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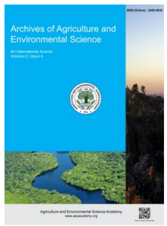

REVIEW ARTICLE

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Alternative protein sources as a replacement of fish meal in the diet of *Oreochromis niloticus*: A review

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ABSTRACT

The farming of Tilapia (*Oreochromis niloticus*) has conquered the significant popularity in tropical and subtropical regions, primarily due to its remarkable faster growth rate. The growth performance of the species makes it an attractive choice for many fish farmers. Additionally, Tilapia exhibits a commendable resilience to disease, further enhancing its appeal as a farming option. Furthermore, the low trophic feeding levels of Tilapia contribute to its desirability, making it an efficient and sustainable choice for nutrition-conscious individuals. Due to the increasing prevalence of aquaculture production, there has been a significant surge in the demand for fishmeal. This particular protein source has relished the widespread popularity for many years and its demand has now more than doubled. The current growth rate of the aquaculture industry is outpacing the available fishmeal supplies, which are insufficient to meet the demand. According to scientific studies, it has been found that fishmeal can be effectively replaced with alternative sources without compromising the overall performance of the fish. This article presents a compelling case for the practicality of replacing fishmeal with alternative protein sources in the diet of Tilapia. These alternatives include terrestrial animal by-products, oilseed plants, single-cell proteins, and protein-rich plant derivatives. In order to mitigate the environmental impact of the fishmeal industry, it is crucial to implement measures that can effectively address this concern. Moreover, it is crucial to highlight the significance of these sources from a nutritional perspective. The blood meal, meat and bone meal are highly beneficial options for incorporating essential amino acids and protein into the diet of Tilapia. These alternatives offer a rich source of nutrients that can effectively replace fishmeal. The minerals instead of amino acids could improve plant protein performance. Due to inconsistent findings, aquatic plants and single-cell proteins in Tilapia meals should be carefully considered. Fishmeal replacers need biological and economic analyses. Long-term evaluations should be done in practical culture systems rather than labs. In conclusion, it is imperative for Tilapia producers to contemplate the utilization of alternative dietary sources, as extensive research has demonstrated the scientific feasibility of substituting the fishmeal in the diet of Tilapia.

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INTRODUCTION

Over the last two decades, aquaculture has grown exponentially due to production system intensification and high-quality diets for farmed fish (FAO, 2006). In 2020, world fisheries and aquaculture production were 178 million tons, largely from aquaculture (FAO, 2020). There is a need to boost aquatic animal production in aquaculture (Rahman *et al.*, 2013). *Oreochromis*, *Sarotherodon* and Tilapia are all Cichlidae fish (Santiago and Laron, 2002). *Oreochromis aureus*, *niloticus*, and *mossambicus* are Tilapia species. After carps, Tilapia is favorite cultured fish in the country (Dan and Little, 2000; El-Sayed, 2006; Miles and Chapmen, 2009). The culture of Tilapia started as early as 2000 – 2500 BC (Chimits, 1957). Since then, the growth trend of cultured *O. niloticus* has increased consistently. Today, more than 22 Tilapia species are grown in tropical and subtropical locations, with a variety of Tilapia products in markets (Avnimelech, 1999; Fitzsimmons, 2000; El-sayed, 2002). The cultural and religious prohibitions on Tilapia consumption are not reported worldwide (Fitzsimmons, 2000). Tilapia growth is attributed to high resistance to diseases, ability to survive at low oxygen tensions and ability to feed on wide range of foods. Nile Tilapias are inexpensive to feed because of their low trophic feeding level. Tilapia can also tolerate larger nutritional fiber and carbohydrate concentrations than most other farmed fish (El-Sayed and Teshima, 1992). The successful production of Tilapia requires a balanced feed to maximize yield and growth at low expense. Although Tilapia species vary slightly, nutritional requirements are mostly based on fish size (El-Sayed and Teshima, 1992).

Demand and cost of fish feed

According to the Food and Agriculture Organization (FAO, 2020), there has been a significant global increase in the price of fishmeal in recent years. According to Tacon and Metian (2008), there was a notable increase in the consumption of fishmeal for Tilapia. The economic sustainability of numerous small-scale farmers has been significantly influenced by the stagnating prices at which aquaculture products are sold directly from the farm, despite the concurrent increase in the costs of fish feed (Rana *et al.*, 2009). The global fish farming industry has faced challenges in accessing aqua-feeds due to the increasing expenses associated with feed components such as fishmeal, fish oil, and cereal, as well as energy and transportation costs. Rola and Hasan (2007) argue that this global phenomenon has the potential to induce small-scale producers to alter their business activities, potentially resulting in poverty, vulnerability, and the loss of their means of subsistence. Protein is identified as the expensive component of fish diets, hence being the primary contributor to operational expenses in the field of aquaculture (Munguti *et al.*, 2012). Tacon (1993) asserts that fish meal (FM) is the expensive protein source employed in the context of aquaculture feeding. According to Aladetohun and Sogbesan (2013), fish require a substantial quantity of protein in their diet due to their reliance on protein as an energy source. FM has historically been utilized as the predominant protein source in the formulation of commercial aqua-feeds due to its elevated protein content and a balanced profile of essential amino acids (EAAs) (Abdel-Tawwab and Ahmad, 2009; Tacon, 1993; Watanabe, 2002; El-sayed and Gaber, 2004; Chen *et al.*, 2013). The use of fishmeal in aquaculture has experienced a significant increase in comparison to other species, whereas extruded diets have been observed to possess a higher cost compared to pelleted diets. Despite the growth of the aquaculture industry, the production of fishmeal and fish oil has exhibited a rather consistent trend internationally and is presently experiencing a declining trend (Tacon and Metian, 2008).

The fishmeal dilemma

Jacquet *et al.* (2010) reported that a significant proportion, specifically up to 36%, of the yearly worldwide fisheries harvest is utilized in the production of fishmeal and oil, mostly for the purpose of feeding farmed aquatic species, poultry, and swine. In the absence of a paradigm change towards the incorporation of non-fisheries resources in the production of fish feed, the increasing consumption of fishmeal (FM) and declining wild fish captures present a pessimistic outlook for the aquaculture industry. It is anticipated that aquaculture would see growth in the forthcoming two decades, leading to an increase in the demand for fishmeal (FM) and fish oil. The potential consequence of this action is an escalation in the fishing effort exerted on wild fish populations, which are already facing a precarious situation (Aladetohun and Sogbesan, 2013). The use of fish resources for feed production is concurrently rising alongside the rate at which fish is consumed as a dietary source by people. The shortage in the global supply of FM, along with the growing demand and competition from both human and animal consumption, has resulted in a surge in FM prices. This price increase has had adverse consequences on the aquaculture industry (Watanabe, 1988). The rapid decline of global fisheries and the concurrent rise in aquaculture production have sparked significant discourse over the sustainability of feeding fish with fishmeal (FM). The aforementioned predicament necessitates immediate attention from both aquaculturists and environmental ecologists.

Tilapia substitutes fishmeal

For aquaculture to be sustained, an alternate feedstock to FM is required (Olukayode and Emmanuel, 2012). We must use locally available feedstuff, especially agricultural by-products, to reduce the cost of feeds for fish aquaculture (Fagbenro, 1999). Due to the escalating expense of conventional Tilapia feeds, producers are looking for alternative feeds to make aquaculture a profitable and desired enterprise (El-sayed, 1998; Fasakin *et al.*, 1999; Hossain, 2002). Tacon *et al.* (1983) not only established a number of substitute protein sources for FM in Tilapia diets but also established the essential nutrients for FM and a method for incorporating them into the substitutes. For optimal growth and development, warmwater fishes need both n-6 and n-3 fatty acids, while cold-water fishes need only n-3 (Takeuchi, 2008). Although optimal utilization of fish resources (trash fish) and exploitation of underutilized ocean resources like Antarctic krill have been suggested, terrestrial animal diets and protein-rich plant derivatives may be the best alternative (Tacon and Metian, 2008). Single-cell proteins, earthworms, insects, snails, maggots, and frogs are alternatives to fish meal (Tacon *et al.*, 1983).

However, economic research is needed for their sustainable production and aquaculture usage. For the replacement of FM in Tilapia feeds, it is important to establish if these alternatives can totally replace FM without reducing productivity (El-Sayed and Tacon, 1997). Aquaculture nutritionists, fish biologists, and fish producers have discussed this topic, albeit with little agreement. According to Jackson's (2009) Fish in- Fish out (FIFO) ratio concept, which reveals only 0.3 kg of FM is required to produce 1kg of tilapia. This suggests that FM replacement in its entirety could become a scientific reality. Below, we discuss the feasibility of using comprehensive FM substitutes in Nile tilapia grow-out diets. In addition, their nutritive qualities, accessibility, and economic viability have been emphasized.

Animal meals

The main terrestrial FM alternatives for Tilapia are chicken by-product meal (PBM), feather meal (FeM), blood meal (BM), and meat and bone meal (MBM). They lack lysine, methionine, and isoleucine, despite their high crude protein concentration (Tacon and Jackson, 1985). The Mixing complementary protein by-product meals yields the desired EAA composition (Davies *et al*., 1989). Animal proteins are inexpensive and widely available, making them potential FM replacements for Tilapia in developing nations (El-Sayed, 1999).

Blood meal (BM)

The formulation of fish feed may benefit from the addition of BM, which is a product derived from animal waste that is easily accessible and may be substituted for expensive protein sources. According to Dominy and Ako (1988), BM products can successfully replace marine proteins in the diets of prawn (*Pannaeus vannamei*) grow-out rations if they are given an additional dose of methionine. After seven weeks of feeding *O. mossambicus* (Mozambique Tilapia) larvae with BM, Davies *et al.* (1989) discovered that up to 75% of the FM in the diets could be adequately replaced by BM. This was the result of their experiment. Otubisin (1987) conducted an experiment in which caged *O. niloticus* fingerlings were fed BM for a period of 120 days. He concluded that including amounts of BM in the diet that exceeded 50% of the FM protein significantly affected fish performance. El-Sayed (1998) also discovered that BM used as the primary protein source in practical diets for Nile Tilapia reared in outdoor concrete tanks for 150 days decreased fish performance. It is absolutely necessary to acknowledge the significance of management elements such as the frequency of feedings, the state in which animals are raised, and other environmental factors. According to Agbebi *et al.* (2009), BM can totally replace fish meal in the diet of juvenile Nile Tilapia and *Clarias gariepinus* without having an impact on the ability of fishes to develop, survive, or convert their food into energy. According to the findings of Hussain *et al.* (2011), the nutrient digestibility values of FM and BM for dry matter and crude fat are essentially similar for the majority of Tilapia fish species. As a result, BM can be utilized as an ideal replacement for FM in diets. According to the findings of the study that was conducted by Aladetohun and Sogbesan (2013), the incorporation of BM into the experimental diet resulted in an increase growth of Tilapia (Table 1). The growth performance metrics for experimental feeding with varied percentage of BM inclusion has shown in Table 1. The authors believe that this may be an underutilized asset that has the potential to be employed in the formulation of fish diets that have the highest profit margins and the lowest manufacturing costs. However, in order to address the possibility of disease transmission from cattle to fish and humans, it is recommended that additional research be conducted about the technique for the formulation of BM feed.

Table 1. Growth and feed utilization of Nile Tilapia (*O. niloticus*) fed with different level inclusions of blood meal (BM) according to Aladetohun and Sogbesan (2013).

Parameter	0% BM	50% BM	100% BM
Experimental days	84	84	84
No of fish stocked	20	20	20
Initial average weight (g)	6.20	6.26	6.15
Final average weight (g)	36.60	48.00	69.00
Average weight gain (g)	24.20	41.74	62.85
Mean weight gain/day (g)	0.29	0.50	0.75
Average weight gain/weekly	2.02	3.48	5.24
Mean weight gain/biweekly	4.40	6.96	10.47
Specific growth rate (SGR)	0.93	1.06	1.27
Total feed intake (g)	8.30	10.14	13.96
Feed conversion ratio (FCR)	0.34	0.24	0.22
Protein intake	2.92	3.49	5.20
Protein efficiency ratio (PER)	56.76	58.38	53.4
Survival (%)	100	100	100

Table 2. Proximate and amino acids composition of meat and bone meal (MBM), poultry by-product meal (PBM) and fish meal (FM) courtesy of Yang *et al.* (2004).

	MBM	PBM	FM
Crude protein %	50.0	58-65	64.6
Crude fat %	10.0	12.0	7.9
Calcium %	8.8	4.0	3.93
Phosphorus %	4.0	2.0	2.55
Ash	25-35	10-18	16.0
Gross Energy (Kcal/kg)	3850	4900	4500
Arginine	3.25	3.94	3.68
Histidine	0.84	1.25	1.56
Isoleucine	1.55	2.01	3.06
Leucine	2.99	3.89	5.00
Lycine	2.6	3.32	5.11
Methionine	0.63	1.11	1.95
Phenylalanine	1.63	2.26	2.66
Threonine	1.75	2.18	2.82
Tryptophan	0.28	0.48	0.76
Valine	2.16	2.51	3.51
Crystine	0.41	0.66	0.61
Tyrosine	1.34	1.56	2.15

Meat and bone meal (MBM)

Due to its high protein digestibility and well-balanced amino acid profile, MBM is an excellent supplemental protein, calcium, vitamin B12, and phosphorus source for most fish (Table 2). The meat and bone meal are a by-product of the animal rendering process, is more affordable than FM but more expensive than BM. The MBM has more minerals and fewer amino acids than FM and BM (Yang *et al.*, 2004). However, it is possible that raw material composition and quality variances are mostly to blame for the commonly observed variations in content of these protein meals. In addition to Rainbow Trout (Bureau *et al.*, 2000), Red Drum (Kureshy *et al.*, 2000), Australian Snapper (Quartararo *et al.*, 1998), and Nile Tilapia (Fasakin *et al.*, 2005), MBM has been used effectively in the diets of a variety of other fish species. MBM can partially or entirely replace FM at levels ranging from 5% to 15%, according to studies (Kellems *et al.*, 1998). However, the ash concentration may limit its application in fish feeds (Fasakin *et al.*, 2005). In diets containing 45% crude protein provided to *O. niloticus* fry for six weeks, Tacon *et al.* (1983) found that MBM supplemented with methionine efficiently substituted up to 50% of FM protein. After seven weeks of feeding, El Sayed and Tacon (1997) found that MBM could replace up to 75% of the FM in the diets of *O. mossambicus* larvae. Even at a 1:1 substitution level, El Sayed and Tacon (1997) found that diets rich in MBM or high MBM/BM ratios outperformed FM. The growth of Tilapia is unaffected by MBM's estimated 10% reduced protein and energy digestibility compared to FM (Table 2), therefore it may be an acceptable replacement for FM (Yang *et al.*, 2004). However, some countries have banned the feeding of MBM due to concerns of disease transmission, and others only permit the feeding of MBM obtained from ruminant animals (European Community, 2002). Furthermore, the MBM as a fish feed element may be threatened by the heavy competition from people. Hanley (1987), Smith *et al.* (1995), and Harding (1996) have all pointed out that there may be a need to limit MBM use because of water quality problems.

Poultry by-product meal

Poultry by-product meal (PBM) is comprised of pulverized, rendered, or sanitized remnants of poultry carcasses. The various species of fish, including Salmon (Yang *et al.*, 2004), Tilapia (El-Sayed, 1998), Sea Bream (Nengas *et al.*, 1999), Channel Catfish (Sadiku and Jauncey, 1995a), and Common Carp (Hasan *et al.*, 1993), have been subjected to experimentation including PBM, yielding varied levels of achievement. PBM has compositional similarities to FM, with the notable distinction of having a reduced number of amino acids (Table 2) (Yang *et al.*, 2004). Generally, FM (fish meal) and PBM (poultry by-product meal) exhibit high digestibility rates for both protein (88%) and energy (82%). According to the study conducted by Yang *et al.* (2004), the digestibility values imply that PBM has the potential to be effectively incorporated into aquafeeds at a comparable level to that of FM. Based on the findings of proximate analysis as presented in Table 2, it can be observed that the protein, lipid, calcium, and phosphorus compositions of PBM are similar to those of FM. This suggests that PBM has the ability to serve as a viable substitute for FM. According to the findings of El-Sayed (1998), it was determined that both Red Tilapia and Nile Tilapia have the ability to effectively utilize PBM (poultry by-product meal) as a primary source of protein. In their study, Belal *et al.* (1995) conducted an experiment to assess the potential of chicken offal silage (COS) as a substitute for fish meal (FM) in the diets of fingerling *O. niloticus*. The researchers varied the inclusion levels of COS from 0% to 20% in the experimental diets. It was determined that the growth and body composition of fish fed with COS were similar to those of fish fed with FM. In a similar manner, Gaber (1996) conducted a study wherein it was observed that the growth of Nile Tilapia fingerlings, when provided with PBM as a substitute protein source for FM at a level of up to 40%, exhibited improved results compared to those fed with 100% FM. Hence, it is plausible to consider that PBM has the potential to entirely substitute FM in the dietary composition of Nile Tilapia. Aquaculture nutritionists should pay attention to this observation as it presents a noteworthy aspect worthy of consideration. However, it is imperative to prioritize increased research endeavors on the sustainable utilization of PBM, especially in underdeveloped countries.

Feather meal (FeM)

According to Munguti *et al.* (2014), the presence of the complex protein keratin in FeM has the ability to endure hydrolysis, thereby increasing its bioavailability. Poppi *et al.* (2011) assert that FeM is a protein component that is extensively utilized in aqua-feeds due to its low cost. According to research conducted by Fowler (1990), FeM has a high concentration of amino acids, including cystine, threonine, and arginine. Additionally, FeM contains a substantial quantity of protein that has been digested by pepsin. Fowler (1990) asserts that the amino acid composition observed in FeM exhibits similarities to that of FM and soybean meal. Several species of fish, including Prawns (Fowler, 1990; Steffens, 1994; Bureau, 2000), Salmon, and African catfish, have previously been subjected to FeM feeding (Fowler, 1990). The utilization of FeM in fish meals is limited due to the presence of a complex protein called keratin (Steffens, 1994). The commercial viability of including hydrolyzed FeM protein into the diet of Tilapia is a plausible prospect. Nevertheless, previous studies investigating the utilization of hydrolyzed FeM in fish meals suggest that it is advisable to employ it at lower substitution rates owing to its limited digestibility and inadequate amounts of crucial amino acids (Steffens, 1994; Mendoza *et al.*, 2001). The research has revealed that the incorporation of hydrolyzed FeM and papaya leaf meal (PLM) has the potential to enhance the nutritional quality of FeM, hence facilitating its utilization in the formulation of Nile Tilapia diets. Furthermore, previous research has demonstrated that the substitution of FM with hydrolyzed FeM dietary levels and PLM does not have a significant impact on the growth of Nile Tilapia when they are raised in cage systems (Munguti *et al.*, 2014). Based on the research conducted by Arunlertaree and Moolthongnoi (2008), it was determined that fermented FeM has the potential to serve as a substitute for FM in a Nile Tilapia diet with a CP content of 30%. The recommended utilization levels of fermented FeM range from 25% to 50%.

Compounds plants rich protein

According to Hardy (1996), plant proteins are digested similarly to FM in terms of protein and amino acids. In contrast to FM, however, their amino acid composition does not meet the requirements of certain fish species (Hardy, 1996). Methionine is scarce in soybean meal (SBM), whereas lysine is absent from maize gluten meal (Gallagher, 1994). The wheat gluten meal studied by Gallagher in 1994 contained low levels of lysine and arginine. Many plant materials are objectionable due to the presence of antinutritional compounds and inadequate bioavailability (Francis *et al.*, 2001). In nutrition research, plant protein has supplanted animal protein (Liti *et al.*, 2006). According to Gallagher (1994), certain plant proteins contain phosphorus phytate, which bonds phosphorus, reduces the palatability of food, and inhibits the absorption of divalent trace elements. However, the growth of Catfish, Tilapia, and Carps was unaffected by plant-based feeds containing soybean meal protein, canola meal, extruded pea seed meal, wheat, and maize meal supplemented with lysine and methionine (Tacon and Metian, 2008).

Soybean meal (SBM)

The soybean meal (SBM) is currently regarded as the best plant-derived protein source based on the protein content data in Table 3 and the essential amino acid (EAA) composition. The scientists have conducted research on the possible use of SBM as a partial or complete replacement for fishmeal in Tilapia diets. However, the results of these studies have been inconclusive. El Sayed (1999) states that the possible substitution of fish meal (FM) with soybean meal (SBM) in fish diets varies depending on factors such as fish species, protein content in the diet, source and processing methods of SBM, and the specific culture system applied. The range of potential substitution might be anywhere from 67 to100% of FM. According to Shiau *et al.* (1989), the substitution of up to 75% of fishmeal (FM) with soybean meal (SBM) in experimental diets for Nile Tilapia fry was accomplished satisfactorily. This finding implies that the addition of the essential amino acid (EAA) that is deficient in SBM may have a negligible impact. The investigation was carried out under two conditions: one with the inclusion of methionine in the diet, and the other without. The investigation conducted by Viola and Zohar (1984) revealed that the inclusion of crystalline EAA in the diets of Nile Tilapia did not yield any discernible enhancement in the performance of the fish. According to El Sayed (1999), it can be inferred that minerals, rather than essential amino acids (EAA), could potentially serve as the constraining factors in the optimal utilization of soybean meal (SBM) for Tilapia. The efficient utilization of soybean meal (SBM) for Tilapia may be constrained by minerals as limiting factors. In their study, Viola *et al.* (1988) found that the growth of Tilapia hybrids (*O. niloticus* x *O. aureus*) fed a diet comprising 100% solid biological material (SBM) supplemented with lysine, methionine, oil, and di-calcium phosphate was similar to that of fish fed a diet consisting entirely of fish meal (FM). Furthermore, the absence of the limiting essential amino acid (EAA) to soybean meal (SBM) diet did not yield any discernible impact on the growth of Tilapia. Moreover, the substitution of fish meal (FM) with SBM supplemented with 3% di-calcium phosphate and oil resulted in complete replacement without any adverse consequences on the growth of Tilapia, as observed in the study conducted by Viola *et al.* (1988). The growth of Blue Tilapia was found to be severely inhibited by the inclusion of soybean meal (SBM) in meals with a protein content of 15%, as observed by Davis and Stickney in 1978. Nevertheless, it was shown that diets comprising 36% protein had the capability of substituting fish meal (FM) entirely with soybean meal (SBM) without inducing noteworthy impairments in growth. There exists a scholarly debate among academics over the suitability of SBM as a protein source for fish.

Table 3. Proximate composition of selected terrestrial plant products. Source: FAO (2006).

	Average composition (% by weight)					
Cereal by-products	**Water**	**Crude protein**	**Crude fibre**	**Ash**	**Calcium**	**Phosphorus**
Brewers' grains	8.4	25.9	14.3	4.3	0.36	0.44
Distillers dried grains	8.2	27.1	11.2	3.8	0.13	0.57
Corn gluten meal	8.6	56.1	2.9	2.1	0.15	0.44
Wheat gluten meal	8.7	80.3	0.3	0.9	0.22	0.10
Rice protein meal	7.5	52.0	1.5	2.6	-	-
Oil seed by-products						
Canola meal	10.0	35.0	12.0	6.1	0.63	1.08
Mustard meal	10.1	42.4	9.1	6.3	-	-
Rapeseed meal	8.5	37.4	4.7	7.0	0.62	1.0
Coconut oil meal	8.7	21.5	14.8	7.1	0.18	0.6
Cotton seed meal	10.0	32.9	21.8	6.0	-	-
Palm kenel meal	9.9	17.5	19.6	3.9	0.38	0.82
Sesame meal	7.6	45.0	6.7	13.0	2.33	1.29
Soybean meal	10.3	44.7	6.0	6.7	0.29	0.65
Sunflower meal	10.0	23.3	31.6	5.6	0.21	0.93
Legume meal						
Lentils	10.9	24.4	3.3	2.5	0.06	0.31
Pea meal	11.3	23.1	6.2	3.2	0.17	0.4

The potential cause of this difference could be attributed to various aspects, including the quality and processing of the soybean meal (SBM), as well as the specific fish species, their size, and the methods employed in their cultivation. Despite the presence of certain anti-nutritional components such as trypsin in soybean meal (El Sayed, 1999), it is feasible to produce high-quality animal feeds using thermal processing techniques (Tacon, 1993). The researchers Wassef *et al.* (1988) made the observation that the process of germination and de-fattening of soybean meal (SBM) leads to a decrease in the activity of protease inhibitors. Similarly, the application of heat to soybean meal (SBM) serves to reduce the presence of anti-nutritional factors and enhance the bio-availability of essential elements (Tacon and Jackson, 1985). The authors propose the integration of SBM (soybean meal) with grain protein concentrates as a means to alter the amino acid composition, thereby surpassing the limitations imposed by some plant proteins. Sadiku and Jauncey (1995a) proposed the integration of additional animal protein sources with soybean meal (SBM) to augment the nutritional composition for Nile Tilapia.

Previous research has confirmed that genetically modified soybean meal, commonly referred to as GM SBM, can serve as a reliable and secure protein source in fish feed (Suharman *et al.*, 2009). Based on a study conducted by Suharman *et al.* (2009), no significant differences were observed in the growth, survival, feed conversion, or fillet composition of Nile Tilapia that were provided with genetically modified soybeans or non-genetically modified sources of soybean meal, in comparison to fish that were fed non-genetically modified soybeans. As stated by Watanabe (2002), defatted soybean meal is widely acknowledged in both qualitative and quantitative terms, and exhibits a favorable amino acid profile in comparison to alternative plant protein sources. Defatted soybean meal is produced by a fat-free process. As stated by Watanabe (2002), soybean meal exhibits consistent availability, is economically viable, and has been found to be widely accepted by a majority of fish species. Given these benefits, it is imperative for nutritionists involved in aquaculture to strive towards the full replacement of fishmeal (FM) with soybean meal (SBM) as a protein source. Multiple studies have demonstrated that substituting SBM is a highly promising alternative to FM (Watanabe, 2002).

Cotton seed meal (CSM)

The protein content and amino acid composition of cotton seed meal can be influenced by the processing techniques (Table 3). Nevertheless, it should be noted that CSM exhibits a deficiency in the essential amino acids i.e., cysteine, lysine, and methionine, while also containing a significant amount of the antinutrient gossypol. This particular composition may impose some limitations on its suitability for inclusion in animal diets (El Sayed, 1999). Gossypol is a compound that exerts inhibitory effects on nutrition absorption. The application of CSM as a protein source for Tilapia has yielded diverse outcomes thus far. El-Sayed (1990) successfully employed prepressed solvent extracted CSM as an exclusive dietary protein source for Nile Tilapia, resulting in superior outcomes compared to fish fed with FM. In contrast, El-Sayed (1990) found that the growth rates of *O. niloticus* and *O. aureus* were significantly reduced when their diets were primarily composed of CSM as opposed to FM. The probable cause for this can be attributed to the presence of gossypol and cyclopropionic acids in CSM. Based on the research conducted by Viola and Zohar (1984), it was found that around 50% of the SBM in the diets of Tilapia hybrids cultivated in floating cages could be effectively replaced with CSM. According to the findings of El-Sayed (1987), it was determined that diets containing 80% CSM protein were found to be the most favorable for promoting the growth of *Tilapia zillii*. In their study, El-Sayed and Kawanna (2008) found that the utilization of CSC (42% CP) as the only feed source for Nile Tilapia, resulted in a notable increase in the fish's weight. In addition to the use of CSC as a protein source in commercial pelleted feeds for tilapia, it can be used as a source of fertilizer in semi-intensive tilapia culture to increase natural food production within fish ponds (El Sayed, 1999).

Other by-products derived from oilseed plants

There are numerous oilseed by-products that can be utilized to give Tilapia an alternative source of protein, including peanut, sunflower, rapeseed, sesame seeds, macadamia, and palm kernel. Despite their high protein content and favourable EAA profiles, there hasn't been sufficient research on their use as full FM replacements. Groundnut cake, sunflower meal, rapeseed meal, and copra meal may each replace 25, 75, 50%, and 75% of FM protein without significantly affecting the growth of *O. mossambicus*, according to research by Jackson *et al.* (1982). However, due to the high quantities of glucosinolate (an anti-nutrient) in rapeseed, Davies *et al.* (1989) found that only 15% of rapeseed meal could successfully replace FM in the diets of *O. mossambicus*, and higher levels led to poor growth. This resulted from the high glucosinolate content in rapeseed. Omoregie and Ogbemudia (1993) found that Nile Tilapia fingerling performance on a diet containing up to 60% palm kernel meal was equivalent to that of fingerling performance on a diet containing 100% FM. Macadamia press cake was successfully used as a protein source for Nile Tilapia by Fagbenro (1999). He found that the growth of Tilapia given a commercial 35.5% CP FM diet for 180 days was comparable to the growth of Tilapia fed 33.4% CP macadamia cake in concrete tanks. The low price of MC favors it as a promising alternative plant protein source for tilapia.

Aquatic plants

There exists a variety of aquatic plant species that possess the capacity to function as replacements for fishmeal in the field of aquaculture. However, previous studies conducted on the incorporation of aquatic plants into the diet of Tilapia have yielded uneven and occasionally conflicting findings. The growth rate of Nile Tilapia was significantly enhanced when *Azolla pinnata* was employed as a replacement for fish meal in the diet of both fingerlings and adult individuals. According to El-Sayed *et al.* (2000), fish that were provided with *Azolla pinnata* as a feed source exhibited significantly suboptimal performance even at the minimum inclusion level of 25%. This trend persisted throughout the entire substitution range, from 0% to 100%. This phenomenon was observed at all replacement levels. The study conducted by Micha *et al.* (1988) yielded comparable results when *Azola microphylla* was utilized as the nutritional substrate for *T. rendalli*. In contrast, Naegel (1997) found that dried *Azolla* meal was effective in replacing up to 30% of the FM diet provided to Nile Tilapia. In addition, Santiago *et al.* (1988a) conducted a study in which they found that a diet containing *Azolla pinnata* up to 42% resulted in higher growth rates for Nile Tilapia fry compared to the control diet consisting of FM. This was in contrast to the growth rates generated by the diet. According to a study by Mbagwu *et al.* (1990), raw duckweed, a member of the Lemnaceae family, is a highly nutritious option for feeding Tilapia. This is because of its high protein content, which ranges from 35 to 45%, and its favorable amino acid and mineral composition. The cultivation of Nile Tilapia in earthen ponds in Bangladesh using duckweed (Lemna and Wolffia) as the only nutritional input proved to be highly effective, resulting in a maximum yield of 7.5 metric tons/ha/year (Skillicorn *et al.*, 1993). In a study conducted by Takeuchi *et al.* (2002), it was found that raw Spirulina exhibits an EAA index value of 81, indicating its viability as a potential food source for larval Tilapia due to its satisfactory nutritional content. Based on the research conducted by Takeuchi *et al.* (2002), it can be inferred that ensuring a sufficient and suitable provision of Spirulina throughout the initial phases is crucial for the typical progression and maturation of Tilapia larvae. Nevertheless, further investigation within the scientific community is necessary to explore the feasibility of utilizing aquatic plants as a complete substitute for FM.

Table 4. Fish grown and yield coefficients of Tilapia fed with conventional pellets in 2 pond experiments for 51 days in courtesy of Avnimelech *et al.* (1989).

	Treatments	
	Conventional control (30%) protein)	**BFT Carbon enriched (20% protein)**
Feed C:N ratio	11.1	16.6
Fish weight (g/fish)		
Initial weight	112	112
Final weight	193	218
Daily gain	1.59	2.0
Mortality (%)	14.6	10.3
Feed conversion coefficient	2.62	2.17
Protein conversion coefficient	4.38	2.42

Table 5. Crude protein contents of some non-conventional potential feedstuffs for Nile Tilapia.

Ingredients	CP (%)	References
Maggot	43.8	Ugwumba *et al.* (2001)
Cotton seed cake	38.9	El-Sayed and Kawanna (2008)
Mucuna seed meal	32.1	Siddhuraju and Becker (2001)
Mango kernel meal	7.5-13.0	Joseph and Abolaji (1997)
Cassava peel	12.1	Oresegun and Alegbeleye (2001)
Pawpaw leaf meal	23.0	Reyes and Fermin (2003)
Dock weed	45.5	Mbagwu *et al.* (1990)
Earthworm meal	56.4	Tacon (1994)
Garden Snail	66.7	Sogbesan *et al.* (2006)

Single cell proteins (SCP)

The production and consumption of single-cell protein (SCP) by Tilapia in culture systems has garnered the interest of aquaculture nutritionists in recent times (El-Sayed, 1999; Avnimelech, 2007). SCP refers to a collection of microorganisms encompassing unicellular algae, fungi, bacteria, cyanobacteria, and yeast. According to Avnimelech (2007), the concept of a heterotrophic food web asserts that fish possess the capacity to obtain protein either through direct or indirect consumption of primary producers. Additionally, fish have the chance to engage in grazing activities on bacteria, which play a crucial role in the decomposition of leftovers within the pond environment. The major objective of the SCP is to facilitate nutrient recycling through the maintenance of an elevated carbon to nitrogen (C: N) ratio in the water. The purpose of this practice is to induce the proliferation of heterotrophic bacteria, commonly referred to as biofloc technology (Avnimelech *et al.*, 1989; Azim and Little, 2008). Biofloc technology is a process that facilitates the conversion of ammonia into microbial proteins. As a by-product, bacteria produce between 60-600 kg ha^{-1} day^{-1} of protein for fish (Avnimelech, 1999). The authors of the study agree that SCP produced using low-cost carbon and nitrogen sources has the potential to partially or completely substitute costly commercial protein sources in meals for *O. niloticus* (Dempster *et al.*, 1995). Based on the findings of Azim and Little (2008), the nutritional composition of SCP includes a protein content of 38%, fat content of 3%, fiber content of 6%, ash content of 12%, and an energy value of 19 KJ g-1. These nutritional components have been determined to be sufficient for the growth and development of Tilapia. Widanarni *et al.* (2012) conducted a study in which they conducted a proximate analysis of a biofloc sample obtained from a system in which Tilapia were fed with single-cell protein (SCP). The results of their analysis indicated the presence of potentially advantageous nutritional components. Widanarni *et al.* (2012) reported that the ideal dietary lipid of Tilapia needs falls within the range of 10 to 25%, with the biofloc constituting a similar proportion. Ogello *et al.* (2014) found that the values mentioned are really much higher compared to the bulk of commercial pellet diets commonly used in aquaculture. The experimental group of fish, which were fed a diet containing 20% crude protein (CP) derived from single-cell protein (SCP), exhibited significantly superior performance compared to the control group of fish, which were fed a diet containing commercial fishmeal (FM) with 30% crude protein (Table 4). Ogello *et al.* (2014) suggest that the enhanced protein utilization observed in fish reared in systems supplemented with single-cell protein (SCP) can be described to the dynamic recycling of proteins facilitated by microbial activity. This information undoubtedly provides valuable insights for farm management, particularly for those aiming to enhance protein recycling efficiency. Further investigation is necessary to ascertain the sustained feasibility of the SCP production systems, as well as the specific bacterial strains present inside them. Several authors have conducted research on a diverse range of viable alternatives to fishmeal (FM) for the development of Nile Tilapia (Table 5).

The FM alternatives' potential from an economic perspective

The assessment of FM substitutes in Tilapia diets has been concentrated on the biological and nutritional dimensions, with limited attention given to the economic considerations in the existing body of research. Although the results of the FM replacers were varied, a cost benefit analysis demonstrated that their utilization is the more financially advantageous choice. For example, a study conducted by El-Sayed (1990) examined the economic viability of using cotton seed meal, maize gluten feed, and animal by-product meal as protein sources for Nile Tilapia. The findings of this study indicated that these alternative protein sources exhibited high cost and profit indices compared to diets based on fish meal. The aforementioned protein sources were utilized as dietary protein sources for Nile Tilapia. In a study conducted by Aladetohun and Sogbesan (2013), the researchers aimed to assess the financial consequences associated with the substitution of FM with BM.

Conclusion and recommendations

The available evidence suggests that FM has the potential to be substituted with alternative protein sources from a technological standpoint. However, it is crucial to maintain an ideal balance of essential amino acids. Furthermore, it is imperative to prioritize the enhancement of nutritional availability and the optimization of the digestible protein to calorie ratio when considering alternate diets. This approach facilitates the efficacy of dietary interventions in promoting optimal health and fortifying the immune system, hence augmenting resistance against diseases. Aquaculture nutritionists want to contemplate the utilization of non-conventional dietary supplies that are readily accessible and cost-effective inside the locations of production. The numerous research has provided evidence about the feasibility of various alternative protein sources in the formulation of Tilapia diets. This study aims to assess the feasibility of replacing FM technology. Consequently, the authors reach the conclusion that FM can be entirely substituted in Tilapia diets. Nevertheless, it is imperative to apply the most effective management strategies for aquaculture.

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