Chapter 1
Tilapia Fish for Future Sustainable Aquaculture

Ghasem Ashouri, Seyed Hossein Hoseinifar, Ehab El-Haroun, Roberta Imperatore, and Marina Paolucci

Abstract Lately, aquaculture has been recognized as the fast-growing industry in the food production sector, and it requires maintainable development to cover the world population's demand for aquatic and seafood products. Among the 400 farmed fish species, warm-water fish species such as tilapia need a little quantity of fishmeal in their diets compared to other species. Tilapia is classified as the second most widespread species whose production is increasing every year; Nile tilapia (*Oreochromis niloticus*) is easily adaptable to a large variety of environments, is capable of reproducing in cavities, has an excellent market position in Asia and Africa, is highly resistant to diseases, has good fillet quality, shows moderate feed conversion ratio and excellent growth rate on many natural and artificial diets. Nile tilapia (*O. niloticus*) is known in the market as "aquatic chicken" due to its high tolerance to adverse physical and environmental conditions and overcrowding, its capability to survive at low oxygen levels, and a wide range of salinity concentrations. Tilapia adapts easily to natural and artificial feeds, has good feed conversion value, grows moderately fast, has a final high yield potential, and is accepted by customers worldwide. In addition, tilapia can grow in different aquaculture systems, ranging from extensive, semi-intensive, and intensive; also it can be grown in monoculture or polyculture techniques. Since tilapia grows well in adverse environmental conditions, tolerates stress factors as handling, and is resilient to disease agents of pathogen infections and infectious diseases, it has become the most

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S. H. Hoseinifar, H. Van Doan (eds.), *Novel Approaches Toward Sustainable Tilapia Aquaculture*, Applied Environmental Science and Engineering for a Sustainable Future, https://doi.org/10.1007/978-3-031-38321-2_1

common species among farmers. Nile tilapia (*O. niloticus*) could be cultured in both fresh and saltwater; and in tropical, subtropical, and temperate climates. The authors in this chapter will cover the environmental and nutritional requirements of tilapia, defined as key factors in profit production. As mentioned above, tilapia has a wide tolerance for high stocking densities and environmental conditions. In addition to these advantages, tilapia grows very well in integrated culture systems with aquatic species such as carp and shrimps, as well as with crops like tomato and lettuce. However, the global extension of tilapia farming growing at a remarkably high rate is likely to pose environmental and socioeconomic threats. This chapter highlights the advantages and challenges of commercial tilapia production including the economic aspects, living behind the improvement of effluent quality to minimize the impact on the environment, which will be covered in a different section.

Keywords Tilapia · Farming · Sustainable · Production

1.1 Introduction

In the last few decades, aquaculture has become the fastest-growing sector in animal livestock production, securing a global food supply that reached 2018 ~115 million tons representing 263,400 million dollars (USD$) (FAO 2020). Feed formulation of warm-water fish species requires less fishmeal compared to other species. Tilapia production represents 40% of cultured fish (Prabu et al. 2019). Annual worldwide production of cultured tilapia was 3.4 million tons in 2011 and reached 6.2 million tons in 2019 (FAO 2020) (Fig. 1.1). Tilapia and catfish are considered to be native to the Middle East and Africa. Tilapia culture, though ancient (probably firstborn in Egypt simultaneously with Chinese polyculture), has experienced a recent commercial development. Today, tilapia has become one of the most attractive fish species in aquaculture due to several advantages such as i) massive adaptability to numerous environmental conditions, ii) easy reproduction in captivity, iii) resistance to environmental stress, diseases, and microbe pathogen infections, iv) good quality of flesh, v) feed on a low trophic level and excellent growth rate on a variety of diets (Welker and Lim 2011; Prabu et al. 2019). In 1980 tilapia was considered an ideal candidate for aquaculture in different regions of the world. Consequently, tilapia culture is currently growing commercially in at least 120 countries (Yue et al. 2016) all around the globe. Asian countries (e.g. China, Egypt, Indonesia, Philippines, and Thailand) are the major producers as well as consumers of tilapia (Chen et al. 2018). The most common cultured genus of tilapia is *Oreochromis*, and around 89% of these farmed fish are Nile tilapia (*Oreochromis niloticus*), due to their good growth performance in ponds (Ng and Hanim 2007).

Egypt and China are considered the main producers of Nile tilapia (*O. niloticus*) and represent one-third of the total global production (FAO 2020). The reasons for such a rapid expansion of the Nile tilapia (*O. niloticus*) culture could be attributed to

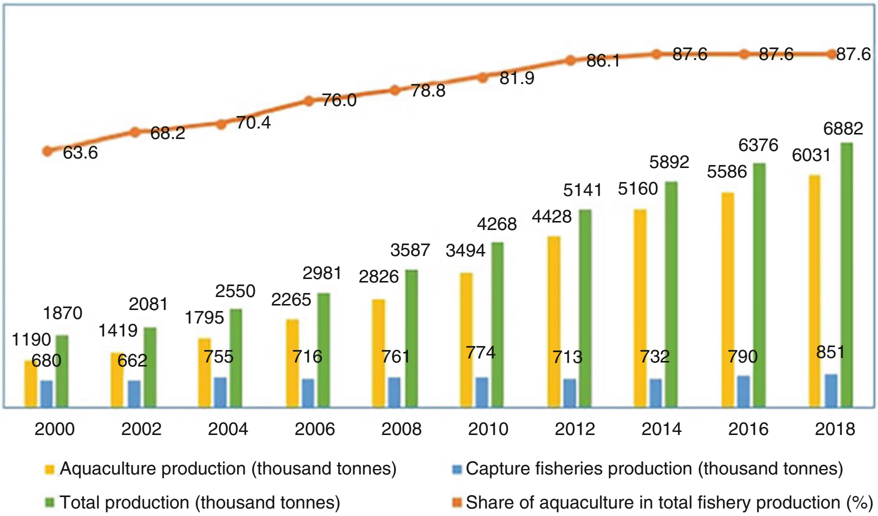

Fig. 1.1 Contribution of aquaculture to world tilapia production, 2000–2018. Data source: FAO (2020). FAO Global Fishery and Aquaculture Production Statistics (FishStat J; March 2020; www.fao.org/fishery/statistics/software/fishstatj/en)

technological advances associated with the intensification of cultural practices (Bhujel 2014b; Watanabe et al. 2002) including, i) development of novel strains and hybrids, ii) possibility to set up monosex male culture, iii) formulated diets, iv) use of a variety of production techniques such as semi-intensive and intensive systems (Ng and Romano 2013), and vi) marketing programmes aiming at enhancing the demand for tilapia on national and international markets (Wang and Lu 2016). Based on the increasing commercialization and continuing growth of the tilapia industry, the product is not only the second most important farmed fish globally (Fitzsimmons 2000), next to carp, but it is also described as the most important of all cultured fishes in the twenty-first century (Celik 2012).

The importance of tilapia among aqua farmers can be summarized as follows: (i) tilapia have fast growth and survival rate, (ii) reproduce easily in captivity, (iii) tolerate low water quality conditions and environmental variables such as temperature, salinity, low dissolved oxygen, etc., (iv) is easily adaptable to mono and polyculture techniques in intensive fish farming, (v) feed on low-quality diets and easily adapt to artificial diets, vi) show high profitability and low production costs, (vii) is highly resistant to stress and disease (lower risks for aqua farmers), and (viii) is highly accepted by consumers, with a good market request (Prabu et al. 2019; El-Sayed 2006b).

Although tilapia's culture is promising for aquaculture, in light of the many advantages above-mentioned, enhancing the production efficiency of tilapia has some challenges and research issues that are of the biggest concern to tilapia culturists (Yuan et al. 2017). For instance, these involve growth performance, unwanted reproduction (Gupta and Acosta 2004; Ng and Romano 2013; Chen

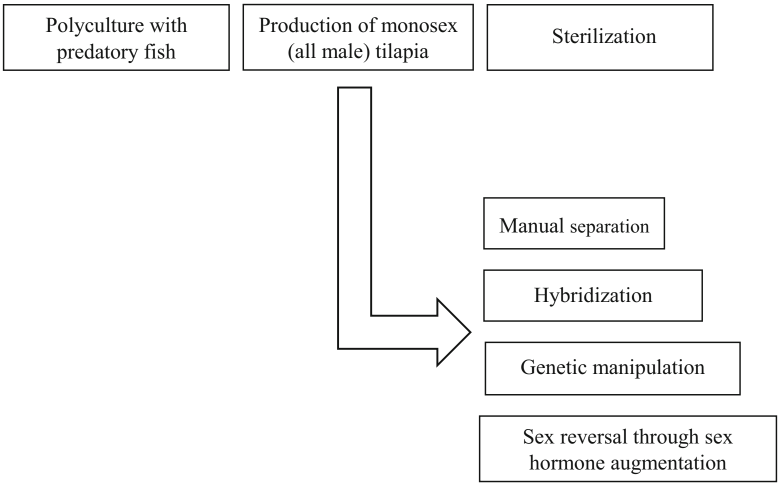

Fig. 1.2 Methods used for inhibiting reproduction or controlling the overpopulation of tilapias

et al. 2018), environmental tolerance (e.g. low temperatures and high salinity), disease resistance (Wang and Lu 2016; Li et al. 2016), quality of fillet yield (Yue et al. 2016), and increased production costs. Other issues of tilapia aquaculture are related to its negative effects on the environment and global biodiversity. Different protocols have been adopted to control and limit unwanted reproduction (Fig. 1.2). A brief overview of these methods is provided in one subsection of this chapter. However, none of these methods is considered 100% effective, and thus a combination of methods is suggested (Fuentes-Silva et al. 2013).

The poor aptitude of tilapia to tolerate low temperatures (<15°C) affects the geographical expansion of tilapia culture (El-Sayed 2006b; Lim and Webster 2006). The most cold-resistant species is blue tilapia, *Oreochromis aureus*, which is suitable for culture in regions with seasonal temperature changes and is usually used in the hybridization for the production of monosex. Moreover, most tilapia species are not tolerant to high salinity, although some (e.g., Mozambique tilapia, *Oreochromis mossambicus*; *Oreochromis spilurus*, redbelly tilapia, *Tilapia zillii*, and red tilapia hybrids) can grow in seawater. In comparison with other cultured fish (e.g. salmon), tilapia shows off-flavours and also minor levels of HUFAS, especially beneficial omega-3 fatty acids such as 20:5 n3 (EPA) and 22:6 n3 (DHA) which cause low market acceptance (Weaver et al. 2008). Finally, today, the disease resistance of tilapia has not received enough attention because rearing programmes have been focused only on growth efficiency and skin colour selection.

In brief, tilapia yield can be affected by several causes, so this chapter provides an overview of some aspects of tilapia culture. In particular, it focuses on some crucial factors for a successful production, such as management and nutritional requirements, evaluation of technological advances and different tilapia farming practices, environmental effects, and some constraints resulting from intensification practices.

1.2 Nutritional and Environmental Requirements

Tilapias possess highly desirable characteristics that make them good candidates for fish production under different production approaches as extensive, semi-intensive, and intensive, such as their ability to tolerate a wide range of environmental conditions (Chervinski 1982), high survival rate, and feed on a low trophic level which makes them attractive species to aquaculture investors. However, dietary requirements under different production techniques and the association with culture conditions are still not yet clear.

1.2.1 Nutritional Requirements

Fish feed generally accounts for as much as 60% or more of production costs in both semi-intensive and intensive aquaculture production systems (Montoya-Camacho et al. 2019). The nutritional requirements of tilapia have been comprehensively reviewed by Ng and Romano (2013), and Chavan et al. (2015). An obstacle to tilapia intensive culture is the rising cost and unpredictable reliability of fishmeal and fish oil global supplies (Ng and Romano 2013). Consequently, several alternative ingredients, in particular of plant origin, have been investigated, and some of them are currently used in tilapia feeds to reduce the fishmeal amount (Montoya-Camacho et al. 2019). Fish meal (FM) and fish oil (FO) are the main sources of, respectively, amino acids and fatty acids for many different species. The investigation of alternative ingredients of FM and FO requires a thorough understanding of the quantity and quality requirements of different nutrients of tilapia, besides the comprehension of the factors that may influence the nutrient utilization efficiency and consequently affect the production (Ng and Romano 2013).

1.2.1.1 Protein and Amino Acid Requirements of Tilapia

Proteins represent the most expensive components in aquafeeds (El-Sayed 1999). Several factors affect protein requirements such as protein source and amino acid (AA) profile, fish species, age, size, and life stage. Tilapia larvae, fry and fingerling require a high level of protein (30–40%) compared to tilapia broodstock (20–25%). Male tilapia requires a higher level of protein than females to reach optimal growth performance (Ng and Romano 2013; Abdel-Tawwab et al. 2010; Sweilum et al. 2005). In terms of protein, it is not just the quantity, but the quality and the essential amino acid (EAA) profile that will tremendously impact the total protein requirement. The ideal proteins to be introduced to the diet are represented by those whose amino acid composition is similar to the ratio required by the animal (Nguyen and Davis 2009). Furthermore, this will also decrease nitrogenous waste related to amino acids being underutilized or deaminated as an energy source (Abdel-Tawwab et al.

Table 1.1 The quantitative essential amino acid requirements of warm-water fish.[a] Table modified from Jauncey (2000)

	Common carp[b]	Channel cattfish[c]	Nile tilapia[d]	Mozambique tilapia[e]
Arginine	3.3	4.3	4.2	2.8
Histidine	2.1	1.5	1.7	1.1
Isoleucine	2.5	2.6	3.1	2.0
Leucine	3.3	3.5	3.4	3.4
Lysine	5.7	5.1	5.1	3.8
Methionine	2.1	2.3	2.7	1.0
Phenylalanine	3.4	5.0	3.8	2.5
Threonine	3.9	2.0	3.8	2.9
Tryptophan	0.8	0.5	1.0	0.4
Valine	3.6	3.0	2.5	2.2

[a]All values as % of dietary protein
[b]Experimentally determined data for common carp (*Cyprinus carpio*) from the review of Tacon (1987). Requirement estimated by the dose-response method
[c]Experimentally determined data for channel catfish (*Ictalurus punctatus*) from the review of Wilson (1991). Requirement estimated by the dose-response method
[d]Experimentally determined data for Nile tilapia (*Oreochronis niloticus*) from Santiago and Lovell (1988). Requirement estimated by the dose-response method
[e]Experimentally determined data for Mozambique tilapia (*O. Mossambicus*) from Jauncey (1983). Requirement estimated by the whole body and muscle amino acid composition method

2010). Prediction of EAA requirement of different fish species could be measured by either dose-response protocol or by measuring the amino acid profile of the whole body of fish. As known, warm-water species including the Nile tilapia (*O. niloticus*) require 10 essential amino acids (Table 1.1). EAA requirements could be covered using a mixture of plant and animal proteins (Montoya-Camacho et al. 2019), or by the inclusion of free amino acids (Nguyen and Davis 2009).

1.2.1.2 Lipid and Fatty Acid Requirements of Tilapia

Lipids and oils are considered to be the main source of digestible energy and essential fatty acids (EFAs) for the normal growth and development of fish. In addition, phospholipids play main functions in cell membrane structure and integrity, facilitate and control the absorption of fat-soluble vitamins, act as forerunners for sex hormones, and improve the texture and flavour of the diet.

Tilapia requirements of lipids rely on several factors including fish species, age, size, source of lipids, protein, and energy content (El-Sayed 2006b). For example, it was noticed that the level of protein decreased in the Nile tilapia (*O. niloticus*) diets from 33.1% to 25.6% by elevating lipid content from 5.2% to 9.1% and carbohydrates (CHO) from 31.7% to 36.7% (Li et al. 1991). The role of increasing lipid content could be described as a sparing protein effect, confirmed by Jauncey (2000) in hybrid tilapia (*O. niloticus* × *O. aureus*). Though increasing lipid levels up to 12% harm the growth of juvenile *O. aureus* × *O. niloticus* hybrids and augments the

Table 1.2 The essential fatty acid requirements of tilapia[a]

Species	Requirement	Reference
Tilapia zillii	1% 18:2n-6 or 1% 20:4n-6	Kanazawa et al. (1980)
Oreochromis niloticus	0.5–1% 18:2n-6 or 1% 20:4n-6	Teshima et al. (1982)
O. niloticus	0.5% 18:2n-6	Takeuchi et al. (1983)
O. aureus	18:2n-6 or 18:3n-3 ≤1%	Stickney and McGeachin (1983)

[a]Table adapted from Jauncey (2000)

accumulation of lipid in the carcass of the fish (Jauncey 2000), also it has a negative impact on the pelleting processing of the diets. However, an extruded feed where fat is added after the pelleting process solved the problem. In general, tilapia require about 10–15% dietary lipids (El-Sayed 2006b); however, the oil inclusion of commercial tilapia feed is typically about 4–5% (Orachunwong et al. 2001). The required EFAs cannot be synthesized by fish and must be provided by the diet (Jauncey 2000). Research on fatty acid requirements revealed that cold-water fish and marine fish require *w*-3 polyunsaturated fatty acids (n-3 PUFA), while freshwater and warm warm-water species require n-6 PUFA. Thus, warm-water species, including tilapia, utilize plant oil as a source of n-6 fatty acids more efficiently than FO and lipids as a source of n-3 fatty acids (El-Sayed 2006b). Several studies have indicated that tilapia requires n-6 EFA rather than n-3 EFA (Table 1.2).

The findings of previous research summarized that EFAs are considered a source of the fatty acid content in tilapia fillets and support the growth of fish. It has been suggested that diets for farmed tilapia should contain 0.5–1.0% of both n-3 and n-6 PUFA (Lim et al. 2011a; Ng 2005). Tilapia-fed diets containing high levels of n-3 PUFA have positive effects on the health of consumers, such as its positive impacts on the cardiovascular system (Lecerf 2009; Russo 2009), immune system (Ruxton et al. 2004) and inflammatory disorders (Calder 2006). In the last few decades, research conducted to find novel ingredients to substitute FO with vegetable oil in tilapia feed has been successfully carried out; however, high interest remains in using palm oil because of the low price compared to other vegetable oils and its easy availability on the market (Ng et al. 2001; Ng et al. 2006; Ng and Gibon 2010; Bahurmiz and Ng 2007). Fortunately, the use of palm oil in the diet does not reduce ($P \leq 0.05$) the performance of the Nile tilapia (Ng et al. 2001). However, the high inclusion of plant oil raises an important question to be addressed by scientists, that is, the plant oil's role in the fish diets and the impact on the fatty acid composition of the final product and, thus, the impact on human health (Huang et al. 1998; Young 2009; Bahurmiz and Ng 2007).

Recently, there has been an interest in conducting research using finishing diets rich in n-3 PUFA to investigate their effect on adjusting the final fatty acid profile of tilapia fillets to enhance their nutritional value before harvest (Ng and Chong 2004; Visentainer et al. 2005; Tonial et al. 2009; Trushenski et al. 2009; Dos Santos et al. 2011; Luo et al. 2012). In this context, Tonial et al. (2009) found that Nile tilapia (*O. niloticus*) fed diets containing soybean oil showed a decrease in the n-6/n-3 ratio in the fillet from 7.4 to 1.0 when reverted to a flaxseed-based diet which is rich in n-3

PUFA. In addition, Teoh et al. (2011) examined the FAs metabolism of both Genetically Improved Farmed Tilapia (GIFT) strain and red hybrid tilapia-fed purified diets with vegetable oil blends, and they found that FAs digestibility was not different among the tilapia strains.

1.2.1.3 Carbohydrates

Previous research carried out on tilapia requirement of carbohydrates (CHO) declared that tilapia does not have CHO specific requirements. Though, Wilson (1994) reported that warm-water fish species such as tilapia utilize CHO more efficiently than cold-water species. The main purpose of CHO inclusion in the diet is to act as an effective source of energy that can spare the protein as a source of energy to support fish growth. In addition, CHO act as a binder, facilitating the pelleting process, also CHO acts as a precursor of different metabolic components (NRC 1993). Fish species can utilize up to 35 to 40% digestible CHO (Anderson et al. 1984; El-Sayed and Garling Jr 1988). Several factors affect CHO digestion and assimilation, including the source of CHO since fish utilize complex carbohydrates (polysaccharides) more efficiently than mono and disaccharides (Shiau and Chuang 1995). It has been shown that increasing the dietary CHO/lipid ratio leads to increased glycolysis and lipogenesis but reduces gluconeogenesis and amino acid degradation in the liver of the Nile tilapia, *O. niloticus* (Shimeno et al. 1993). Moreover, it has been reported that CHO metabolism is influenced by their fibre content (Shiau and Yu 1999) and is affected by the dietary protein source (Shiau and Suen (1992). In this context, El-Sayed (1991) found that sugarcane bagasse could be included in *T. zillii* diets without a negative impact on both growth and feed digestibility, while the inclusion of sugarcane in Nile tilapia (*O. niloticus*) diets resulted in poor performance. Also, larger fish of the hybrid of *O. niloticus* × *O. aureus* utilized CHO better than smaller ones (Tung and Shiau 1993). Finally, previous research concluded that increasing feed frequency from 2 to 6 times/day enhanced growth, CHO utilization, and protein sparing effect (Tung and Shiau (1991); Shiau and Lei (1999); (Jauncey 2000).

1.2.1.4 Vitamin and Mineral Requirements of Tilapia

Micronutrients such as vitamins and minerals are essential cofactors in several metabolic mechanisms involved in different physiological processes in fish health and welfare. Different factors affect vitamin and mineral requirements, such as culture conditions and chemical dietary composition (Celik 2012). For example, in both extensive and semi-intensive fish production system, the inclusion of vitamins and minerals are not necessary since the fish consume natural food such as phyto-plankton and zooplankton that contain enough amounts of vitamins and minerals that fulfil the fish requirements (El-Sayed 2006b) On the contrary, in intensive systems the presence and availability of natural food are limited or absent. Thus vitamins and minerals must be incorporated into the diets to support growth, health, and survival rate (Ng and Romano 2013). Fish feed manufacturers usually over-supplement feed with vitamins and minerals to counteract losses due to processing, storage, and leaching. It is well known that the nutritional requirements of vitamins and minerals depend on the life stage of tilapia. Tables 1.3 and 1.4 refer to the water-soluble and lipid-soluble vitamin requirements of tilapia fry and fingerlings stages, respectively. Shiau and Lung (1993) indicated that vitamin B12 is not required for tilapia hybrid (*O. niloticus* × *O. aureus*), likely due to the ability of gut bacteria to synthesize it (Shiau and Lung 1993; Shiau and Huang 2001; Barros et al. 2009). In terms of vitamin A requirement, Guo et al. (2010) reported that Nile tilapia (*O. niloticus*) does not require supplementation of vitamin A since cod liver oil, with its high content of vitamin A, is used as a source of lipids in the diet. In addition, Hu et al. (2006) reported that tilapia hybrids (*O. niloticus* × *O. aureus*) can synthesize vitamin A from β-carotene.

Mineral requirements of tilapia have been comprehensively reviewed by Ng and Romano (2013), and also Makwinja and Geremew (2020). Vital minerals are involved in many physiological processes, such as

- build skeletal structures
- osmoregulation (e.g., Na^+/K^+-ATPase)
- nerve and muscle contraction
- regulation of the pH of the blood and other body liquids
- metabolism-related enzyme activity (lipase, alkaline phosphatase) as cofactors
- key components of many enzymes, vitamins, hormones, and respiratory pigments

Nile tilapia (*O. niloticus*) usually require minerals from two major sources: water and feed. Brackish/marine environments are considered as main sources of minerals. However, since tilapias are mostly farmed in freshwater/low salinity waters, supplementing the diets with minerals is important to fulfil their needs to achieve optimal health and productivity. Previous research conducted to measure the mineral requirements of hybrid tilapia stated that the requirement of dietary NaCl or KCl ranged between 1.5 and 2–3 g kg^{-1} of diet, respectively (Shiau and Lu 2004); (Shiau and Hsieh 2001). Correct mineral requirement fulfilment is considered essential since the deficiency or excess of minerals leads to depressed growth performance.

Previous research confirmed the function of minerals as essential to support growth performance and the health status of different fish species. Robinson et al. (1987) reported that the inclusion of a 7 g Ca kg^{-1} purified diet was important to maintain the optimum growth of blue tilapia. Also, Shiau and Tseng (2007) found that hybrid tilapia-formulated diets should be supplemented with 2.7–3.3 g L^{-1} Ca and purified diets supplemented with 3.5–4.3 g Ca kg^{-1} to achieve optimum growth and feed efficiency. Research carried out on magnesium showed that 0.59 to 0.77 g and 0.50 to 0.65 g kg^{-1} diet were required for optimum performance of the Nile tilapia, *O. niloticus,* and blue tilapia, *O. aureus* (Dabrowska et al. 1989: Reigh et al. 1991), respectively. Moreover, trials conducted on phosphorus showed that a 5 g P kg^{-1} diet of phosphorus is required for the best growth and bone mineralization of *O. aureus* (Robinson et al. 1987).

Table 1.3 Dietary water-soluble vitamin requirements of tilapia species. Units are mg kg^{-1} of diet unless otherwise stated

Vitamin	Species and size (g)	Recommended level	Deficiency signs	Reference
Choline	*O. niloticus* (3.0)	3000		Kasper et al. (2000)
	O. niloticus × *O. aureus* (0.6)	1000	poor growth, reduced survival, reduced blood triglyceride and phospholipids concentrations	Shiau and Lo (2000)
Thiamin (B1)	*O. mossambicus*	2.5	anorexia, light coloration, nervous disorder, poor growth and poor feed efficiency, low hematicrit and red blood cell count, and increased serum pyruvate	Lim et al. (1991)
	O. niloticus	4.0		Lim et al. (2000)
	O. niloticus (4–5)	3.5		Lim et al. (2011b)
Riboflavin (B2)	*O. aureus* (0.7)	6.0	lethargy, anorexia, poor growth, high mortality, loss of colour, fin erosion, short body dwarfism, and cataracts	Soliman and Wilson (1992b)
	O. mossambicus × *O. niloticus*	5.0		Lim et al. (1993)
Niacin (B3)	*O. niloticus* × *O. aureus* (2.2)	26 (fed glucose) 121 (fed dextrin)	haemorrhage, deformed snout, gill and skin oedema, fin and mouth lesions	Shiau and Suen (1992)
Pantothenic acid (B5)	*O. aureus* (0.7)	10	poor growth, haemorrhage, sluggishness, high mortality, anaemia, hyperplasia of gill lamellae, and increased mortality	Soliman and Wilson (1992a)
	O. niloticus (13.7)	10		Ayyat et al. (2011)
Pyridoxine (B6)	*O. mossambicus* × *O. niloticus*	3		Lim et al. (1995)
	O. niloticus × *O. aureus* (0.7)	1.7–9.5 (28% CP) 15.0–16.5 (36% CP)	poor growth, high mortality, abnormal neurological signs, caudal fin erosion, mouth lesion, and convulsions	Shiau and Hsieh (1997)
Biotin (B7)	*O. niloticus* × *O. aureus* (1)	0.06	poor growth reduced hepatic pyruvate carboxylase and acetyl CoA carboxylase activities	Shiau and Chin (1999)
Folic acid (B9)	*O. niloticus* ()	0.5	anorexia, reduced growth, lethargy, increased mortality, low haematocrit	Lim and Klesius (2001)
	O. niloticus × *O. aureus* (0.4)	0.8		Shiau and Huang (2001)

	O. niloticus (14.5)	0.5–1.0		Barros et al. (2009)
Vitamin B12	*O. niloticus* × *O. aureus* (1.0)	Not required		Shiau and Lung (1993)
Vitamin C[a]	*O. niloticus* × *O. aureus* (1.5)	80 (Ascorbic acid) (41–48) C2S (37–42) C2MP-Mg	lordosis, scoliosis, poor growth, feed efficiency, poor wound healing, haemorrhage, anaemia, exophthalmia and gill, and operculum deformity	Shiau and Hsu (1999)
Inositol	*O. niloticus* (5.8)	Not required		Peres et al. (2004)
	O. niloticus × *O. aureus* (0.5)	400	poor growth, higher muscle/liver lipid	Shiau and Su (2005)

O. Oreochromis sp., *CP* crude protein

[a]Since ascorbic acid is unstable, storage, more stable forms of ascorbic acid such as L-Ascorbyl-2-sulphate (C2S) and L-ascorbyl-2-monophosphate-magnesium (C2MP-Mg) should be used

Table 1.4 Dietary lipid-soluble vitamin requirements of tilapia species. Units are mg kg^{-1} of diet unless otherwise stated

Vitamin	Species and size (g)	Recommended level	Deficiency signs	Reference
Vitamin A	*O. niloticus* (11.4)	5000 IU kg^{-1}	poor growth, abnormal swimming, restlessness, exophthalmia, high mortality, haemorrhage, and reduce the mucus secretion	Saleh et al. (1995)
	O. niloticus × *O. aureus* (1.6)	6000–7000 IU kg^{-1}		Hu et al. (2006)
	O. niloticus (7.7)	Not required		Guo et al. (2010)
β-carotene	*O. niloticus* × *O. aureus* (0.5)	29.0–44.0		Hu et al. (2006)
Vitamin D	*O. niloticus* × *O. aureus* (0.8)	375 IU kg^{-1}	poor growth, low haemoglobin, reduced hepatosomatic index, and alkaline phosphatase	Shiau and Hwang (1993)
	O. aureus (2.3)	Not required		O'Connell and Gatlin (1994)
Vitamin E	*O. niloticus* (7.5)	20–100		Eleraky et al. (1995)
	O. niloticus × *O. aureus*	63–206 (12% CL)	poor growth, anorexia, haemorrlage, impaired erythropoiesis, muscle degeneration, ceroid deposition in liver and spleen and lack of skin colour	Shiau and Shiau (2001)
	O. niloticus × *O. aureus* (0.7)	42–44 (5% CL)		Huang et al. (2003)
Vitamin K	*O. niloticus* × *O. aureus*	5.2	poor growth and low plasma prothrombin	Lee (2003)

O. Oreochromis sp., *CL* crud lipid

Chromium (Cr), zinc (Zn), copper (Cu), selenium (Se), and Iron (Fe) are considered trace elements, and research on these elements showed their importance in improving the growth and health status of tilapia. Shiau and Shy (1998) found that the inclusion of 140 mg Cr kg^{-1} improved the growth of hybrid tilapia due to its role as a cofactor in the activity of insulin and enhancing carbohydrate utilization. Furthermore, (Eid and Ghonim 1994) and do Carmo Sá et al. (2004) stated that the inclusion of 0.03 g Zn kg^{-1} for fry and 0.08 Zn kg^{-1} for fingerling diet is required for optimum growth. More research conducted by Watanabe et al. (1988) found that Nile tilapia (*O. niloticus*) required 2 to 3 mg Cu kg^{-1}. Shiau and Su (2003) found that hybrid tilapia (*O. niloticus* × *O. aureus*) required 150 to 160 mg kg^{-1} Fe.

1.2.1.5 Nutrition and Immunity

The production of the Nile tilapia (*O. niloticus*) under a semi-intensive and intensive production system exposes the fish to pathogen infections and disease outbreaks. The main strategy to maintain fish health in aquaculture is the provision of a balanced diet supplemented with immune stimulants that help boost the immune system and keep it under control of disease outbreaks. Functional feed additives such as prebiotics, bioactive compounds derived from medicinal plants, and probiotics could avoid the use of antibiotics and chemotherapy and aid in limiting disease outbreaks by controlling fish mortality in intensive aquatic farms (Merrifield et al. 2010; Hoseinifar et al. 2016: Dawood and Koshio 2016). Functional feed additives modify the gut microbiome, increase the activity of beneficial bacteria, increase the secretion of digestive enzymes, and decrease harmful bacteria. In addition, these feed additives upregulate gene expression related to immunity and inflammatory cytokines such as *IL-1*, *IL-8*, and *Lyz*, oxidative enzymes such as catalyse, superoxide dismutase, and glutathione, and growth genes such as *GH* and *IGF-1*. Such compounds act as health factors capable of modulating the immune responses in tilapia (Table 1.5 included as supplementary data), and other cultivated fish species.

Furthermore, functional feed additives have a positive impact on the immune system defence system by (i) stimulating the production of plasma proteins (globulin and albumin), which play a vital role in the synthesis of antibodies (immunoglobulins), (ii) enhancing the activity of lysozyme, (iii) increasing the production of defence cells such as leukocytes and lymphocytes that produce antibodies), (iv) stimulating the production of macrophages, which are responsible for the phagocytosis, and (v) modulating the composition of the gut flora and improving gut health via the increase in villi length, width goblet cells, improving mucus secretion, and reducing gut inflammation.

Probiotics, generally defined as live microorganisms, are provided via the diet or rearing water (when supplied in an adequate amount). They possess different beneficial characteristics leading to the exclusion of pathogenic bacteria and the modulation of the immune system of the host, by improving the microbial balance of the host (Merrifield et al. 2010). The most common probiotics used in aqua feeds are

Table 1.5 Tilapia studies to evaluate the effects of functional feed additives on immunity*

Feed additives	Tilapia species	Immune responses	Immune-related genes	Stress-regulating genes	Anti-oxidative capacity	Haematological and biochemical parameters	Disease challenge	Disease resistance and survival rate	Reference
Probiotics									
L. rhamnosus	Nile tilapia (*O. niloticus*)	LZM↑, PA↑, ACH50↑	–	–	–	–	*E. tarda*	↑	Pirarat et al. (2006)
Commercial probiotics[a]		LZM↑, BA↑, NBT→	–	–	–	Neutrophil↑, Hb↑, Plasma protein↑	*E. tarda*	↑	Taoka et al. (2006)
S. cerevisiae		BA↑	–	–	–	Neutrophil↑, RBCs↑, Hb↑, Ht↑, Albumin↑, Globulin↑	*A. hydrophila*	↑	Abdel-Tawwab et al. (2008)
B. subtilis + *L. acidophilus*		NBT↑, LZM↑, BA↑	–	–	–	Ht↑	Mixed species pathogen[b]	↑	Aly et al. (2008)
E. faecium		LZM↑, C3↑, RBA↑	–	–	MPO↑	Serum protein→, Albumin→, Globulin→	–	–	Wang et al. (2008)
P. acidilactici		LZM↑, RBA→	–	–	–	WBCs↑, RBCs→, Serum protein→, Albumin→, Globulin→	–	–	Ferguson et al. (2010)
B. coagulans		LZM→, RBA↑	–	–	SOD↑, CAT↑, MPO↑	Serum protein↑, Albumin→, Globulin↑	–	–	Zhou et al. (2010a)
Lactococcus lactis		LZM↑, RBA↑	–	–	SOD↑, MPO↑	–	*A. hydrophila*	↑	Zhou et al. (2010b)

L. rhamnosus		LZM→, PA↑, ACH50↑, RBA→, BA↓	*TNF-α*↑, *IL-1*↑	–	–	–	–	–	Pirarat et al. (2011)
P. acidilactici		LZM→, IEL↑, GC↑	*TNFα*↑	–	–	WBCs↑, Neutrophils↑, Monocytes↑,	–	–	Standen et al. (2013)
L. acidophilus		BA↑	*IL-1β*	–	–	–	*A. hydrophila*	↑	Villamil et al. (2014)
B. licheniformis		LZM↑, C3↑	–	–	SOD↑	–	*S. iniae*	↑	Han et al. (2015)
B. subtilis + *S. cerevisiae*		RBA↑	–	–	–	WBCs↑, Lymphocyte↑, Monocyte↑, RBCs↑, Ht↑, Hb→,	*A. hydrophila* *S. iniae*	↑	Iwashita et al. (2015)
L. plantarum		Total Ig↑, PA↑, LZM↑	*IL-4*↑, *IL-12*↑, *IFN-γ*↑,	–	–	WBCs↑, RBCs↑, Hb↑, Serum protein↑, Albumin↑, Globulin↑	*A. hydrophila*	↑	Hamdan et al. (2016)
AquaStar® Growout[c]		IEL↑, GC↑	*TLR2*↑, *TNF-α*↑, *IL-1β*↑, *IL-10*↑, *TGF-β*↑	*Caspase-3*↑, *PCNA*↑, *HSP70*↑	–	–	–	–	Standen et al. (2016)
AquaStar® Growout[c]	Nile tilapia (*O. niloticus*)	ACH50↑, RBA→, LZM→	–	–	CAT↑, GPx↑, GR↑, GSH↑	WBCs→, RBCs→, HT→	–	–	Ramos et al. (2017)
L. plantarum/ *B. velezensis*		Serum ACH50↑, RBA↑, PA↑; Serum and mucus LZM↑,	–	–	Serum and mucus Peroxidase activity↑	–	*S. agalactiae*	↑	Van Doan et al. (2018c)

(continued)

Table 1.5 (continued)

Feed additives	Tilapia species	Immune responses	Immune-related genes	Stress-regulating genes	Anti-oxidative capacity	Haematological and biochemical parameters	Disease challenge	Disease resistance and survival rate	Reference
		Peroxidase activity↑,							
L. rhamnosus / *Lactococcus lactis*		–	*TNF-α*↑, *IFN-γ*↑, *Lyzc*↑, *IL-1β*↑	*HSP70*↑	–	–	*S. agalactiae*	↑	Xia et al. (2018)
B. subtilis/ *S. cerevisiae*		LZM↑	–	–	–	WBCs↑, RBCs↑, Hb↑, Serum protein↑, Albumin↑, Globulin↑	–	–	Opiyo et al. (2019)
R. stabekisii		RBA↑, PA↑; serum LZM↑,	*TNF-α*↑, *IL-1β*↑, *TGF-β*↑	*HSP70*↑	SOD↑	–	*A. hydrophila*	↑	Tan et al. (2019)
Bacillus sp.		LZM↑, IgM↑, GC↑	–	–	SOD↑, CAT↑	ALP↑	*A. hydrophila*	↑	Kuebutornye et al. (2020)
B. subtilis / *B. cereus*		–	*Lyzc*↑	–	–	–	*S. agalactiae*	↑	Xia et al. (2020)
S. cerevisiae	Hybrid tilapia (*O. niloticus* ♀ × *O. aureus* ♂)	LZM↑, PA↑, RBA↑, C3↑, C4↑	–	–	–	–	–	–	He et al. (2009)
B. subtilis		–	*TNF-α*↑, *IL-1β*↑, *TGF-β*↑	*HSP70*↓	–	–	–	–	He et al. (2013)
L. brevis/ *L. acidophilus*		–		*HSP70*↑	–	–	*A. hydrophila*	↑	Liu et al. (2013)

			TNF-α↑, *IL-1β*↑, *TGF-β*↑						
L. plantarum			*TNF-α*↑, *IL-1β*↑	*HSP70*↑			*A. hydrophila*	↑	Ren et al. (2013)
Lycogen™[d]	Red tilapia (*O. mossambicus* × *O. niloticus*)	LZM↑, ACH50↑	–	–	–	–	–	–	Chiu and Liu (2014)
Bacillus spp.		–	*IFN-γ*↑, *IL-8*↑, *IRF-3*↑, *MX*↑, *RSAD-2*↑	–	–	–	TiLV[e]	↑	Waiyamitra et al. (2020)
Prebiotic									
β-glucan	Nile tilapia (*O. niloticus*)	LZM↑	–	–	–	–	*S. iniae*	↑	Whittington et al. (2005)
Sangrovit®[f]		LZM→	–	–	–	WBCs↑, RBCs→, Hb→, ALT→	–	–	Rawling et al. (2009)
Inulin		LZM↑, NBT↑	–	–	–	Ht↑	*A. hydrophila*	↑	Ibrahem et al. (2010)
GroBiotic®-A[g]	Nile tilapia (*O. niloticus*)	LZM↑, NBT↑	–	–	SOD↓, CAT↓	–	*A. hydrophila*	↑	Zheng et al. (2011)
GroBiotic®-A[g]		LZM→, ACH50→, total Ig→	–	–	–	Serum total Protein→	*S. iniae*	→	Vechklang et al. (2012)
β-glucan		Serum LZM→, ACH50→, RBA↑, BA→	–	–	–	WBCs→, RBCs→, Hb→, Ht→	*S. iniae*	→	Welker et al. (2012)
Inulin or JA[h]		LZM↑, ACH50↑, total Ig↑, GC↑	–	–	–	Albumin↑, Total Protein↑	–	–	Tiengtam et al. (2015)

(continued)

Table 1.5 (continued)

Feed additives	Tilapia species	Immune responses	Immune-related genes	Stress-regulating genes	Anti-oxidative capacity	Haematological and biochemical parameters	Disease challenge	Disease resistance and survival rate	Reference
MOS		LZM→, RBA→	–	–	–	Serum total Protein→	–	–	Yuji-Sado et al. (2015)
FOS		LZM↑, serum IgM↑, NO↑	–	–	SOD↑CAT↑, GPx↑, MDA↑	–	–	–	Abd El-Gawad et al. (2016)
LMWSA		LZM↑, Serum ACH50↑, RBA↑, PA↑	–	–	–	–	*S. agalactiae*	↑	Van Doan et al. (2016b)
XOS		Serum and mucus LZM↑, Serum ACH50↑, RBA↑, PA↑	–	–	Serum and mucus Perox-idase activity↑	–	*S. agalactiae*	↑	Van Doan et al. (2018b)
COS	Hybrid tilapia (*O. niloticus* ♀ × *O. aureus* ♂)	–	*TNF-α*↓, *TGF-β*↑	*HSP70*↓	–	–	*A. hydrophila*	↑	Qin et al. (2014)
GOS	Red hybrid tilapia red tilapia (*O. niloticus* × *O. mossambicus*)	–	–	–	–	WBCs↑, RBCs↑, Ht→	*S. iniae*	↑	Plongbunjong et al. (2011)
Synbiotic									
S. cerevisiae + β-glucan	Nile tilapia (*O. niloticus*)	LZM→, total Ig→, ACH50→	–	–	–	Serum total protein→	–	–	Shelby et al. (2009)
L. plantarum + LMWSA		Serum LZM↑, ACH50↑, RBA↑, PA↑	–	–	–	–	*S. agalactiae*	↑	Van Doan et al. (2016a)

B. subtilis + Malic acid		–	–	–	–	WBCs↑, RBCs↑, Ht↑, Hb↑, total Protein↑, Albumin↑, globulin↑, ALT↓, AST↓	–	↑	Hassaan et al. (2018)
L. plantarum + CCM[i]	Nile tilapia (*O. niloticus*)	Mucus LZM↑, Serum LZM↑, ACH50↑, RBA↑, PA↑	–	–	Serum and mucus Peroxidase activity↑	–	–	–	Van Doan et al. (2017a)
Kefir[j] + LMWSA		Serum LZM↑, ACH50↑, RBA↑, PA↑	–	–	–	–	*S. agalactiae*	↑	Van Doan et al. (2017b)
ASP[k] + β-glucan		NBT↑, LZM↑, IgM, BA↑, PA↑	–	–	SOD↑, CAT↑, GPx↑, MDA↓	WBCs↑, RBCs↑, Ht↑, Hb↑, total Protein↑	–	–	Dawood et al. (2020)
L. plantarum + XOS		Mucus LZM↑, Serum LZM↑, ACH50↑, RBA↑, PA↑	–	–	Serum and mucus Peroxidase activity↑	–	*S. agalactiae*	↑	Van Doan et al. (2020b)
Lactobacillus spp. + FOS	Hybrid tilapia (*O. niloticus* ♀ × *O. aureus* ♂)	–	–	–	–	–	*A. hydrophila*	↑	Liu et al. (2017)
Plant compounds									
Garlic (*Allium sativum*)	Nile tilapia (*O. niloticus*)	–	–	–	–	WBCs↑, RBCs↑, Ht↑, Hb↑, ALT↓, AST↓	*A. hydrophila*	↑	Shalaby et al. (2006)
		Serum LZM↑, RBA↑, PA↑	–	–	–	–	–	–	Yin et al. (2006)

(continued)

Table 1.5 (continued)

Feed additives	Tilapia species	Immune responses	Immune-related genes	Stress-regulating genes	Anti-oxidative capacity	Haematological and biochemical parameters	Disease challenge	Disease resistance and survival rate	Reference
Chinese herbs (*Astragalus radix*)									
Garlic (*Allium sativum*)		NBT↑	–	–	–	–	*P. fluorescens*	↑	Diab et al. (2008)
Ginseng Herb (Ginsana® G115)		–	–	–	–	WBCs↑, RBCs↑, Ht↑, Hb↑	–	–	Goda (2008)
Psidium guajava		–	–	–	–	–	*A. hydrophila*	↑	Pachanawan et al. (2008)
Garlic (*Allium sativum*)		–	–	–	SOD↑, CAT↑, GPx↑, MDA↓	Serum total Protein↑, ALT↓, AST↓	–	–	Metwally (2009)
Echnicacea and Garlic[1]		–	–	–	–	WBCs↑, Ht↑, Neutrophil↑, Lymphocyte↑	*A. hydrophila*	↑	Aly and Mohamed (2010)
Rosmarinus officinalis	Nile tilapia (*O. niloticus*)	–	–	–	–	–	*S. iniae*	↑	Zilberg et al. (2010)
Ginger (*Zingiber officinale*)		LZM↑, IgM↑	–	–	–	–	*A. hydrophila*	↑	El-Sayed et al. (2014)
Aloe vera		LZM→	–	–	–	WBCs↑, RBCs↑, Ht↑, Hb↑, Neutrophil↑, monocytes↑	*S. iniae*	↑	Gabriel et al. (2015)

Moringa oleifera		–	–	–	–	ALT↓, AST↓	*A. hydrophila*	↑	Gbadamosi et al. (2016)
Ginger (*Z. officinale*)		–	–	–	SOD↑, CAT↑, MDA↓	WBCs↑, RBCs↑, Ht↑, Hb↑, Neutrophil↑, monocytes↑	*A. hydrophila*	↑	Şahan et al. (2016)
Orange pectin		Mucus LZM↑, Serum LZM↑, ACH50, PA↑↑, RBA→	–	–	Serum and mucus Peroxidase activity↑	–	*S. agalactiae*	↑	Van Doan et al. (2018a)
Withania sominefera		NBT↑	–	–	Liver SOD↑, CAT↑, GST↑, GSH↑, GPx↑, MDA↓, serum TAC↑	–	*A. hydrophila*	↑	Zahran et al. (2018)
Ocimum basilicum		Serum LZM↑	–	–	–	Ht→, Hb↑, Plasma total Protein↑, ALT↓,	–	–	de Souza et al. (2019)
Thai ginseng (*Boesenbergia rotunda*)		Mucus LZM↑, Serum LZM↑, ACH50↑, RBA↑, PA↑	–	–	Serum and mucus Peroxidase activity↑	–	*S. agalactiae*	↑	Van Doan et al. (2019)
Berberine powder		Mucus LZM↑, Serum LZM↑, ACH50↑, RBA↑, PA↑	–	–	Serum and mucus Peroxidase activity↑	–	*S. agalactiae*	↑	Van Doan et al. (2020a)
Organic acids									
Alginic acid	Nile tilapia (*O. niloticus*)	–	–	–	–	–	–	–	Merrifield et al. (2011)
calcium lactate		–	–	–	–		–	–	

(continued)

Table 1.5 (continued)

Feed additives	Tilapia species	Immune responses	Immune-related genes	Stress-regulating genes	Anti-oxidative capacity	Haematological and biochemical parameters	Disease challenge	Disease resistance and survival rate	Reference
						Ht↑, Hb↑, Plasma total Protein↑, ALT↓, AST↓			Hassaan et al. (2014)
L-malic acid		LZM↑	–	–	SOD↑, MDA↑	–	–	–	Chen et al. (2016)
OAB[m]	Red hybrid tilapia red tilapia (*O. niloticus* × *O. mossambicus*)	–	–	–	–	–	*S. agalactiae*	↑	Ng et al. (2009)

Arrows indicate an increase (↑), decrease (↓), or no change (→) in the response

Probiotic genera abbreviations: *B.*: *Bacillus*, *E.*: *Entercoccus*, *L.*: *Lactobacillus*, *P.*: *Pediococcus*, *R.*: *Rummeliibacillus*

Pathogens genera abbreviations: *A.*: *Aeromonas*, *E.*: *Edwardsiella*, *P.*: *Pseudomonas*, *S.*: *Streptococcus*

Prebiotic abbreviations: *COS:* Chito-oligosaccharides, *FOS:* Fructooligosaccharide, *GOS:* Galactooligosaccharide, *MOS:* Mannan oligosaccharide, *XOS:* Xylooligosaccharides, *LMWSA:* Low molecular weight sodium alginate

*Parameters investigated abbreviations: *ACH50:* alternative complement haemolytic 50 activity, *BA:* Bactericidal activity, *C3 & C4:* Complement component 3 & 4, *Ig:* Immunoglobulins, *LZM:* Lysozyme activity, *PA:* Phagocytic activity, *RBA:* Respiratory burst activity, *NBT:* Nitroblue tetrazolium, *NO:* Nitric oxide activity, *RBCs:* Red blood cells, *WBCs:* Leucocytes, *Ht:* Haematocrit, *Hb:* Haemoglobin, *ALP:* Alkaline phosphatase, *ALT:* Alanine aminotransferase activity, *AST:* Aspartate aminotransferase activity, *SOD:* Superoxide dismutase, *CAT:* Catalase, *GPx:* Glutathione peroxidase, *GR:* Glutathione reductase, *GSH:* Glutathione, *GST:* Glutathione S-transfrase, *TSA:* Total antioxidant capacity, *MPO:* Myeloperoxidase, *MDA:* Malondialdehyde activity, *IEL:* Intraepithelial leucocyte levels in the intestine, *GC:* Gablet cells, *IL:* Interleukin, *TNFα:* Tumour necrosis factor-α, *TLR:* Toll-like receptors, *IFN-γ:* Interferon gama, *TGF-β:* Transforming growth factor beta, *IRF-3:* Interferon regulatory factor, *Mx:* Transcription of *mx*, *RSAD-2:* Radical S-Adenosyl Methionine Domain Containing 2 gene (*VIPERIN* gen), *PCNA:* Proliferating cell nuclear antigen, *HSP70:* Heat shock 70 kDa proteins, *Lyzc:* C-type lysozyme

[a]The commercial probiotics contained *Bacillus subtilis*, *Lactobacillus acidophilus*, *Clostridium butyricum,* and *Saccharomyces cerevisiae*.

[b]The mixed pathogens include *A. hydrophila*, *P. fluorescens,* and *S. iniae*

[c]A commercial probiotic product contains *Bacillus* spp., *Pediococcus* spp., *Enterococcus* spp., and *Lactobacillus* spp.

[d]A commercial carotenoid product from the extract of probiotic Rhodobacter sphaeroides mutant strain WLAPD911 (Lycogen™) contains neurosporene, β-carotene, spheroidenone and methoxyneurosporene rather than lycopene.
[e]Tilapia lake virus (*Tilapia tilapinevirus*).
[f]A commercial product containing the isoquinoline alkaloid sanguinarine.
[g]GroBiotic®-A is a mixture of partially autolyzed brewer's yeast Saccharomyces cerevisiae, dairy components, and fermentation products such as β-glucan and oligosaccharides.
[h]Jerusalem artichoke (*Helianthus tuberosus*).
[i]Mushroom (*Cordyceps militaris*) substrate
[j]Kefir is a complex community of yeasts (*Kluyveromyces, Saccharomyces,* and *Torula*), lactobacilli (*Lactobacillus*, *Lactococcus*, *Leuconostoc*, and *Streptococcus* spp.), and acetic acid bacteria (*Acetobacter*).
[k]*Aspergillus oryzae.*
[l]*Echinacea purpurea* and *Allium sativum.*
[m]OAB, organic acids blend (Sunzen Corporation, Malaysia); PDF, potassium diformate (FORMIs, ADDCON, Norway).

Bacillus spp., lactic acid bacteria (LAB), certain Gram-negative spp., and yeast. They are incorporated into fish diets and lead to high levels of colonization and moderate gut microbial ecology populations (Merrifield et al. 2010).

A prebiotic is defined as a feed additive derived from vegetables and fruit that enhances the fish's performance and/or modifies the community of gastrointestinal beneficial bacteria, which consequent improvement of the host's well-being and health (Gibson and Roberfroid 1995). The criteria used to identify and recognize compounds as prebiotics are: (i) compounds that are neither hydrolysed nor assimilated by the gut; (ii) these compounds should be fermented by the gastrointestinal microbe community, (iii) they should be beneficial for bacteria to the colon through the enhancement of their growth and/or metabolism activation; finally, (iv) they should be able to transfer the colonic flora into healthier compounds to the host (Gibson and Roberfroid 1995; Lauzon et al. 2014).

Ringø et al. (2014) reported that the most common prebiotics used in aquafeeds are fructooligosaccharides (FOS), mannanoligosaccharides (MOS), galactooligosaccharides (GOS), and many commercial products that could be fermented by the gut flora and recognized as non-digestible compounds. Bioactive compounds and oils derived from medicinal plants have a positive impact on the host, including enhancement of performance, immune system response, modification of the gut flora, reduction of free radicals from the metabolic process, and enhancement of the host health and welfare against pathogen microbes (Alemayehu et al. 2018; Jeney et al. 2015).

Organic acids are also employed as a functional feed additive to enhance gut health and performance in fish (Lim et al. 2015). Organic acids have three different mechanisms of action in the gastrointestinal tract of fish: (i) the pH-reducing action of organic acids in the gastrointestinal tract leads to enhanced activity of the digestive enzymes, (ii) the reduction of pH inhibits the growth of pathogens bacteria in the gastrointestinal tract, and (iii) the organic acids integrated into aquafeeds decrease the potential risk of microbial contamination including pathogenic bacteria and moulds or fungi during feed storage (Lim et al. 2015).

1.2.2 Environmental Requirements

The tilapia genus is recognized as the most widely cultured group of species since they are raised in different regions of the world and are highly adaptable to a wide range of environmental conditions (Table 1.6).

Tilapia is tolerant to a wide range of rearing conditions such as salinity, ammonia, pH, dissolved oxygen (DO), and temperature. Among tilapia species, the least adaptable species is Nile tilapia (*O. niloticus*), while the most tolerant species to saltwater are Mozambique tilapia (*T. mossambicus*), blue tilapia (*O. aureus*), and red belly tilapia (*T. zilli*) (El-Sayed 2006b, c).

El-Sayed (2006c) reported that the best salinity level to attain optimum growth in different tilapia species is up to 19 ‰. The optimal growing temperatures range

Table 1.6 Limits and optima of water quality parameters for tilapia

Parameter	Range	Optimum for growth	Reference
Salinity (‰)	Up to 36	<19	El-Sayed (2006c)
DO (mg L^{-1})	Down to 0.1	>3	Ross (2000)
Temperature (°C)	8–42	22–29	Mjoun et al. (2010)
pH	3.7–11	7–9	Ross (2000)
Ammonia (mg L^{-1})	Up to 7.1	<0.05	El-Sherif and El-Feky (2008)

between 22 and 29 °C, while the best temperature for spawning is higher than 22 °C. (El-Sayed 2006c) stated that tilapia can survive below 10° C and Nile tilapia (*O. niloticus*) is the least tolerant to cold water while *O. aureus* is the most tolerant to cold water. (Ross 2000) found that tilapia can tolerate a wide range of dissolved oxygen (DO); however, the optimum level of DO to achieve better growth performance is higher than 3 mg $L^{-1,}$ and the best DO for optimum feed utilization efficiency is 7 mg L^{-1} (Bergheim 2007). (Shelton and Popma 2006) found that Tilapia requires a pH of ~7 or slightly higher than 7 to achieve the best growth. In general, tilapia tolerate a wide range of pH between 3.7 and 11, but the optimum growth rate is achieved between pH 7.5 to 9.5 (Ross 2000).

In terms of ammonia, a concentration higher than 2 mg L^{-1} is considered toxic (Shelton and Popma 2006). While ammonia at a concentration of 1.2 mg L^{-1} causes low appetite and reduces growth (Celik 2012; El-Sherif and El-Feky 2008). (El-Sherif and El-Feky 2008) reported that the optimum ammonia concentration for Nile tilapia (*O. niloticus*) is estimated to be below 0.05 mg L^{-1}.

1.3 Comparative Assessment of Tilapia Culture Systems

The selection of the culture technique is principally affected by the purpose of the aquaculturists or determined by the geographical conditions which involve site selection, substructure, environmental and physical conditions (especially climate), socioeconomic aspects, technical knowledge, and marketing potential. Different types of tilapia production are well known all over the world as monoculture or polyculture in different rearing units such as cages, ponds, and tanks. Also new production systems are practised in different regions of the world as aquaponics, hydroponics, and biofloc. Tilapia production is divided into three categories: (i) extensive: where the stocking density is low and organic and inorganic fertilizers used to promote the natural food, (ii) Semi-intensive: where the source of food combined between fertilization to promote natural food includes phytoplankton and zooplankton plus supplemented diets; (iii) intensive: based on high stocking density, high water exchange rate, and balanced complete feeds are provided. The approximate annual yields of polyculture systems including tilapia with carps reach or exceed 5 tonnes/ha (Prabu et al. 2019).

The major challenges of tilapia production are deprived growth, pathogen infections, and disease outbreaks. However, there have been several solutions that could help to expand tilapia production outside their tropical and sub-tropical regions. Some of these include compiled intensive-extensive systems, closed-cycle that aids in controlling the environmental variables, and intensive system indoor using RAS system with advanced water treatment methods such as biofloc. The common production approach of Nile tilapia (*O. niloticus*) in Asia and Latin America in lakes and reservoirs in different countries is represented by the intensive system in floating cages. The success of intensive technique using cage/tank systems relies on several factors such as (i) cage/tank size and shape, (ii) stocking density and iii) water exchange/water flow rate. Cage culture offers several advantages as follows: (i) minimizes fertilization, (ii) allows the recovery of eggs by spawning fish, (iii) allows the fish to grow in a real environment. The pros of using cage production techniques could be summarized in the following points as stated by (Bhujel 2014a):

– Use of water bodies that cannot be drained or seined and would otherwise not be suitable for aquaculture.
– Flexible and convenient for management.
– No accumulation of ammonia, nitrite, nitrate, and other waste products that are quickly flushed out with water flow from the cage.
– High feeding rates are feasible, and a higher fish growth rate could be achieved.
– Predators (e.g., birds, otters, etc.) can be easily controlled.
– Ease and low cost of harvesting.
– Easy monitoring of fish feeding and health status.
– Low capital investment compared to other production techniques.

Nevertheless, some cons of cage culture involve: (i) poaching risk, (ii) failure of ability to prevent poor water quality conditions because of pollution by industries or factories, iii) difficulties in treating disease and parasites, (iv) need to frequently scrub the cages, (v) risk of fish escape from the cage, (vi) inability to provide natural foods and dependence on manufactured fish diets (complete in nutritional composition), and finally (vii) there may be criticism raised by environmentalists (Bhujel 2014a).

Thereafter, tanks and raceways can be another option to replace pond or cage culture if the conditions are not suitable for the cage technique. (Liao and Chen 2001) stated that in Asia, the intensive tilapia production system in tanks is commonly practised in Taiwan, Malaysia, and Philippines. Taiwan is considered a pioneer for tilapia-intensive culture in concrete tanks (small to medium-level operation), with a production of over 55,000 tons/year. In comparison to the pond production system, tanks and raceways are easy to monitor and handle the stocks and possess a high degree of control of the environmental conditions, specifically water quality parameters. On the contrary, the disadvantages of using tank and raceway culture are given by the high cost of construction, operation, and production and the requirement of proficient attention due to the higher risk of major fish mortality caused by disease outbreaks.

1.3.1 Biofloc Technology

Wastewater with high ammonia, nitrite, and nitrate concentrations damages the fish culture system and pollutes other natural water bodies, so there is a need to look for alternative culture techniques to decrease the environmental damages caused by aquaculture (Gutierrez-Wing and Malone 2006). "Biofloc" Technology (BFT) is considered a promising alternative technique to avoid the harmful environmental impact caused by aquaculture. Biofloc technology through aeration and the addition of extra carbon to the aquaculture system increases the nitrifying bacterial colonies that maintain water quality and, together with phytoplankton and zooplankton are considered additional foods in the aquaculture farming system (Gutierrez-Wing and Malone 2006). The basic concept and function of biofloc are to stimulate the growth of heterotrophic microbial bacteria that convert a toxic source of nitrogen "NH_3" to a safe source of nitrogen, in addition to converting nitrogenous waste to a microbial protein that could be used as another source of protein to the fish (De Schryver et al. 2008). To date, BFT technology has achieved worthwhile attention due to its higher production efficiency, protein recycling from food leftover through nitrifying bacteria, water quality improvement, and a novel approach to infectious disease prevention (Ekasari et al. 2015a). In addition, Ekasari et al. (2015a, b) reported that BFT technique employment could boost the reproductive performance of Nile tilapia (*O. niloticus*) broodstock by enhancing fecundity and larval survival rate and also improving the immune system against infectious diseases. Therefore, all the above advantages of biofloc technology attract the attention of scientists to conduct their research in BFT systems to guarantee and secure the factors within the recommended levels to achieve aquaculture sustainability and food security.

1.4 Genetic Improvement

Research for genetic improvement, particularly quantitative genetic approaches, can have a tremendous impact on aquaculture and can be responsible for increased production efficiency and improved productivity in aquatic animals. Over the past decades, the importance of tilapia in global aquaculture has increased, as well as the intensity and diversity of research for genetic improvement (Gupta and Acosta 2004). In addition, aquatic animals give the opportunity to scientists to implement different approaches for improving fish genetics, including hybridization, selective breeding, sex control, and crossbreeding. Recently research in fish genetics proved that using and implementing new approaches help discover new strains with high growth rate, feed efficiency, survival rate, tolerance to a wide range of environmental conditions, and disease resistance. Moreover, the adoption and implementation of new genetic approaches could help discover new strains of fish and shrimp that could grow in either freshwater or/and brackish water systems (Nguyen et al. 2010; Ninh et al. 2014). Nowadays, most tilapia genetic research has focused on hybridization and monosex male fry production. The most relevant findings of this research indicate that tilapia males grow faster than females, and tilapia shows early maturation, which leads to consecutive spawning during the growing period and thus inhibits and limits growth. Thereafter, female tilapia shows difficulty growing uniformly, so male fry is preferred (Chen et al. 2018; Martínez et al. 2014). This shows the importance of searching for novel techniques and modification and improvement of the existing ones such as manual sexing, interspecific hybridization, androgenesis, triploid, transgenesis, hormonal sex reversal, and YY male technology to produce monosex tilapia for successful and intensive tilapia production (Beardmore et al. 2001; Ponzoni et al. 2011). The current approaches to producing 'all male' tilapia have limitations that make them expensive, unmaintainable, or not acceptable. For example, manual sexing is labour-consuming, and attention to maintaining broodstock for interspecific hybridization is needed. Although the most widespread approach to producing monosex offspring is tilapia masculinization with hormone therapies or adrenal malfunction, hormone therapies have posed concerns because they may influence consumer acceptance and marketability of the fish, and hormone residues may have irreversible effects on biodiversity and water quality. In the case of the YY approach, the production of YY males requires at least three generations of breeding. Moreover, the employment of YY technology depends on the contribution of an outstanding laboratory with advanced facilities for the creation of YY males (Baroiller et al. 1995; Abucay et al. 1999; Baroiller and D'Cotta 2001; Tessema et al. 2006). Therefore, there is a need to look for alternative techniques to create 'all male' tilapia. Some research indicates an effect of temperature on genotype interaction, such as increasing the male: female ratio in response to thermal treatment. For example, thermal treatment of about 38 °C for 10 days after post-hatching succeeded in producing above 80% of males (Ponzoni et al. 2011). It should be mentioned that of all the genetic techniques, just selective breeding presents the chance of permanent genetic achievements because the achievements can be transferred from generation to generation. Finally, a combination of classic selective breeding using marker-assisted selection (MAS) and polygenic selection could considerably promote the male-to-female ratio as a response to thermosensitivity.

1.5 Environmental Impacts

Currently, tilapias have been introduced as exotic species in most countries worldwide, with successful growth and reproduction in new habitats. The traditional tilapia culture in semi-intensive, small-scale systems with minimum negative effects on the environment is now being replaced with intensive, large-scale farming systems. Since the use of manufactured inputs such as artificial feed, chemotherapeutic agents, and hormones will become inevitable in intensive culture systems. The worldwide expansion of tilapia rearing at an extremely high rate is very presumably to cause environmental and socioeconomic risks. In the last few decades, Nile tilapia (*O. niloticus*) production expanded to increase the seafood supply and fulfil the global demand for animal protein and food security. Nevertheless, although tilapia produces substantial economic growth, its fast expansion has caused numerous environmental threats like the destruction of wild habitats, the interaction between alien and endemic species, disturbance of wildlife, use of artificial culture inputs (e.g. chemotherapeutic agents, antibiotics, hormones, and fuels), and eutrophication because of the aquaculture wastewater (El-Sayed 2006a). Thus, the use of advanced and efficient management approaches is necessary. In this regard, some innovative methods have been recommended to boost responsible aquaculture activities including the amalgamation of aquaculture practices with livestock farming and agriculture (e.g. aquaponic, hydroponic, etc.), and also using the BFT and RAS systems that could help to control or manage infectious diseases outbreak and discharges of aquaculture farms (Wang and Lu 2016; Forio and Goethals 2020). These approaches can be the basis for effective long-term solutions for eco-friendly and green aquaculture in the future. Therefore, novel approaches are required if sustainable and green aquaculture is to be meaningfully understood and implemented (Montoya-Camacho et al. 2019). Since eutrophication, a process that is caused by the excessive input of nutrients (e.g., phosphorous and nitrogen), is largely recognized as a serious threat to the environment (Nakano et al. 2016), in the past few decades, researchers have been investigating techniques to reduce aquaculture waste outputs, mainly phosphorus and nitrogen, from aquaculture operations to obtain satisfaction of environmentalists (Azim and Little 2008; Pinho et al. 2017; Boyd 2019). The well-known techniques to achieve eco-friendly aquaculture are the BFT technique and the integrated multi-trophic approach. The biofloc approach has been accomplishing acceptance as an efficient alternative water quality management system (Emerenciano et al. 2013; Dauda 2020). This technique presents the elimination of nutrients from water with the production of microbial communities, which can be consumed by the culture species in situ as natural foods (De Schryver et al. 2008). The other approach is the integrated multi-trophic aquaculture which is defined as a unique self-cleaning approach for aquaculture ponds since the waste from one species (including uneaten feed, faeces, and metabolic excretion) is the source of feed to support the growth of other species (Sampantamit et al. 2020).

Another factor that could affect the tilapia aquaculture community environment is the introduction of alien species destroying the ecosystem compositions and posing risks the global biodiversity (Brown et al. 2018; Anton et al. 2019). Although transgenic tilapia provide several advantages for tilapia farming, the rate of genetic alteration in transgenic tilapia is such that their phenotypic and behavioural attributes cannot be easily predicted (Mair 2002). Furthermore, transgenic tilapias are a new tool that introduces new strains into the community of wild tilapia and may have negative effects on the environment and other native species. The negative impact of transgenic is the replacement of native populations with novel strains that could become a part of the gene pool and also change the hierarchy of the natural populations (Dunham 1999).

Unfortunately, despite the negative effects that the extension of tilapia rearing may have on the environment, most introductions have not been preceded by any environmental impact evaluation. Instead, in most cases, the evaluation was performed after the introductions took place. In such a case, modulating and managing the impacts of introduced tilapia in their new environments will be very challenging, or even unfeasible. Therefore, cautious and thorough assessment, as also proper management plans and programmes must be adopted to be carried out before any introductions or transfer of tilapia.

1.6 Some Constraints and Suggestions for Solutions to Tilapia Farming

Although tilapia farming holds great promise, there are some constraints to its development. Some constraints and their possible solutions are reported as follows:

1. Training resource allocation related to tilapia farming. In general, aquaculture needs education about new technologies and farm management, because education can play a substantial role in enhancing the skills and experiences of farmers and also resolving the restrictions and challenges facing aquaculture (Olaoye et al. 2013). Previous research expressed the importance of the aquaculturists' education level to select reasonable technologies and manage the facilities efficiently (Ogunmefun and Achike (2017); Uddin et al. (2021). Therefore, resource allocation for training courses and workshops for tilapia farmers has to be considered.
2. Insufficient supply of tilapia fry. The lack of larvae production to respond to the growing world demand is one of the major bottleneck restrictions to the development of the tilapia-intensive culture (El-Sayed 2002). One of the most important obstacles to high-quality tilapia fry production is the poor reproductive performance of bloodstock due to asynchronous spawning cycles and low fecundity rate.

   Bhujel (2000) stated that the monitoring and management of the environmental and nutritional status of brood stocks can improve their efficiency. Moreover, the selective breeding of superior brood stocks and strains with preferable size and age for breeding objectives could remarkably improve larvae production. Among the environmental factors, high salinity and low temperature might be helpful for the control and synchronization of broodstock reproduction when fry demand is low (Bhujel 2000).
3. Environmental tolerance. Environmental tolerance is the major factor in controlling the success of tilapia production. Although some tilapia like Mozambique tilapia can grow in seawater, most tilapia species are categorized as freshwater fish and not tolerant to high salinity (El-Sayed 2006b; Shelton and Popma 2006). One of the promising techniques to improve salinity tolerance is the crossbreeding between Nile tilapia (*O. niloticus*) and Mozambique tilapia

(*O. mossambicus*). Furthermore, the limited ability of tilapias to tolerate low temperatures (<15 °C) (El-Sayed 2006b; Shelton and Popma 2006) restricts the expansion of tilapia culture in a different geographic zone. Using warm water such as cooling water of some industries, thermal effluents, and/or warm springs and also maintaining tilapia in a greenhouse or indoor ponds because of their non-resistance to cold water can help them to overwinter in subtropical scopes of tilapia culture.

4. Early maturation. Tilapia's first maturity occurs at an early age (2–3 months old) and a short length (10–12 cm length). The most preferable and cost-effective technique is to create 'all male' tilapia because males grow faster than females and also have a more standard size (see Sect. 1.4).
5. Genetic deterioration. In some conditions, there is evidence of genetic deterioration. Genetic deterioration of introduced stocks is widely attributed to poor broodstock management resulting in inbreeding and introgression of less favourable genes. With the rapid advance of next-generation sequencing techniques (Metzker 2010), marker-assisted selection and genomic selection will significantly accelerate the genetic improvement of tilapias (Sonesson 2011; Yue 2014). In general, the desirable characteristics of improved tilapia have been focused on higher production efficiency, better appearance, tolerance to certain environmental conditions, and, especially, control of unwanted breeding.

   Remarkable interests in improved growth rate and performance of tilapia under farm conditions have been shown from breeding programmes for selection and sex control. The achievements of the implementation of such breeding strategies have been introduced to aquaculture through technically and economically sustainable programmes (Mair 2002). For example, farming the Genetically Improved Farmed Tilapia (GIFT) strain rather than the not-improved local strain of the Nile tilapia (*O. niloticus*) can enhance the growth rate and production efficiency of tilapia. Since feed accounts for over 50% of the cost of production, the higher feed conversion ratio of the GIFT strain would decrease production costs. The GIFT strain has a remarkably higher growth performance, better feed conversion ratio, and higher production efficiency than the local strain (Ridha and Cruz 2002).

   The other important aspect is the genetically improved strains dissemination to achieve the targeted beneficiaries effectively, including monitoring of the impact and adoption of improved breeds. On the other hand, genetic improvement programmes will require the development of production stocks that are acceptable to each environment. Therefore, success in genetic improvement programmes will require long-term support and collaboration between partners from the government, university, and industry.
6. Disease resistance. Since tilapia, cultural practices have been intensified, and the densities of tilapia have increased in different systems and culture has expanded into the colder climatic zones, where suitable environmental factors are more difficult to maintain, infectious diseases have emerged (Watanabe et al. 2002). Developing approaches for fish health stability through genetic improvement,

water quality management, stress reduction, and the use of preventive immunostimulants are required to control infectious diseases.

7. Lack of access to freshwater. Tilapias are freshwater fish; however, access to freshwater resources is one of the most critical environmental issues in developed and industrialized countries (Hankins 2002). Therefore, it is suggested to use water supplies that are not suitable for human consumption or agriculture such as brackish water or seawater. Moreover, the use of recirculating systems is another fit approach for water quality and quantity management.
8. Negative impacts on the environment and global biodiversity. It is clear from the previous section (see Sect. 1.5) that mismanaged transfers and/or introductions of tilapia can lead to destructive environmental impacts. If tilapias are established in their new environment, it would be approximately infeasible to control and reduce their catastrophic impacts. It is hence necessary that strict regulations be established to control the introduction of tilapias in a new habitat and also precise monitoring programmes and certification of tilapia farms are mandatory to protect the environment and aquatic biodiversity (Bush et al. 2013).

   Yue et al. (2016) expressed that the recirculating aquaculture systems and cage culture can mitigate the adverse effects of tilapia culture on the environment and aquatic biodiversity. Therefore, they would probably be developed in the production and technological advances of tilapia culture. These systems facilitate aquaculture and hence will be the key parts of next-generation aquaculture.
9. Flesh quality problems of tilapias. Tilapia, flesh quality issues, are as follows: (i) odour and flavour, which are attributed to culture conditions, (ii) high percentage of bone if the harvest has occurred in small-size fish, and (iii) farmed tilapia species contain low levels of omega-3 fatty acids compared with other fish, especially salmon (Weaver et al. 2008). Likely, selective breeding (Gjedrem and Baranski 2010) and supplementing tilapia feeds with marine microalgae containing a high level of omega-3 (Tadesse et al. 2003) can increase the essential fatty acid content of tilapias. Moreover, finishing diets and also the GIFT breeds (reviewed by Eknath and Hulata 2009) and transgenic tilapia can moderate this problem. Although, before the commercialization of transgenic fish, food safety issues should be addressed.
10. Failed marketing of products. The lack of attention given to marketing and business has also been recognized as one of the restrictions to the achievement of commercial tilapia production. The assessment of the tilapia market is rarely undertaken by aquaculturists due to time and expense and difficulties in attracting the cooperation of wholesalers and retailers, which should be considered (Watanabe et al. 1997).

1.7 Conclusions and Recommendations

This chapter may be considered as a short preface to tilapia rearing needs. Tilapia culture has gained significance increasingly in the world. Tilapia has a lot of positive characteristics that make it proper for culture. Amongst these are its general resilience, high tolerance to unfavourable environmental conditions and adaptability to high stocking densities, its potential ability to tolerate low levels of dissolved oxygen and a wide range of salinity concentrations, and its infectious diseases resistance. Tilapia can utilize and grow in a wide variety of natural and artificial feeds, has a high survival rate, acceptable feed conversion ratio, fast growth rate, and high yield potential, and is accepted by a wide range of farmers and consumers. Moreover, tilapia can grow well in different aquaculture systems, ranging from extensive systems with simple substructures to more intensive systems with complex infrastructure. With the increasing demand for tilapia products, tilapia farming will continue to be a source of different business benefits, since it is a cheap and easy source of affordable and inexpensive animal protein and provides several job opportunities to the community in developing countries. Finally, suitably designed fish farms, precisely selective breeding of tilapia strains, selection of a proper tilapia production system by the aquaculturists, government support on supply seed, feed, and instruments, training, extension services, and advice to the aquaculturists regarding tilapia culture, and the development of an organized marketing agenda would increase the commercial profitability and sustainability of tilapia production in many countries around the world.

Therefore, it can be unavoidable to conduct research studies on resolving the issues met in tilapia culture because tilapia culture will guarantee the socioeconomic advantages and food security of developing countries. For example, although tilapia feed on a wide range of natural and artificial feeds, specific dietary requirements are yet lacking, and the interactions among nutrients and with cultured conditions and tilapia health and welfare are not completely known. Nowadays, research and interest in dietary feed additives such as immunostimulants and growth stimulants, especially phytobioactive compounds to improve fish health and growth performance are likely to continue, which will fill existing research gaps. Moreover, more research work and resource and management development are required to improve breeds that are more cold-tolerant, salt-tolerant, and disease resistant.

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