Tilapia, *Oreochromis* spp.

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Introduction

Tilapias are mainly lacustrine fish and are well adapted to enclosed water. They are fast-growing, resistant to disease and handling, easy to reproduce in captivity and able to tolerate a wide range of environmental conditions. They are widely cultured in tropical and subtropical regions of the world and constitute the third largest group of farmed finfish, with an annual production growth rate of about 11.5% (El-Sayed, 1999). Global production of farmed tilapia has increased more than threefold since 1984, from 186,544 Mt to 659,000 Mt, representing 4.48% of total farmed finfish in 1995 (Tacon, 1997).

Most cultured tilapias are grouped into two genera (Trewavas, 1982): *Tilapia*, which are macrophagous and substrate spawners, and *Oreochromis*, which are microphagous and mouth-breeders. The main cultured species are *Oreochromis niloticus*, *Oreochromis aureus*, hybrid *O. niloticus* × *O. aureus*, *Oreochromis mossambicus* and *Tilapia zillii*. For the mouth-breeders of the *Oreochromis* genus, there exists a marked delay in the growth of females and monosex culture of males is preferred. Thus, it is important to indicate the sex of the cultured fish, and whether sex control was obtained through manual sorting, sex-reversal by hormone treatment or hybridization.

As the industry expands and technology development continues, traditional extensive culture of tilapia is being replaced by semi-intensive and intensive production systems. Natural pond organisms are the only source of nutrients for the growth of fish in extensive culture. In semi-intensive farming systems, supplemental diets, which consist of locally available, low-cost single foodstuffs, such as rice bran, maize meal, copra meal, coffee pulp, brewery by-products and/or their combination, are generally used as supplements to natural food (Lim, 1989). As stocking rates increase, the contribution of natural food decreases and more nutritionally complete diets are needed. In semi-intensive and intensive culture systems, diet is the most expensive cost item, often ranging from 30% to 60% of the total variable expenses, depending on the intensity of the culture operation. Thus, the use of least-cost, nutritionally balanced diets and good feeding management are two most important requisites for successful fish production.

Nutrient Requirements

Protein and amino acids

Proteins are indispensable nutrients for the structure and function of all living organisms, including tilapia. Since proteins are continually being used for maintenance, growth and reproduction, a continuous supply of proteins or their component amino acids is needed. Fish do not have a true protein requirement, but need a well-balanced mixture of indispensable and dispensable amino acids. Inadequate intake of protein will result in retardation or cessation of growth due to the withdrawal of protein from less vital tissues to maintain the function of more vital ones. If too much protein is supplied, however, only part will be used to synthesize new tissues and the remainder will be converted to energy (NRC, 1983).

Many investigators have used semipurified and purified diets to estimate the optimum dietary protein level for tilapia. Most of these values have been derived from dose–response curves yielding the minimum of dietary protein necessary for maximal growth. The optimum dietary protein level for tilapia appears to be influenced by the size or age of the fish and ranges from 28% to 50% (Table 20.1). For fry (first feeding to approximately 0.5 g), dietary protein levels ranging from 36 to 50% have been shown to produce maximum growth (Davis and Stickney,

Table 20.1. Protein requirements of tilapia cultured in fresh water.

Species	Fish size (g)	Requirement (%)	Reference
O. mossambicus	1.0–2.5	29–38	Cruz and Laudencia (1977)
	Fry	50	Jauncey and Ross (1982)
	0.5–1.0	40	
	6–30	30–35	
	1.8	40	Jauncey (1982)
O. niloticus	1.5–7.5	36	Kubaryk (1980)
	3.2, 3.7	30	Wang *et al.* (1985)
	0.838	40	Siddiqui *et al.* (1988)
	40	30	
	24	27.5–35	Wee and Tuan (1988)
	0.012	45	El-Sayed and Teshima (1992)
O. aureus	0.3–0.5	36	Davis and Stickney (1978)
	0.16	40	Santiago and Laron (1991)
Tilapia zillii	1.7	35–40	Teshima *et al.* (1978)
	1.65	35	Mazid *et al.* (1979)
O. niloticus × *O. aureus*	0.6–1.1	32	Shiau and Peng (1993)
	21	28	Twibell and Brown (1998)

1978; Jauncey and Ross, 1982; Santiago and Laron, 1991; El-Sayed and Teshima, 1992); for juveniles (approximately 0.5–5 g), 29–40% has been determined to produce optimal growth (Cruz and Laudencia, 1977; Teshima *et al.*, 1978; Mazid *et al.*, 1979; Kubaryk, 1980; Jauncey, 1982; Jauncey and Ross, 1982; Wang *et al.*, 1985; Siddiqui *et al.*, 1988; Shiau and Peng, 1993); and, for young adult fish (up to 40 g), 27.5–35% appears to be optimal (Jauncey and Ross, 1982; Siddiqui *et al.*, 1988; Wee and Tuan, 1988; Twibell and Brown, 1998).

Practical diets for grow-out of tilapias usually contain 25–35% crude protein. In ponds, however, fish may have access to natural food that is rich in protein; thus dietary protein levels as low as 20–25% have been estimated to be adequate (Newman *et al.*, 1979; Lovell, 1980; Wannigama *et al.*, 1985). Water salinity appears to affect the protein requirements, being lower at higher salinity (Table 20.2).

Tilapias require the same ten essential amino acids (arginine, histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine) as other fish and terrestrial animals. The quantitative requirements for these essential amino acids for growth of young Nile tilapia (*O. niloticus*) determined by Santiago and Lovell (1988) are presented in Table 20.3.

Non-essential amino acids can be adequately synthesized by fish but their presence in the diet has nutritional significance because it reduces the need for fish to synthesize them. Two specific examples of sparing action are the conversion of methionine to cystine and phenylalanine to tyrosine. These non-essential amino acids can only be synthesized from the essential amino acid precursor (NRC, 1983). Tilapias actually have a requirement for sulphur-containing amino acids, which can be met by either methionine alone or the proper mixture of methionine and cystine. Dietary cystine can replace up to 50% of the total sulphur-containing amino acid requirement for *O. mossambicus* (Jauncey and Ross, 1982). A similar relationship exists between aromatic amino acids. The presence of tyrosine in the diet will reduce some of the requirement for phenylalanine (NRC, 1993).

In general, protein sources having an essential amino acid profile that closely matches the essential amino acid requirements are likely to have a high nutritional value. Fish-meal is used as the main conventional protein source in aquaculture diets. Attempts have been made to partially or totally replace

Table 20.2. Protein requirements of tilapia at different salinities.

Species	Fish size (g)	Salinity (p.p.t.)	Requirement (%)	Reference
O. niloticus	0.024	0	30.4	De Silva and Perera (1985)
		5	30.4	
		10	28.0	
		15	28.0	
O. niloticus × *O. aureus*	2.88	32–34	24.0	Shiau and Huang (1989)
Florida red tilapia	10.6	37	20.0	Clark, A.E. *et al.* (1990)

Table 20.3. Essential amino acid requirements of tilapia.

Amino acids	Requirement (% of dietary protein)*
Arginine	4.20
Histidine	1.72
Isoleucine	3.11
Leucine	3.39
Lysine	5.12
Methionine	2.68†
Phenylalanine	3.75‡
Threonine	3.75
Tryptophan	1.00
Valine	2.80

* Data resulting from growth experiments (Santiago and Lovell, 1988).
† Total sulphur amino acid (methionine plus cystine) requirement is 3.21% of the protein.
‡ Total aromatic amino acid (phenylalanine plus tyrosine) requirement is 5.54% of the protein.

fish-meal with less expensive, locally available protein sources for tilapia. Soybean meal has been studied extensively, with various degree of success. Factors such as antinutritional factors (Tacon, 1993), limiting amino acids (Jackson *et al.*, 1982; Tacon *et al.*, 1983; Viola and Arieli, 1983; Teshima and Kanazawa, 1988; Shiau *et al.*, 1989a), minerals (Viola *et al.*, 1986, 1988) and dietary protein levels (Shiau *et al.*, 1987, 1989a; Viola *et al.*, 1994a,b) have been discussed. A comprehensive review of alternative dietary protein sources, including animal by-products, oil-seed plants, aquatic plants, single-cell proteins, grain legumes and plant protein concentrates, for tilapia is available (El-Sayed, 1999).

Energy

Energy is not a nutrient but is a property of nutrients that are released during the metabolic oxidation of proteins, carbohydrates and lipids. Generally, protein is given the first priority in formulating fish diets because it is the most expensive component of the prepared diets. However, energy should be the first nutritional consideration in diet formulation since tilapias, like other fish, eat to satisfy their energy needs. If insufficient non-protein energy is available, part of the protein is used as an energy source. However, excess energy may produce fatty fish, reduced diet consumption (reducing total protein intake) and inhibit proper utilization of other feedstuffs. Kubaryk (1980) observed that, as the digestible energy (DE) content in the diet increased, consumption by *O. niloticus* decreased, but the amount of protein in the diet did not affect consumption.

Available data on energy requirements of tilapias have been reported in terms of gross energy (GE), DE or metabolizable energy (ME) in relation to the

Table 20.4. Optimum protein-to-energy ratio of tilapia.

Species	Fish size (g)	Optimum P/E ratio	Reference
O. mossambicus	1.80	116.6 mg kcal^{-1} ME	Jauncey (1982)
	5.19	99.48 mg kcal^{-1} DE	El-Dahhar and Lovell (1995)
O. niloticus	0.012	110 mg kcal^{-1} GE	El-Sayed and Teshima (1992)
	1.7	120 mg kcal^{-1} DE	Kubaryk (1980)
O. aureus	2.5	123 mg kcal^{-1} DE	Winfree and Stickney (1981)
	7.5	108 mg kcal^{-1} DE	Winfree and Stickney (1981)
Tilapia zillii	1.65	95.3 mg kcal^{-1} DE	Mazid *et al.* (1979)
	50	103 mg kcal^{-1} DE	El-Sayed (1987)
O. niloticus × *O. aureus*	0.16	111 mg kcal^{-1} DE	Santiago and Laron (1991)

dietary level of protein (P) (Table 20.4). Generally, the dietary protein-to-energy ratio required for maximum growth decreases with increasing size of fish. For fry (to about 0.5 g) and juveniles (from 0.5 to 5 g), a protein/energy (P/E) ratio ranging from 95.3 to 123 mg protein kcal^{-1} DE (Mazid *et al.*, 1979; Kubaryk, 1980; Winfree and Stickney, 1981; Jauncey, 1982; Santiago and Laron, 1991; El-Sayed and Teshima, 1992; Table 20.4) and, for adult fish (5–50 g), 99.48–108 mg protein kcal^{-1} DE appears to be optimal (Winfree and Stickney, 1981; El-Sayed, 1987; El-Dahhar and Lovell, 1995). Shiau and Huang (1990) reported maximum growth of *O. niloticus* × *O. aureus* (1.60 g) reared in sea water (32–34 p.p.t. salinity) when fed a 21% and 24% protein diet with P/ME ratio of 67.74 and 104.35 mg protein kcal^{-1}.

Lipids and fatty acids

Protein is responsible for a large part of the cost of most prepared diets. The protein fraction should be utilized for growth rather than serve as an energy source for fish. Knowledge of the protein-sparing effects of non-protein nutrients such as lipids is necessary and should be used to reduce diet costs and maximize nitrogen retention. Moreover, dietary lipids are the only source of essential fatty acids needed by fish for normal growth and development. They are also important carriers and assist in the absorption of fat-soluble vitamins. Lipids, especially phospholipids, are important for cellular structure and maintenance of membrane flexibility and permeability. Lipids also serve as precursors of steroid hormones and prostaglandins, improve the flavour of diets and affect the diet texture and fatty acid composition of fish.

Studies on *T. zillii* (Teshima *et al.*, 1978; El-Sayed and Garling, 1988) indicated that increasing dietary lipid up to 15% resulted in a significant improvement in protein efficiency ratio (PER) and protein production value (PPV). Similar results were reported by Teshima *et al.* (1985) with *O. niloticus*. Hanley (1991) indicated that tilapia were able to store significant quantities of lipid in their carcass and viscera, but could not utilize this energy source to improve growth. However, this study was conducted outdoors, where natural productivity in the culture system may have influenced the results. Dietary lipids have been shown to have a sparing effect on the utilization of dietary protein. The level of protein in the diet of *O. niloticus* can be reduced from 33.2% to 25.7% by increasing dietary lipid from 5.7% to 9.4% and carbohydrate from 31.9% to 36.9% (Li *et al.*, 1991). A dietary lipid level in excess of 12% depressed growth of juvenile *O. aureus* × *O. niloticus* hybrids (Jauncey and Ross, 1982). The growth of *O. aureus* can be substantially improved when menhaden oil or fish-oil is provided at 7.5–10% of the diet as compared with lower levels. However, best performance was obtained with menhaden oil at 10% of the diet (Stickney and Wurts, 1986). The optimal dietary lipid level for tilapia was quantified by Chou and Shiau (1996). Five isoenergetic and isonitrogenous purified diets containing 0–20% lipid (maize oil, cod-liver oil and pork lard at a 1 : 1 : 1 ratio) in 5% increments were fed to the juvenile tilapia hybrid, *O. niloticus* × *O. aureus*. Results indicated that 5% dietary lipid appeared to be sufficient to meet the minimal requirement of juvenile tilapia, but a level of 12% was needed for maximal growth.

Cold-water fish have a higher requirement for n-3 polyunsaturated fatty acid (PUFA), whereas warm-water fish tend to require greater quantities of n-6 fatty acids. Several studies have reported the fatty acid requirements of various tilapia. Kanazawa *et al.* (1980a) indicated that *T. zillii* is unable to convert much 18:2n-6 to 20:4n-6. However, Kanazawa *et al.* (1980b) suggested that this same species probably does convert dietary 18:2n-6 to 20:4n-6. Stickney and McGeachin (1985) indicated that growth of blue tilapia, *O. aureus*, was not affected by dietary linoleic acid levels as high as 2%. When blue tilapia were fed diets containing soybean oil, growth improved as the percentage of linoleic acid increased (Stickney *et al.*, 1985). Takeuchi *et al.* (1983) found that the growth of the tilapia *O. niloticus* was significantly reduced with a fish-oil-containing diet (pollock liver oil) as compared with maize oil or soybean oil diets. Ramachandran Nair and Gopakumar (1981) reported unusually high levels of 22:6n-3 in eggs of *O. mossambica*, suggesting some important role of docosahexaenoic acid in reproduction and embryo development. However, Santiago and Reyes (1993) indicated that, although a fish-oil (cod-liver oil) high in 22:6n-3 promoted the highest weight gain in Nile tilapia, this same lipid resulted in the poorest reproductive performance of this species. Blue tilapia have been reported to grow well on practical diets containing either 10% soybean oil, which is high in 18:2 n-6, or 10% menhaden oil, which is high in 20:5n-3 and 22:6n-3 (Stickney and McGeachin, 1983). Stickney and Hardy (1989), however, reported that *O. aureus* have a requirement for a relatively high level of n-6 fatty acids, though the requirement can be reduced when n-3 fatty acids are present. Stickney and Wurts (1986) compared the growth of blue tilapia fed diets containing graded levels of catfish and menhaden oil, and the best growth was obtained with the 10% menhaden-oil diet. These studies gave contradictory results as to the requirement of tilapia for dietary n-3 and n-6 PUFA. Recently, Chou and Shiau (1999) demonstrated that both n-3 and n-6 highly unsaturated fatty acids are essential for maximum growth of hybrid tilapia (*O. niloticus* × *O. aureus*). Further quantification of essential fatty acid requirements for tilapia species and hybrids is needed.

Carbohydrates

Carbohydrates are the least expensive form of dietary energy for human and domestic animals, but their utilization by fish varies and remains somewhat obscure. Fish in general utilize dietary carbohydrate poorly. No dietary requirement of carbohydrate has been demonstrated in fish. It has been reported that the utilization of starch was significantly higher than that of glucose by tilapia (Anderson *et al.*, 1984; Tung and Shiau, 1991; Shiau and Chen, 1993; Shiau and Lin, 1993). It has also been reported that tilapia utilizes disaccharides better than glucose but more poorly than starch. Of the disaccharides, maltose was better utilized, followed by sucrose and lactose (Shiau and Chuang, 1995). Lin and Shiau (1995) reported that malic enzyme, glucose-6-phosphate dehydrogenase (G-6-PD) and phosphogluconate dehydrogenase (PGD) activities were higher in tilapia fed the starch diet than in fish fed the glucose diet. Changing the diet from starch to glucose decreased malic enzyme, G-6-PD and PGD activities, whereas changing the diet from glucose to starch increased these enzyme activities in fish liver. The authors suggest that lipogenic enzyme activity in tilapia liver can adapt to dietary carbohydrates.

Tung and Shiau (1991) have studied the effect of daily feeding frequency on the utilization of carbohydrate by tilapia. Diets containing 44% of glucose, dextrin and starch were fed either twice or six times a day. The authors found that fish fed all carbohydrate sources six times a day had significantly higher weight gain, diet efficiency, protein deposition and energy retention than fish fed these diets twice a day. This study also demonstrated that, as the feeding frequency increased from twice a day to six times a day, fish fed the starch and dextrin diets gained more weight than fish fed the glucose diet, but the differences were not statistically significant. It was also noted that the growth performance of tilapia fed the glucose diet six times a day was higher than that of fish fed the starch or dextrin diets twice a day. The effect of feeding strategy on carbohydrate utilization by tilapia has recently been confirmed by Shiau and Lei (1999), when they re-evaluated the effects of continuous feeding and two meals a day on carbohydrate utilization by tilapia. Results indicated that continuous feeding improves carbohydrate utilization.

Shiau *et al.* (1988) studied the influence of carboxymethylcellulose (CMC) on growth, digestion and gastric emptying time of tilapia. In their studies, CMC was incorporated at 2, 6, 10 and 14% of the diet. Dextrin was used as the carbohydrate source. Both weight gain and diet conversion ratio decreased as the dietary CMC level increased. Shiau *et al.* (1989b) studied the effects of five different dietary fibres (guar gum, agar, carrageenan, CMC and cellulose) on the utilization of dextrin and glucose in tilapia. Each fibre was added at 10% of the diet. Results indicated that the weight gain was significantly lower for tilapia fed fibre-containing diets than those fed the dextrin or glucose diet. The intestinal absorption of carbohydrate and the blood-sugar content were low in fish fed diets containing fibre, regardless of source. Recently, Shiau and Yu (1999) demonstrated that dietary supplementation of chitin or chitosan depresses growth in tilapia, regardless of the supplementation level (2, 5 and 10%).

Niacin is a precursor of certain coenzymes needed for carbohydrate metabolism. Shiau and Suen (1992) demonstrated that the amount of niacin needed in tilapia varies with the sources of dietary carbohydrate. They found that the adequate dietary niacin level for maximal growth of tilapia fingerlings was 26 mg kg^{-1} diet in fish fed the glucose diet and 121 mg kg^{-1} diet in fish fed the dextrin diet, indicating that the dietary niacin requirement for tilapia is affected by the type of dietary carbohydrates.

Shiau and Peng (1993) conducted a study to evaluate the possible protein-sparing effects of carbohydrates in tilapia. Three dietary protein levels (32, 28, 24%) were achieved by substitution with three levels (33, 37, 41%) and three sources (glucose, dextrin, starch) of dietary carbohydrates. Results indicated that the protein-sparing effect of carbohydrates (dextrin or starch) only occurred when the dietary protein level was suboptimal. Shiau and Chuang (1996) also reported that carbohydrate utilization by tilapia is affected by dietary protein source.

Other nutrients, such as chromium, have also been reported to affect carbohydrate utilization by fish. Shiau and Lin (1993) first demonstrated that dietary chromium supplementation in the form of chromium chloride significantly improved glucose but not starch utilization by tilapia. Shiau and Chen (1993) later reported that the improvement of glucose utilization by tilapia fed diets supplemented with chromic oxide was markedly higher than with other forms of chromium, including chromium chloride. Shiau and Liang (1995) reported that the level of chromic oxide in the diet alters glucose utilization by tilapia. Fish fed a glucose diet with 5000 mg chromic oxide kg^{-1} diet had a higher weight gain than fish fed a glucose diet with 20,000 mg chromic oxide kg^{-1} diet. They speculated that the poorer growth performance of tilapia fed the higher level of chromic oxide may be due to a toxic effect of dietary chromium. More recently, Shiau and Shy (1998) reported that maximum growth and glucose utilization in hybrid tilapia were achieved with a glucose diet containing 204.4 mg chromic oxide kg^{-1} diet.

Lin *et al.* (1995) indicated that plasma insulin concentration in tilapia ingested with glucose was higher than that ingested with starch and that the plasma insulin pattern of tilapia was similar to that of humans. However, the exact mechanism of insulin in the utilization of carbohydrate by tilapia is still not clear.

Ammonia excretion and oxygen consumption of tilapia are affected by the type of carbohydrate ingested. Shiau and Cheng (1999) fed tilapia diets containing three levels (33, 37 and 41%) of carbohydrates (starch and glucose) for 8 weeks. Fish fed a starch diet had lower total ammonia excretion than fish fed a glucose diet at all three carbohydrate levels. Ammonia excretion in the glucose-fed fish decreased as the carbohydrate inclusion level increased. In the starch-fed fish, ammonia excretion was significantly lower at the 41% inclusion level than at the 33 and 37% inclusion levels. Total oxygen consumption was significantly higher in the starch-fed fish than in the glucose-fed fish. In both the glucose- and starch-fed fish, higher oxygen consumption was observed at the 37 and 41% inclusion level than at the 33% inclusion level.

Biotic factors, such as physiological stages, may also influence the utilization of carbohydrates by tilapia. Tung and Shiau (1993) compared the utilization of two carbohydrate sources (glucose, starch) by two sizes (4.55, 0.46 g) of tilapia. They found that the larger fish gained significantly more body weight and had a better diet conversion ratio, protein and energy deposition than the smaller fish when fed a glucose diet. However, these parameters were similar in the larger and smaller fish when the starch diet was fed.

Vitamins and minerals

Vitamin supplements are often not included in practical diets for tilapias stocked at moderate densities in fertilized ponds. In intensive systems where limited or no natural foods are available, supplemental vitamins must be added.

Table 20.5 presents the vitamin requirements of various tilapia. Water-soluble vitamin requirements of tilapias that have been studied are:

Table 20.5. Vitamin requirements of various tilapia.

	Requirement (mg kg^{-1} diet)				
Vitamins	*O. niloticus* × *O. aureus*	*O. aureus*	*O. niloticus*	*O. mossambicus* × *O. niloticus*	*O. spilurus*
Thiamine	–	–	–	2.5[a]	–
Riboflavin	–	6[b]	–	5[c]	–
Pyridoxine	1.7–9.5 (28% C.P.)[d] 15–16.5 (36% C.P.)[d]	–	–	3[e]	–
Vitamin B_{12}	Dispensable[f]	–	Dispensable[g,h]	–	–
Niacin	121[i]	–	–	–	–
Biotin	0.06[j]	–	–	–	–
Folic acid	–	–	–	–	–
Inositol	–	–	–	–	–
Choline	1000[k]	Dispensable[l,m]	–	–	–
Pantothenic acid	–	6–10[n,o]	–	–	–
Ascorbic acid	79 (C1)[p] 41–48 (C2S)[t] 37–42 (C2MP-Mg)[t] 63.4 (C2MP-Na)[u]	50 (Cl)[q]	420 (C1)[r]	–	100–200 (C2S)[s]
A	–	–	–	–	–
D	0.00937 (374.8 IU kg^{-1})[v]	Dispensable[w]	–	–	–
E	42–44 (5% lipid)[x] 60–66 (12% lipid)[x]	10 (3% lipid)[y] 25 (6% lipid)[y]	50–100 (5% lipid)[z] 500 (10~15% lipid)[z]	–	–
K	–	–	–	–	–

[a]Lim and LeaMaster (1991); [b]Soliman and Wilson (1992b); [c]Lim *et al.* (1993); [d]Shiau and Hsieh (1997); [e]Lim *et al.* (1995); [f]Shiau and Lung (1993); [g]Lovell and Limsuwan (1982); [h]Sugita *et al.* (1990); [i]Shiau and Suen (1992); [j]Shiau and Chin (1999); [k]Shiau and Lo (2000); [l]Roem *et al.* (1990a); [m]Roem *et al.* (1990b); [n]Roem *et al.* (1991); [o]Soliman and Wilson (1992a); [p]Shiau and Jan (1992); [q]Stickney *et al.* (1984); [r]Soliman *et al.* (1994); [s]Al-Amoudi *et al.* (1992); [t]Shiau and Hsu (1995); [u]Shiau and Hsu (1999); [v]Shiau and Hwang (1993); [w]O'Connell and Gatlin (1994); [x]Shiau and Shiau (2001); [y]Roem *et al.* (1990c); [z]Satoh *et al.* (1987).

thiamine, riboflavin, pyridoxine, vitamin B_{12}, niacin, biotin, choline, pantothenic acid and ascorbic acid. Thiamine deficiency signs observed in red hybrid (*O. mossambicus* × *O. niloticus*) fingerlings cultured in sea water (32 p.p.t. salinity) were reduced growth and diet efficiency and a low haematocrit. A dietary thiamine level of 2.5 mg kg^{-1} diet was sufficient for maximum growth and prevention of deficiency signs (Lim and LeaMaster, 1991). Typical deficiency signs reported for tilapias fed a riboflavin-free diet were anorexia, poor growth, high mortality, fin erosion, loss of normal body colour, short body dwarfism and lens cataracts. The dietary riboflavin requirements were 6 mg kg^{-1} diet for juvenile *O. aureus* grown in fresh water (Soliman and Wilson, 1992b) and 5 mg kg^{-1} diet for red tilapia (*O. mossambicus* × *O. niloticus*) grown in 32 p.p.t. sea water (Lim *et al.*, 1993).

Fish fed a diet without pyridoxine supplementation developed abnormal neurological signs, anorexia, convulsions, caudal fin erosion, mouth lesions, poor growth and high mortality. Weight gain and hepatic alanine aminotransferase activity analysed by broken-line regression indicated that the optimum dietary pyridoxine requirements in juvenile *O. niloticus* × *O. aureus* reared in fresh water were 1.7–9.5 mg kg^{-1} diet and 15.0–16.5 mg kg^{-1} diet containing 28% and 36% protein, respectively (Shiau and Hsieh, 1997). A dietary pyridoxine level of 3 mg kg^{-1} diet was reported to be adequate for *O. mossambicus* × *O. niloticus* fed 38% protein diets and reared in sea water. Tilapias produced vitamin B_{12} in their gastrointestinal tract through bacterial synthesis and did not have a dietary requirement for this vitamin (Lovell and Limsuwan, 1982; Sugita *et al.*, 1990; Shiau and Lung, 1993).

Niacin is a dietary essential for the *O. niloticus* × *O. aureus* hybrid but the level required varies depending on the source of dietary carbohydrate. Optimum dietary levels for maximum growth have been reported to be 26 mg kg^{-1} diet for fish fed a glucose diet and 121 mg kg^{-1} diet for fish fed a dextrin diet. Fish deprived of dietary niacin developed haemorrhages, a deformed snout, gill oedema and skin, fin and mouth lesions (Shiau and Suen, 1992). The dietary biotin requirement for maximal growth of *O. niloticus* × *O. aureus* has been estimated to be 0.06 mg kg^{-1} diet (Shiau and Chin, 1999). While it was suggested that a high level of dietary methionine may have partially satisfied choline requirement in *O. aureus* (Roem *et al.*, 1990a,b), Shiau and Lo (2000) recently established that the optimal dietary choline requirement for *O. niloticus* × *O. aureus* was 1000 mg kg^{-1} diet.

Pantothenic acid deficiency causes poor growth, haemorrhage, sluggishness, high mortality, anaemia and severe hyperplasia of the epithelial cells of gill lamellae in *O. aureus*. A dietary level of 10 mg of calcium-pantothenate kg^{-1} diet was sufficient to prevent these deficiency signs (Soliman and Wilson, 1992a). Roem *et al.* (1990b) reported that *O. aureus* could satisfy their requirement for pantothenic acid by feeding on bacteria in a recirculating system.

Tilapias showed classical vitamin C deficiency signs when fed a vitamin-deficient diet in the absence of natural foods. The requirement for normal growth of *O. aureus* has been reported to be 50 mg ascorbic acid kg^{-1} diet (Stickney *et al.*, 1984). In juvenile *O. niloticus* × *O. aureus*, a dietary level of 79 mg ascorbic acid

kg^{-1} diet is needed for maximum growth (Shiau and Jan, 1992). A recommended dietary vitamin C inclusion level for *O. niloticus* is 420 mg kg^{-1} diet (Soliman *et al.*, 1994). In all these studies, L-ascorbic acid was used as the source of vitamin C. L-Ascorbic acid (C1) is unstable and most of its activity in practical diets is lost during processing and storage. Shiau and Hsu (1993) found that about 75% of the initial amount of supplemented C1 in aquatic diets can be lost during processing and storage at ambient temperature. Because of the unstable nature of C1, the use of more stable forms of ascorbic acid is necessary. Several derivatives of C1 have been shown to have antiscorbutic activity for tilapia. L-Ascorbyl-2-sulphate (C2S) has been shown to have equal antiscorbutic activity to L-ascorbyl-2-monophosphate-magnesium (C2MP-Mg) for *O. niloticus* × *O. aureus*. The optimum dietary level is 41–48 mg of C2S kg^{-1} diet and 37–42 mg of C2MP-Mg kg^{-1} diet (Shiau and Hsu, 1995). The optimum dietary L-ascorbyl-2-monophosphate-sodium (C2MP-Na) for *O. niloticus* × *O. aureus* is 63.4 mg kg^{-1} diet. It was suggested that C2MP-Mg is about 85% as effective as C2MP-Na in meeting the vitamin C requirement for tilapia (Shiau and Hsu, 1999). The requirement for optimum growth of *Oreochromis spilurus* in sea water has been determined to be between 100 to 200 mg C2S kg^{-1} diet (Al-Amoudi *et al.*, 1992).

Available information on fat-soluble vitamins for tilapias concerns only vitamin D and E. The optimum vitamin D_3 (cholecalciferol) requirement for maximum growth of *O. niloticus* × *O. aureus* is 374.8 IU kg^{-1} diet (Shiau and Hwang, 1993). O'Connell and Gatlin (1994) reported that vitamin D_3 is not a dietary essential for *O. aureus*. Vitamin E-deficient *O. aureus* exhibited anorexia, reduced weight gain and diet efficiency, skin haemorrhages, impaired erythropoiesis, muscle degeneration, ceroid in liver and spleen and abnormal skin coloration. The dietary vitamin E requirement increased with increasing levels of dietary lipid. The requirement of *O. aureus* was estimated at 10 mg and 25 mg D,L-α-tocopheryl acetate kg^{-1} diet in diets containing 3% and 6% dietary lipid, respectively, or 3–4 mg α-tocopheryl acetate for each per cent of dietary lipid (Roem *et al.*, 1990c). The dietary vitamin E requirement of *O. niloticus* was reported to be 50–100 mg kg^{-1} diet for a diet containing 5% lipid, increasing to 500 mg kg^{-1} diet for a diet containing 10–15% lipid (Satoh *et al.*, 1987). Recently, tilapia has been shown to require both n-3 highly unsaturated fatty acid and n-6 fatty acid for maximal growth (Chou and Shiau, 1999). Consequently, the vitamin E requirement of tilapia has been re-evaluated to be 42–44 mg kg^{-1} and 60–66 mg kg^{-1} in 5% and 12% lipid diets, respectively (Shiau and Shiau, 2001). No studies have been conducted on the requirements of vitamin A and K for tilapias.

There is little information on mineral requirements of tilapias. Five minerals – namely, calcium, phosphorus, magnesium, zinc and potassium – have been quantified for their requirements in tilapias (Table 20.6). In low-calcium water, supplementation of 7.0 g (0.7%) calcium and 5.0 g (0.5%) phosphorus kg^{-1} diet are required for normal growth and bone mineralization of *O. aureus* (Robinson *et al.*, 1984, 1987). The requirement of phosphorus for maximum growth and normal bone mineralization for *O. nilotica* was reported to be less than 0.9% in the diet (Watanabe *et al.*, 1980). For *O. aureus*, levels of 0.05% magnesium (Reigh *et al.*, 1991) and 0.002% zinc (McClain and Gatlin, 1988) are needed for optimum growth, whereas requirements of 0.059–0.077% magnesium (Dabrowska *et al.*, 1989) and 0.003% zinc (Eid and Ghonim, 1994) were reported for *O. niloticus*. The dietary potassium requirement for *O. niloticus* × *O. aureus* is about 0.2–0.3% (Shiau and Hsieh, 2001). Dietary levels of 0.0012% manganese and 0.0003–0.0004% copper were recommended for *O. niloticus* (Watanabe *et al.*, 1988). However, the quantitative data on the requirement of these two minerals are not available.

Practical Diets

Tilapia have been successfully cultured on diets prepared for other species, such as carp and catfish. The practical formulations commonly consist of only three or four feedstuffs, mainly of plant origin. Commercial diets formulated for tilapia usually contain 24–28% protein. Natural pond foods contribute a significant amount of protein, so this level is assumed to be high enough (Lim, 1989). However, few pond studies have been conducted to compare various diet formulations for semi-intensive and intensive culture of tilapias. A 25% protein pellet composed of 15% fish-meal, 20% soybean meal, 20% ground wheat and 45% ground sorghum has been used successfully in Israel in this type of production (Viola and Arieli, 1983). The importance of micronutrient supplementation in pond diets for tilapia is not well known. Due to the extreme variation in the culture practices used, formulation of practical diets to efficiently supplement the nutrient contribution of the natural food is practically impossible. In intensive culture, such as in raceways or cages, tilapia rely solely on the prepared diets as a source of nutrients. Thus, a nutritionally complete diet containing all essential nutrients is required.

Tilapia accept a variety of diets, in meal form and in moist, sinking and floating pellets. Crude feedstuffs, such as rice bran, are offered in meal form, whereas the compounded diets are most often processed into pellets. Crude feedstuffs may be uneconomical when pelleted for pond feeding of tilapia; however, high-quality

Table 20.6. Mineral requirements of tilapia.

	Requirement of diet (% of diet)		
Minerals	*O. aureus*	*O. niloticus*	*O. niloticus* × *O. aureus*
Ca	0.7[a]	–	–
P	0.5[b]	< 0.9[c]	–
Mg	0.05[d]	0.059–0.077[e]	–
Zn	0.002[f]	0.003[g]	–
K	–	–	0.21–0.33[h]

[a]Robinson *et al.* (1984); [b]Robinson *et al.* (1987); [c]Watanabe *et al.* (1980); [d]Reigh *et al.* (1991); [e]Dabrowska *et al.* (1989); [f]McClain and Gatlin (1988); [g]Eid and Ghonim (1994); [h]Shiau and Hsieh (2001).

diets should be processed into pellets to minimize ingredient separation, selective feeding on a single ingredient, loss of water-soluble nutrients and waste.

Tilapia seem to prefer smaller pellets than channel catfish and salmonids of comparable size. Recommended pellet sizes for tilapias are available (Jauncey and Ross, 1982). For feeding tilapias to a marketable size of 500 g, the most common pellet size is approximately 3–4 mm in diameter and 6–10 mm in length. Diets in meal or crumble forms are used for fry and fingerlings. These are made by first pelleting or extruding the diet mixture and then reducing the particles to a desirable size by crumbling.

Feeding Practices

It is generally recognized that smaller fish consume more diet on a per cent weight basis than larger fish. Suggested feeding rates for different sizes of tilapias are given in Table 20.7. Water temperature influences the metabolic rate and energy expenditure, thus having profound effects on the feeding rate. Tilapia will consume less diet in cold weather than in warmer weather. Luquet (1991) suggested that feeding tilapia should be stopped at a water temperature below 16°C. In semi-intensive culture systems, natural food can make a significant contribution to the nutrient requirements of fish. Under these conditions, the amount of diet used should be less than that for fish grown under intensive systems.

Since there are many factors that influence diet consumption of fish, satiation feeding (feeding as much as the fish can eat) may be a better alternative to feeding a prescribed amount based on the percentage of fish biomass. Clark, J.H. *et al.* (1990) obtained maximum growth of Florida red tilapia *Oreochromis urolepis hornorum* × *O. mossambicus* reared in marine cages at feeding rates near satiation (90%). Diet cost, however, could be reduced without significant growth reduction by feeding at 70% of satiation.

Diets are offered to fish by hand, blower, automatic feeder or demand feeder. Hand-feeding is labour-intensive but has advantages over other methods of feeding in that it allows the feeder to observe feeding activity and behaviour and thus to regulate the amount of diet fed to prevent overfeeding. However, this method of feeding is not feasible in large commercial farms. The most common method of feeding with large ponds is blowing the diet on to the water surface

Table 20.7. Feeding rate and frequencies for various sizes of tilapia at 28°C (from Lim, 1997).

Size	Daily feeding rate (% of body weight)	Daily feeding frequency
2 days old to 1 g	30–10	8
1–5 g	10–6	6
5–20 g	6–4	4
20–100 g	4–3	3–4
> 100 g	3–2	2–3

using mechanical devices that are either mounted on or pulled behind vehicles. Automatic feeders, driven by time-clock or electrical devices, allow farmers to preset the amount of diet to be fed at various time intervals. Demand feeders consist of a hopper with a top opening for loading the diet and a bottom opening, which serves as a movable gate for diet delivery. Attached to the gate is a rod whose tip extends down into the water, where it can be activated by the fish. As long as the fish continue to hit the rod, diet will continue to flow out. Clark J.H. *et al.* (1990) indicated that the demand feeder may prove to be the best method for feeding tilapia in marine cages as it provides good growth and feed conversion with reduced labour.

Frequency of feeding varies with fish size. Feeding frequency decreases as the fish grows (Table 20.7). Feeding three to four times per day is common for smaller fingerlings but decreases to two to three times per day for grow-out. Because of the continuous feeding behaviour and smaller stomach capacity, tilapias respond better to more frequent feeding than do channel catfish and salmonids. *Oreochromis niloticus* fingerlings grew faster when fed four times a day than when fed twice a day but did not grow faster when fed eight times a day (Kubaryk, 1980).

Acknowledgements

I wish to thank my graduate students, Min-Hsien Lee, Ming-Hsun Wu, Yu-Hung Lin, Shih-Ying Huang, Yu-Ming Lin, Yi-Ting Wang and Li-Wen Su, for their valuable assistance during the preparation of this chapter.

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