteins (SCPs) are an alternative high-protein (up to 60% protein content) source (34), replacing fishmeal in experimental diets by 20-30% (34).

Insect meals, especially black soldier fly larvae (*Hermetia illucens*) are becoming a new sustainable source of protein, comprising 40-50% protein and essential amino acids, with trials demonstrating similar growth to fishmeal-based diets (33). Low-cost feeds based on agricultural byproducts (rice bran and cassava leaves) are applied in smallholder farmers (especially in Africa and Asia), which decrease the feed costs in large-scale systems by 30 to 40% (35). Omega-3 fatty acids containing algal oils and microalgae are being investigated as alternatives to fish oil and it has been suggested that tilapia fed algae-based diets have seen a 15% improvement in lipid profiles (34).

The challenges include lower digestibility of certain plant-based feed ingredients, possible anti-nutritional agents (e.g., phytates in soybean meal) and the scalability of newer ones such as insect meal (35). Innovations in recent times are on the fermentation process and the enzyme treatment as a method to complement nutritive values of alternative feeds, increasing digestibility of up to 10 to 15% (33). The innovations contribute to the sustainability of tilapia aquaculture because they limit negative impacts on marine resources and follow circular economy principles, even though they require more investigation to maximize on cost and scale to become acceptable (34).

Health and Disease Management

Health and disease management are important in the sustainability and profitability of tilapia aquaculture activities because the spread of disease outbreak may lead to huge economic losses, with death of up to 50-90% in large scale cases. Tilapia has strong resistance to environmental factors, which makes it a hardy species, however the conditions of intensive farming promote the risk of disease.

Common diseases in tilapia aquaculture

Tilapia is prone to various types of infection or illness due to bacteria, virus, parasite, and fungi, more so during high density systems. One of the most common ones is bacterial infections of *Streptococcus agalactiae* and Aeromonas hydrophila causing septicemia, skin lesions, and a 30 to 70% mortality rate in the infected farms (36). Streptococcus is especially prevalent in hot weather, and the symptoms of such infections are chaotic swimming and exophthalmia, and they are enhanced by unsanitary and overpopulated water (37). Tilapia lake virus (TiLV) is another viral pathogen that is of global concern since it has led to mortality rates of up to 20 to 90% in some countries (38), with TiLV being declared the first TiLV outbreak country in Thailand in 2014 (38).

The damage of gills and impaired growth due to parasitic infections, specifically infestation by *Ichthyophthirius multifiliis* (ich), and Trichodina species, also experiences more prevalence within ponds and cage systems (39). Less prevalent, but possible, are fungal infections, such as parasitized by the Saprolegnia species, which occurs following stress or injury to fish and in lower temperatures. Disease susceptibility is reinforced by environmental stress or high ammonia or temperature levels or other stress factors, and research shows that infection rates rose by 15 to 25% in low-quality environments (36). New diseases, e.g. tilapia parvovirus, are also being watched, but their effects are poorly studied (38). The proper diagnosis, usually by means of the PCR-based methods, is necessary to ensure immediate treatment and minimize economic losses.

Biosecurity measures

Disease introduction and spread in tilapia aquaculture is a particularly important issue in intensive systems in which the rapid growth of pathogens can be problematic; biosecurity is therefore crucial to stop introduction and prevent the spread of a disease. Important measures are quarantine of new supplies where they should be held in quarantine at least 14 days to know the presence of the latent infection and use of pathogen-free fingerlings certified by the hatcheries (40). Regular monitoring of ammonia, nitrite and dissolved oxygen in water quality can alleviate stress and diminish the risk of diseases and ideal limits (e.g. ammonia less than 1 mg/L) can reduce the incidence of infection by 20 to 30% (40). A physical barrier like net cleaning and fencing on perimeter of

Table 1.Comparison of selected tilapia species by key aquaculture parameters.

Species	Aquaculture Methods (Stock Density)	Common Diseases	Environmental Requirements	Nutrition Requirements	Source
Oreochromis niloticus (Nile tilapia)	Pond: 1–5 fish/m² Cage: 20–50 fish/m³ Tank: 10–20 kg/m³ RAS: 20–40 kg/m³	Bacterial: *Streptococcus iniae, Aeromonas hydrophila, Edwardsiella tarda* Viral: Tilapia Lake Virus (TiLV) Parasitic: *Ichthyophthirius multifiliis, Trichodina spp.* Fungal: *Saprolegniasis*	Temp: 25–30°C (opt), 15–35°C (tol) Salinity: 0–10 ppt pH: 6.5–8.5 DO: >4 mg/L	Protein: 28–35% (juveniles), 25–30% (adults) Lipids: 6–12% Carbs: 30–40% Vitamins & minerals: Standard for fish	(42)
Oreochromis mossambicus (Mozambique tilapia)	Same as above	Same as above	Temp: 25–30°C (opt), 20–35°C (tol) Salinity: 0–20 ppt pH: 6.5–8.5 DO: >4 mg/L	Same as above	(43)
Oreochromis aureus (Blue tilapia)	Same as above	Same as above	Temp: 25–30°C (opt), 14–35°C (tol) Salinity: 0–15 ppt pH: 6.5–8.5 DO: >4 mg/L	Same as above	(44)
Oreochromis spilurus	Same as above	Same as above	Temp: 20–30°C (opt) Salinity: up to 20 ppt (brackish tolerant) pH: 6.5–8.5 DO: >4 mg/L	Same as above	(45)
Coptodon zillii (Redbelly tilapia)	Same as above	Same as above	Temp: 20–30°C (opt), cold-tolerant Salinity: 0–10 ppt (fresh to brackish) pH: 6.5–8.5 DO: >4 mg/L	Same as above	(46)

farms do not allow entry of pathogens by wild fish or contaminated equipment.

Biosecurity measures at the farm level will involve limited access to culture areas, decontamination of the equipment, and footbaths to curb the transmission of pathogens to others by humans (40). Unlike cage systems, sites devoid of a polluted water body can be identified to limit the exposure of environmental pathogens whereas, in RAS, microbial loads can be diminished through UV sterilization and biofiltration (41). The education of the farmer in biosecurity measures has been proven to decrease the incidence of the disease by 15-20%

especially with small notations in Asia and Africa (40). Challenges include the high cost of biosecurity infrastructure, which can increase operational costs by 10 to 15%, and limited awareness among small-scale farmers, necessitating extension services and policy support (41).

Advances in disease prevention and treatment

New technologies of prevention and control of the diseases have reshaped the functionality of disease control in tilapia with pronged emphasis on prophylactic and sustainable disease control. Immunisation The potential of vaccination programmes, especially against *Streptococcus agalactiae*, has become clear, and it was found that immersion and injectable vaccinations decreased mortality by 30-50% in experiments (47). TiLV vaccines are being developed and experimental DNA vaccines have shown up to 60% protection in the laboratory, though they are not commercially available (38). Probiotics (such as Lactobacillus species) and immunostimulants (such as β-glucans), added to the functional feed, promote tilapia immunity and decrease diseases by up to 25%, as well as increasing the growths (39).

Although antibiotics remain proactive in dealing with bacterial infections, there is a reduction in their use because of the suspicion of antimicrobial resistance (AMR), particularly in Aeromonas that has been verified to be present in 20 to 30% of Aeromonas isolated in fish farms (40). Other solutions like phage treatments and herbal extract treatment (e.g, oregano oil) are being tested and have been found effective in pilot trials with phage treatments actually dropping Streptococcus infections by 40% currently (47). Specifically, there are diagnostic tools that help detect pathogens on-farm quickly. Portable PCR kits and CRISPR-based assays have the ability to reduce the current diagnosis time of days to hours, which positively affects response time (41). Combined with biosecurity, vaccination, and nutritional methods, integrated health management is growing in popularity, and model farms have recorded 20 to 22% savings on disease losses (40). Research should also be continued so that cost-effective vaccinations can be developed and alternative treatments to the smallholder farmers can be scaled up.

Environmental and Sustainability Issues

Although the tilapia farming industry is very crucial in feeding the world and its economic growth, it has been a challenge to the environment and the industry needs to correct these malpractices in order to support a sustainable tilapia farming business. Water pollution and habitat destruction are the antecedents of environmental effects prevalent in tilapia cultivation thus prompting the introduction of sustainability practices and certifications and the strategy of adapting to climate changes (48).

Environmental impacts of tilapia farming

Tilapia farming has a high potential to affect the aquatic ecosystem especially fish farms such as ponds and cages. Wastes such as the leftover feed and fish waste, which are high on nitrogen and phosphorus, pollute nutrients and cause eutrophication of water bodies and subsequent algal blooms and oxygen depletion (48). As an example, by utilizing the cage culture in water lakes, the accumulation of phosphorus is possible, and by 2030, its level can rise by 20 to 30%, which has a detrimental impact on the water quality and biodiversity (49). The importance of escaping introduced tilapia, especially *Oreochromis niloticus*, is high since they have the ability to displace indigenous species, forcing the food web and decreasing biodiversity in such areas as Latin America and Southeast Asia where non-indigenous populations have been reported in more than 90 countries (50).

Another issue is the use of water, especially in pond-based systems, whereby a high rate of water exchange (10 to 20 % per day) may run out nearby water sources, especially in arid locations (48). Poor construction of ponds can result in habitat destruction, and researchers estimate that 5 to 10% of mangrove systems in Southeast Asia have been cleared to build ponds, some of which maintain populations of tilapia (51). The discharge of effluents, which consists of organic matter and antibiotics, may impair downstream ecosystems, and in water samples collected up to 25 meters downstream of tilapia farms, antibiotic residues are present in 15 to 25% of samples (49). Such effects point towards the necessity of better management systems, where the ecological footprint needs to be reduced, without sacrificing efficiency of production.

Sustainable practices and certifications

In order to counter the environmental impacts of tilapia farming, there has been the introduction and development of sustainable practices and certifications to improve this farming and make it responsible to an extent where no further harm can be done to the environment. The best management practices (BMPs) comprise feeding less to reduce waste (through precision feeding, the release of nutrients can be reduced by 15-20%) and including sediment traps in ponds to trap organic matter (7).

Recirculating systems (RAS) and integrated multi-trophic aquaculture (IMTA) minimize the amount of water used and contamination of the nutrients with IMTA systems recycling 10 to 15 % of nitrogen by co-culturing it with algae or shellfish (52). In excess of 70% and 80% of phosphorus and nitrogen is as well removed during the effluent treatment, presenting better quality water which is discharged into the environment, e.g., constructed wetlands (51).

Environmental and social responsibility certifications like the Aquaculture Stewardship Council (ASC) and Global Aquaculture Alliance Best Aquaculture Practices (BAP) provide criteria in the areas of water control, feed, and community. In the case of ASC-certified tilapia farms, the discharge of phosphorus in water must be less than 20 kg to every ton of produced fish, and by 2023, more than 500 of such farms were certified around the world (52). The certifications boost access to markets especially in Europe and North America, but the cost of compliance has been found to add to the production costs by between 5 to 10% which is challenging to smallholder farmers (7). Some of the emerging projects are aimed at streamlining the certification of small-scale producers into group certification models and are seeing a 15% rise in adoption in regions such as Africa (50). A further endeavour should be taken to reconcile economic feasibility with environmental regulations.

Climate change and adaptation strategies

Recorded climate change has major implications on Tilapia aquaculture such as high temperatures, changing rainfall, and more incidences of harsh weather changes. Excessive temperature that exceeds the optimal levels of 25 to 30oC can decrease the growth rates of tilapia by 10 to 15% and predisposes them to disease mainly in tropical areas (53). There is a change in rainfall patterns which has the impact on the water we use to support our pond systems with droughts resulting in a 20 to 30% reduction in production rates in semi-arid regions, and floods potentially leading to escapes and infrastructure destruction (54). Stagnation in the volume of coastal tilapia farms is a serious risk to the even more minimally raised coastal territories in the group of the lowest lands, the example of Bangladesh being one of them, where 10-20% of the aquaculture zones are salted (53).

Adaptation strategies subject to experimentation involve genetic adaptation involving breeding of heat-resistant tilapia strains through the production of lines of *Oreochromis niloticus* with 10 to 20% higher survival in 35oC (55). Most water-conserving systems, including RAS and low-water-exchange ponds, lessen the usage of freshwater by 80 to 90% of freshwater use in traditional systems (54). The practices that can reduce the threats of floods are floating cage farming in deeper waters, embanking ponds stronger in more profound areas and polyculture using salinity-tolerant plants, such as shrimp (55). Subsidies on climate-resilient technologies being among the policies that have boosted the uptake of these strategies by 15% in Asia (7). They still work on the development of early warning systems that work on satellite-derived data to predict climate effects, making farms more resilient and cutting losses by 10 to 15 % (53).

Economic and Social Aspects

Tilapia aquaculture in the food systems has become major in the world supporting livelihoods, especially in the developing nations, through the production of low-cost protein food. The strong market demand and trade makes the sector economically important, and its social consequences benefit the society in terms of job creation and food security as well as providing labor and market constraints (4). The industry grows and is being sustained by policy and regulatory frameworks.

Market trends and global trade

The world market of tilapia has grown tremendously due to the growing demand of low cost and high protein sea food. The market has been estimated to be valued at roughly USD 12.5 billion in 2023 and it is projected to have a growth to USD 16.8 billion in 2030 and at a compound annual growth rate of 4.5% (4). Tilapia is relatively cheap, mild tasting, and flexible, which positions it as a reliable food source both in the developing world and in developed economies; with China, Indonesia, and Egypt leading the pack as major tilapia producers contributing to more than 70% of worldwide production of 6.9 million metric tons in 2023 (4). The United States and European Union are key importers, with the U.S. consuming over 220,000 tons annually, primarily as frozen fillets from Asia and Latin America (56).

The better processing and cold-chain logistics make global trade a reality and 60% of all tilapia export is processed (fillets or frozen whole fish) to address the markets with preferences to this product in the West (4). Nevertheless, trade barriers (e.g., tariffs and strict import standards, e.g., EU sanitary regulations) raise export prices of the developing nations by 5-10%. The new tendencies in the sphere of the world market are establishing the increasing number of sustainably certified tilapia demand in which the product certified by the Aquaculture Stewardship Council (ASC) has a price premium of 10 to 15% on the European market (56). Direct-to-consumer sales and E-commerce also contribute to increasing, especially in the Asian market, the participation of small-scale producers by 20%, which is also contributing to market access (57). Hurdles are that the price fluctuates with change in feed costs, and competitors are other species of whitefish hence the need to diversify the market.

Socioeconomic benefits and challenges

Tilapia fish farming leads to enormous socioeconomic benefits, especially in the developing nations and that is due to the factor it creates employment, revenues as well as food security. It provides livelihoods to approximately 12 million people around the world, including farmers, processors and traders; 60% of these people work at smallholder farms located in Africa and Asia (58). Tilapia farming in sub-Saharan Africa helps to reduce poverty, and the household income improves by 30 to 50% in communities that practice small-scale fish farming (10). Its low price (USD 1 to 2 per kg in local markets) increases food security as it offers high-protein food that can be reached by the low-income population (57).

Nonetheless, there are still issues to overcome such as the lack of access to capital and technology among smallholder farmers, which limits production and growth capacity as 40% of farmers across Africa count restrictions in loans as an obstacle (58). Gender gaps are also prominent with women forming the 30% of the aquaculture labourers yet many of them work in low wage jobs such as processing and get paid 20 to 30% less than their male counterparts (10). Occupational health-related issues can occur such as injury due to pond management, and affect ten to fifteen% of the workforce every year (57). There is still the challenge of market access as there is a large cost of transport and bargaining power of smallholders which minimizes the profits with average levels of 15 to 20% reduction (4). To solve these issues, special measures, including microfinance schemes and gendered training, are needed to increase equality and financial stability.

Technological Innovations

There are technological advances that are revolutionizing the tilapia aquaculture with increased efficiency, sustainability, simplicity and scalability to address global need of affordability protein. Production is being optimized through improvements in automation, biotechnology and precision aquaculture though there are rising trends and issues that are likely to become evident (59).

Automation and smart aquaculture technologies

The dynamic and decentralized management of farms is already transforming the tilapia farming industry through its capability to enhance monitoring, management, and resources. Real-time monitoring (such as dissolved oxygen, pH, and temperature) of water quality parameters with Internet of Things (IoT)based sensors connects with water quality monitoring systems to save 20 to 30% of labor costs and a 10 to 15% growth increase under intensive systems (60). Machine learning algorithms are applied to automated feeding systems to adapt the delivery of the food to the behavior of fish and environmental conditions and allow a reduction of up to 25% of feed waste and lower the feed conversion ratios (FCR) to 1.3 in recirculating aquaculture systems (RAS) (59).

Water quality and stock monitoring have also been frequently performed with drones and remote sensing technologies in ponds and cages systems, reducing operating costs by 10-20% and allowing them to detect disease or stress before it occurs (61). As an illustration, imaging with drones in Asian tilapia farms has enhanced stocking density control and minimized mortality (15%) (60). Robotics including automated net cleaners in cage systems improve biosecurity and the need to labour, but the equipment has large investment costs (USD 10,000 to 50,000 per unit) to apply on small-scale farms (59). The combination of data of multiple sensors into cloud-based platforms allows predictive modeling of disease outbreaks, and optimized crop-harvesting schedules where trial results already predicted harvests with 20% more reliability (61). The challenges are the availability of decent internet connection and computer training especially in rural settings where, only 30% of farmers are digitally equipped (62).

Biotechnology and precision aquaculture

The areas of biotechnology and precision aquaculture are leading to the improvements of tilapia health, growth, and environmental sustainability. Experimental lines have demonstrated a 30 to 40% natural protection to the *Streptococcus agalactiae* disease using genetic engineering techniques, including CRISPR-Cas9 systems, to develop strain of tilapia with stronger disease resistance (12). Marker-assisted selection (MAS) increases the pace of the breeding program, since in strains such as the Genetically Improved Farmed Tilapia (GIFT), growth can be increased by 10 to 15% and feed efficiency by 5 to 10% (12). In controlled environments, genetically modified tilapia having growth hormone gene have posted growth rates that are 20 to 30% faster, but concern about regulation and consumer perception have constrained the application of this technology to the marketplace (12).

Precision aquaculture is a combination of genomics, proteomics and environmental information that is used to refine management practices. As an example, the application of nutrigenomics investigations in determining the ideal compositions of feed of particular tilapia strains to hatcheries decreased FCR by 10% in RAS (62). Vaccines have been developed using nanoparticles that increase immune responses and cut the tilapia lake virus (TiLV) mortality during experiments by 25 to 35% (63). Implementation of precision monitoring with biofloc technology enhances the presence of microbes in culture systems, ensuring water quality and dropping nitrogen release by 20% to 30% (12). However, high costs of biotechnological applications (USD 50,000 to 200,000 for genetic screening programs) and ethical concerns about genetically modified organisms (GMOs) pose barriers, particularly in developing countries where regulatory frameworks are weak (63).

Emerging trends and research gaps

The use of artificial intelligence (AI), blockchain to ensure the supply chain transparency, and the circular economy are some emerging trends in the farm-to-fork process in tilapia aquaculture. Using AI-based models, environmental and health risk is predicted and pilot projects in China have seen up to 15% and 20% reductions in mortality due to early intervention (60). Blockchain technology improves traceability, and it leads to compliance with sustainability certifications and consumer confidence, as 10% of the tilapia export in 2023 will be conducted on blockchain platforms (59). When the fish waste is used to produce biogas, or are used to produce fertilizer the practices of the circular economy are helped since the practices result in less environmental impact and can provide new revenue streams and in trials cost savings of 10 to 15% were recorded (61).

Enormous gaps in studies are still significant. The modest scientific evidence about long term ecological effect of tilapia genetically modified limits the same thus only 5% of the production globally is done using refined genetic concepts (12). Little studies have been conducted on the scalability of smart technologies among smallholder farmers, whereby 70% of them have examined the large-scale systems (62). In developing countries, AI and blockchain implementations are hampered by the lack of infrastructure, which creates the need to invest more in access to the digital world (60). Also, the social consequences of the automation like the loss of employment (predicted to be 10-15% in automated farms) should be discussed (63). In future, cost effective technologies, digital inclusions and environmental risk analyses should be given priority foreseeing an escalating growth in tilapia aquaculture in a fair and sustainable manner.

Summary of Key Findings

Tilapia continues to be one of the most important cultured fish species in the world, as it contributes a large portion of the world food security, employment (estimated at 12 million livelihoods), and an increase in rural incomes (30-50% of income in many communities). This is due to its high adaptability, quick growth, omnivorous nature of feeding and ability to fit in most production systems such as ponds, cage, RAS and IMTA where the production level can be from 5–20 t/ha in ponds to over 200 kg/m³ in RAS. The feed efficiency (FCR 1.3-1.8), reduced disease losses (20-50%) and environmental footprint in certified operations have been achieved through advancements in alternative feeds (e.g. insect meal, single-cell proteins), functional additives, vaccination, probiotics, precision technologies (IoT, AI) and genetic improvement. However, the industry is still facing severe limitations, such as climate-induced loss of yields (10-30%), nutrient pollution, threat of invasive species, antimicrobial resistance issues, gender inequality and access to capital among small-scale farmers, and slow technology adoption in resource-poor environments.

Recommendations

In order to achieve sustainably and inclusively a long-term growth of the tilapia aquaculture, it is important that:

- Governments and development partners amplify access to affordable microfinance, digital training and group certification models suited to small-scale farmers including targeted support for women producers.
- Research and breeding programmes should speed up the development and dissemination of climate resilient disease resistant tilapia strains for smallholder conditions.
- Precise tools that cost less, e.g. solar-powered aerators and the simple IoT sensors, should be prioritised and those biosecurity and vaccination programmes that are scalable to the developing country should be developed.
- There should be strong compliance enforcement of effluent treatment, escape prevention and ASC/ BAP certification compliance with incentives of IMTA and circular economy practices.
- The barriers to trade and the promotion of regional value chains should be reduced by

policy measures to improve market access and price stability of the small producers.

Conclusion

With almost 7 million metric tons of tilapia production and a market volume of USD 12.5 billion, tilapia farming can be described as a pillar of food security in the world. Its fast breeding and feeding capabilities including omnivores as well as its flexibility in various conditions like temperatures (25-30oC), makes it possible to farm it in more than 120 countries with systems such as ponds, cage and high-yield recirculating systems. Improved nutrition (with attendant sustainable feeds such as insect meal) has the capacity to save up to 40%, health strategies (vaccination) cut losses due to illnesses by 30-50%, supporting 12 million livelihoods, especially in emerging economies. Sustainability of the sector is threatened by environmental and social challenges. Climate change also threatens crop productivity that may fall by up to 30% due to the increase in temperature and droughts as well as nutrient pollution and invasive tilapia that affect the ecosystem negatively. Socioeconomic constraints, like gender payment disparities and trade restrictions, restrict the advantages of the smallholders, regardless of the income upsurges of 30-50%. Environmentally-friendly practices, such as the integrated systems of multi-trophic interactions or certifications can be used to limit effects but are expensive, which does not allow small-scale farmers to use them. There are also technological developments like automation and genetic breeding which make things more efficient, saving 20-30% on costs and increasing resistance to the diseases. Nevertheless, they are expensive and require inadequate access to digital sources to be used by the smallholders. Expanded support with particular attention to more appropriate technology, supportive policies, and climate resilient approaches should be aimed at making tilapia aquaculture sustainable, equitable, and in a position to scale to fulfilling global requirements of protein.

Contribution of Authors

Idris Abdulhakeem Abdulhakeem led the conceptualization of the review, emphasizing the biological and ecological dimensions of tilapia aquaculture. He made substantial contributions to drafting and revising sections on species diversity, physiological adaptations, and environmental tolerances. Nazym Sapargaliyeva investigated the economic and global significance of tilapia farming, including market trends and sustainability challenges. She provided key insights into production systems and the role of tilapia in food security for developing regions. Gulnar Kegenova reviewed technological and innovative aspects of tilapia aquaculture, such as precision farming, disease management, and integrated systems. She contributed to discussions on future directions, including genetic improvements and biosecurity measures to enhance productivity and ecological balance.

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Conflict of Interest

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Data Availability

Data are not available.

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