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Fishmeal replacers for tilapia: A review

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SUMMARY - The paper highlights the growing importance of tilapia as a farmed *food fish* species over the coming decade; tilapia currently being the third largest group of farmed finfish species produced after the cyprinids and salmonids, with global tilapia production increasing three-fold since 1984 from 186,544 mt to 599,135 mt in 1994 (4.6% total finfish production and valued at US$ 835 million) and growing at an average compound rate of 12.4% per year. However, as with the majority of finfish species produced within intensive farming systems the development of commercial aquafeeds for these species has usually been based (although to a lesser extent than for carnivorous finfish species) upon the use of fishmeal as the main source of dietary protein. The paper consequently reviews the major studies and efforts which have been conducted to date concerning the dietary replacement of fishmeal within compound aquafeeds for tilapia with alternative protein sources or *fishmeal replacers*, including fishery and terrestrial animal by-product meals, oilseed meals and by-products, aquatic plants, single-cell proteins, and legumes and cereal by-products. In addition, the paper presents information on the nutritive value, dietary inclusion level, constraints, and cost-benefit of using the most promising fishmeal replacers, and also discusses some generalized approaches for conducting and reporting investigations on the development of fishmeal replacers.

Key words: Tilapia, aquafeeds, fishmeal replacers, feed ingredients.

RESUME *- "Remplacement des farines de poisson pour Tilapia : passage en revue". Cet article met en évidence l'importance grandissante du tilapia comme espèce piscicole pendant les prochaines dix années ; le tilapia se situe actuellement en troisième position parmi les espèces piscicoles après les cyprinidés et les salmonidés, avec une production globale de tilapia qui s'est multipliée par trois depuis 1984 en passant de 186.544 mt à 599.135 mt en 1994 (4,6% de la production piscicole totale, pour une valeur de US$835 millions) et augmente selon un taux moyen de 12,4% par an. Cependant, de même que pour la plupart des espèces piscicoles produites en systèmes intensifs, le développement des aliments commerciaux pour l'aquaculture destinés à ces espèces s'est normalement fondé (quoique à un degré moindre que pour les espèces de poissons carnivores) sur l'utilisation de farine de poisson comme principale source de protéine alimentaire. Cet article passe donc en revue les principales études et les efforts menés jusqu'à cette date concernant le remplacement des farines de poisson entrant dans les aliments composés pour tilapia, par des sources de protéine alternatives ou produits de remplacement des farines de poisson, comme des farines élaborées à partir de sous-produits de la pêche et de l'élevage de bétail, d'oléagineuses et de leurs sous-produits, de plantes aquatiques, de protéines unicellulaires, de sous-produits des légumineuses et des céréales. En outre, cet article présente des informations sur la valeur nutritive, le niveau d'incorporation dans le régime, les contraintes et les coûts/avantages de l'utilisation des produits de remplacement des farines de poissons les plus prometteurs ; il étudie également quelques approches généralisées pour mener et présenter des recherches sur le développement des produits de remplacement de farines de poisson.*

Mots-clés *: Tilapia, aliments pour poissons, remplacement des farines de poisson, ingrédients alimentaires.*

INTRODUCTION

Although total global tilapia production constituted only 4.6% of total farmed finfish production in 1994 (Table 1), they represent one of the oldest and most rapidly growing cultured finfish species in modern times. For example, tilapia culture was first reported about 2,000-2,500 BC in ancient Egypt (Chimits, 1957; Bardach, Ryther and McLarney, 1972), and in 1994 the Nile tilapia *Oreochromis niloticus* was the fifth most cultured finfish species in the world with a total production of 426,773 mt and exhibiting an average compound growth rate of 20.5% per year since 1984; the top four cultured finfish species being freshwater cyprinids, and the production of Nile tilapia *O. niloticus* exceeding that of either Atlantic salmon *Salmo salar* or rainbow trout *Oncorhynchus mykiss*. On a species basis tilapia represented the third largest group of farmed finfish species in 1994 after the cyprinids (9.17 mmt or 70.4% total finfish) and salmonids (0.81 mmt or 6.2% total finfish), with global production increasing three-fold since 1984 from 186,544 mt to 599,135 mt in 1994 (representing 4.6% total finfish production and valued at US$ 835 million) and growing at an average compound rate of 12.4% per year (FAO, 1996). Moreover, the bulk of tilapia production is currently being realized within developing countries (585,897 mt or 97.8% total production in 1994) as a moderately priced and therefore affordable *food fish* for domestic consumption; tilapia production being reported within 72 different countries in 1994 and the Asian Region accounting for 86.7% of the total production (Table 1; FAO, 1996).

However, as with the majority of finfish species produced within intensive farming systems, the development of commercial aquafeeds or complete formulated diets for these species has usually been based upon the use of fishmeal as the main source of dietary protein; the nutritional characteristics of fishmeal protein approximating almost exactly to the nutritional requirements of cultured finfish (Tacon, 1993). For example, although the dependency of tilapia upon fishmeal is not as great as that of carnivorous finfish and shrimp species, fishmeal is still generally the preferred protein source for use within compound aquafeeds for tilapia because of its high nutritional quality and biological value to tilapia, and its ready availability in most international markets (ADCP, 1983; FDS, 1994). Moreover, apart from being a good source of high quality animal protein, fishmeal is also a good source of essential fatty acids, digestible energy, macro and trace minerals, vitamins, and generally acts as a feeding stimulant for most finfish species. Despite this, there is an urgent need for the aquafeed manufacturing industry to reduce its current almost total dependence upon fishmeal as a feed ingredient which apart from being of uncertain supply and cost in the future, is also inefficient in terms of resource-use in that high quality low-priced wild-caught *food fish* rendered in the form of fishmeal are being used to produce higher-priced farmed *food fish* in the form of tilapia; the later having an essentially herbivorous feeding habit! With this in mind the present paper aims to review the major studies and efforts which have been reported to date concerning the dietary replacement of fishmeal within compound aquafeeds for tilapia with alternative protein sources or *fishmeal replacers*, including fishery and terrestrial animal by-product meals, oilseed meals and by-products, aquatic plants, single-cell proteins, and legumes and cereal by-products.

Fishery by-products

A wide variety of fishery by-products have been evaluated and used in aquafeeds, including fish silage and fish protein hydrolysates, shrimp head meal, krill meal, and squid meal. For example, Toledo and co-workers were able to replace fishmeal within aquafeeds with shrimp head meal (up to a level of 15% of the diet) with no loss in the growth or feed efficiency of Blue tilapia *Oreochromis aureus* (Toledo *et al.,* 1986; Toledo *et al.,* 1987). Studies with fish silage have also been very promising. For example, Fagbenro and Jauncey (1993) found that lactic acid fermented fish silage (FFS) could be stored at 30°C for six months with little or no nitrogen loss and change in nutritional quality, and reported that protein autolysis was directly related to ambient temperature. Moreover, experimental aquafeeds containing FFS were reported to have very good water stability and low nitrogen loss irrespective of the binder used (Fagbenro and Jauncey, 1995). Furthermore, during feeding trials excellent apparent digestibilities for dry matter, crude protein, and lipid were reported for FFS-based diets when fed to Nile tilapia *O. niloticus* (Fagbenro and Jauncey, 1994a, 1995) and Mozambique tilapia *Oreochromis mossambicus* (Hossain *et al.* 1992), respectively. Similarly, Lapie and Bigueras-Benitez (1992) found no difference in the growth and feed efficiency between Nile tilapia *O. niloticus* fed a formic acid preserved fish silage (FS) blended with FM (1:1 ratio) or a FM-based ration, although growth performance was reduced when the FS:FM ration was increased to 3:1. Furthermore, Fagbenro (1994) reported no difference in the performance (ie. growth, feed efficiency, protein digestibility, body composition, and blood haematocrit and haemoglobin content) between tilapia *O. niloticus* fed a 30% crude protein ration containing blended FFS (1:1, w/w) with soybean meal, poultry by-product meal, hydrolysed feather meal or meat and bone meal with fish fed a control FM-based ration. Moreover, Fagbenro *et al.* (1994) found that up to 75% of the FM protein could be successfully replaced with a dried 1:1 mixture of blended FFS:soybean meal in feeds for all male Nile tilapia *O. niloticus.*

Terrestrial animal by-products

Terrestrial by-product meals which have been tested as fishmeal replacers within tilapia feeds have included poultry by-product meal (PBM), hydrolyzed feather meal (HFM), blood meal (BM), and meat and bone meal (MBM). Despite their usually high crude protein content, these fishmeal replacers are usually deficient in one or more essential amino acids (EAA); the limiting EAAs generally being lysine (Lys: PBM, HFM), methionine (Met: MBM, BM, HFM), and isoleucine (Iso: BM; NRC, 1993; Tacon and Jackson, 1985). However, these imbalances can be overcome to a large extent by mixing complementary protein by-product meals so as to obtain the desired EAA profile (Davies et al., 1989).

For example, Tacon *et al.* (1983) found that hexane extracted MBM or MBM:BM (4:1, mixture) supplemented with Met successfully replaced up to 50% FM protein within diets containing 45% crude protein fed to Nile tilapia *O. niloticus* fry over a six-week period. By contrast, in the same study HFM supplemented with Met, histidine (His) and Lys could replace only 30% of the FM protein. However, when improved and more appropriate ratios can be maintained between the dietary components used, even better results can be achieved as reported by Davies *et al.* (1989). Thus, these authors found that optimum MBM/BM ratios could effectively replace up to 75% of the FM in diets fed to Mozambique tilapia *O. mossambicus* fry over a seven-week period. In fact, diets containing MBM or high MBM/BM ratios (3:1 and 2:3) were found to be superior to FM even at a 100% substitution level; when BM was used a total replacement for FM, fish growth was still comparable to the control diet (Davies *et al.* 1989).

The results obtained with the use of hydrolyzed feather meal (HFM) as a FM replacer within aquafeeds for tilapia has been more controversial. For example, Tacon *et al.* (1983), Viola and Zohar (1984) and Davies *et al.* (1989) all reported poor growth in tilapia (*O. niloticus, O. mossambicus,* and all male tilapia hybrids, respectively) when fed HFM or HFM-based diets. By contrast, Falaye (1982) and Bishop *et al.,* (1995) reported that HFM could replace up to 50% and 66% of the FM or FM:MBM within diets for *O. niloticus* fingerlings and fry with no loss in growth performance, respectively; growth of fish fed these rations being comparable with that of fish fed the FM control ration. More recently, Rodriquez-Serna *et al.,* (1996) studied the use of commercially defatted animal by-product meal (ABM; a combination of BM, MBM, HFM and FM), with soybean oil or a soybean oil:fish oil mixture (1:1), as a replacement for FM within feeds for *O. niloticus* fry over a seven-week period. These authors reported that ABM could replace up to 75% of the FM within the control diet tested, and that ABM supplemented with soybean oil could totally replace FM within the diets with no loss in fish performance.

As mentioned previously, the majority of the above studies have been short-term in duration and conducted within closed indoor rearing systems (ie. fish usually being reared within small artificial rearing tanks or aquaria within a water recirculation system). It follows therefore that long-term studies should also be conducted under actual farming conditions (ie. within outdoor tanks, cages or ponds). For example, the long-term feeding trials (120-days) of Otubusin (1987) with cage-reared *O. niloticus* fingerlings (3g initial body weight) concerning the use of BM as a FM replacer found that dietary BM inclusion levels above 50% of the FM protein significantly reduced fish performance (10% replacement level being the most efficient). These results are in agreement with the studies of Viola and Zohar (1984) who found that up to 50% of FM could be successfully replaced within tilapia feeds by poultry by-products.

Plant oilseeds

Soybean meal

Although soybean meal (SBM) is generally considered to be one of the best readily available plant protein sources in terms of its protein quality and EAA profile (with the exception of Met), like most other plant proteins it does contain a wide variety of endogenous antinutrients which require removal or inactivation through *processing* prior to usage within aquafeeds (for review see Tacon, 1995a).

Despite this, numerous studies have been conducted using *processed* SBM as a FM replacer within tilapia feeds. In general the studies have shown that between

67% to 100% of the dietary protein could be supplied in the form of SBM; the inclusion level depending upon a variety of different factors, including fish species and size, SBM source and processing method, aquafeed processing and manufacturing method, and culture system employed. For example, prepressed solvent extracted or full-fat SBM, with or without Met supplementation successfully replaced up to 75% of FM within diets fed to *O. niloticus* fry (Pantha, 1982; Tacon *et al.,* 1983), *O. mossambicus* (Jackson, Capper and Matty, 1982), and tilapia hybrids (Shiau *et al.,* 1989). From these studies it appears that dietary supplementation of SBM-based diets with limiting EAA does not improve the nutritional value of SBM for tilapias, since they appear to gain little or no benefit from crystalline EAA (Viola and Arieli, 1983; Teshima and Kanazawa, 1988). Similarly, Viola *et al.,* (1988) studied the limiting factors in SBM for tilapia hybrids (*O. niloticus x O. aureus*) reared within outdoor ponds and found that fish fed a SBM-based diet supplemented with Lys, Met, lipid, and dicalcium phosphate (DCP) had the same performance as fish fed a FM-based diet (at 100% substitution level). Moreover, the dietary omission of EAA did not result in any growth retardation and a SBM-based diet supplemented with 3% DCP and lipid completely replaced FM without any negative effects on fish growth. The authors concluded that phosphorus (and not deficient EAA) was the limiting factor in SBM under the prevailing experimental conditions. This finding was in agreement with their earlier studies (Viola *et al.,* 1986). Furthermore, Viola *et al.,* (1994) and Viola *et al.*, (1994a) found that dietary supplementation with crystalline Lys to SBM-based diets was ineffective at 25% or 30% dietary crude protein levels, and at 35% crude protein levels, reducing Lys/protein levels impaired fish growth. The apparent non-essentiality of supplemental crystalline EAA for tilapia has also been reported for *T. zillii* fed a sesame meal-based diet (El-Sayed, 1987) and *O. niloticus* fed a cottonseed meal-based diet (El-Sayed, 1990).

It is also of interest to note that the dietary inclusion of SBM in tilapia feeds is affected by the dietary protein level. For example, Davis and Stickney (1978) fed *O. aureus* SBM-based diets at dietary protein levels ranging from 15 to 36%, and found that whilst SBM impaired fish growth at 15% crude protein levels, that SBM could totally replace FM within diets containing 36% crude protein. These results are contrary to the studies of Shiau *et al.,* (1987) with *O. niloticus x O. aureus* hybrids who reported that FM could be partially replaced by SBM within diets containing sub-optimal protein levels (24%), whereas at optimum protein levels (32%) the dietary replacement of FM with 30% SBM significantly depressed fish performance. However, these discrepancies may have been due to differences in the nutritional quality of the SBM used within the experimental test diets (depending upon source of SBM and processing method employed) and experimental methodology used by the different research groups (ie. different fish species and sizes, and feeding methods). For example, Wee and Shu (1989) reported that the nutritional value of full-fat SBM for *O. niloticus* was improved and the trypsin inhibitor activity level reduced by boiling for one hour prior to usage; for additional information on the effects of processing on SBM quality see El-Sayed (1994) and the workshop proceedings of Akiyama and Tan (1991).

Cottonseed meal and cake

Cottonseed meal (CSM) and cottonseed cake (CSC) have been widely used within tilapia feeds, although with conflicting results. For example, Ofojekw and Ejike

(1984) and Robinson *et al.*, (1984) reported lower growth rates and feed efficiency in *O. niloticus* and *O. aureus* fed CSC and CSM-based diets than with fish fed FM-based diets. The poor response was attributed to the antinutrients gossypol and cyclopropionic acids contained within glanded and glandless CSM, respectively. Moreover, glandless CSM was found to be better utilized than glanded CSM (Robinson *et al.*, 1984).

In contrast, prepressed, solvent extracted CSM was successfully used as the sole source of dietary protein for *O. mossambicus* (Jackson *et al.,* 1982) *and O. niloticus* (El-Sayed, 1990), if low prices of CSM are considered. Moreover, Viola and Zohar (1984) found that 50% CSM could replace SBM in diets for cage -reared tilapia hybrids, and El-Sayed (1987) reported that *T. zillii* grew reasonably well on a diet containing 80% CSM protein used as a dietary replacement for casein:gelatin protein (El-Sayed, 1987). Cottonseed cake (CSC) has also been widely used both as a feed and fertilizer within semi-intensive pond farming systems. For example, CSC (42% crude protein) was successfully used as the sole feed input for *O. niloticus* reared within earthen ponds fertilized with cattle manure; fish being fed CSC at 3 and 6% body weight per day over a 100-day feeding period and growing from ca. 88g to 303g and 321g, respectively (Middendorp, 1995a; Middendorp and Huisman, 1995). However, fertilization alone resulted in negative fish growth. Furthermore, there was no beneficial effect of mixing brewery waste with CSC as feed inputs, with fish performance tending to be negatively affected by the dietary addition of brewery waste (Middendorp, 1995).

Other oilseed by-products

Limited attention has also been given to the use of other oilseed meals and by-products as sources of dietary protein for tilapia, including groundnut, sunflower, rape seeds, sesame seeds, copra, macadamia, and palm kernel. For example, Jackson *et al.,* (1982) evaluated the use of groundnut cake, sunflower meal, rapeseed meal, and copra meal within diets containing 30% crude protein for *O. mossambicus* over a seven to nine week rearing period. They found that 25%, 75%, 75% and 50% of these protein sources, respectively, could effectively replace FM protein in the control diets without a significant retardation in fish performance.

El-Sayed (1987) studied the effects of replacing a casein:gelatin protein mixture with sesame protein within experimental diets for *T. zillii* fingerlings, and found that fish fed sesame seed-based diets exhibited poor growth performance and displayed disease symptoms including haemorrhage and red spots in the mouth and at the bases of the fins even at the lowest sesame seed level tested (25%). Since sesame seeds were known to be deficient in Lys and zinc (Zn), the diets were re-evaluated after dietary supplementation with Lys and Zn. Interestingly, fish growth increased and disease symptoms disappeared when either Lys or Zn was added to the diets; indicating that either Lys or Zn met the requirement of the other, and in turn supported the thesis that EAA deficiency may not be the limiting factor in tilapia feeds.

Table 1. Total World Production Of Farmed Tilapia In 1994[1/]

SPECIES	Production	% change 93-94	Growth rate 84-94[2/]
Nile tilapia *(Oreochromis niloticus)*	426,773	+ 12.6%	+ 20.5%
Tilapia spp. (species not given)	105,185	- 07.7%	+ 02.7%
Mozambique tilapia *(O. mossambica)*	51,870	+ 07.3%	+ 07.3%
Blue tilapia *(O. aureus)*	11,871	+ 02.1%	- 01.7%
Three spotted tilapia (*O. andersonii*)	2,200	+ 04.8%	+ 21.8%
Redbreast tilapia (*Tilapia rendalli*)	868	+ 21.6%	+ 196% (since 1985)
Tilapia (*O. macrochir*)	350	0.0%	+ 45.8% (since 1987)
Tilapia (*T. zillii*)	18	+ 63.6%	+ 16.9% (since 1987)
Group total	**599,135**	**+ 07.7%**	**+ 12.4%**
Asia (86.7% total world production)	**519,192**	**+ 07.3%**	**+ 12.9%**
- China (39.4%)	235,940	+ 23.4%	+ 29.3%
- Philippines (15.7%)	94,322	- 02.1%	+ 11.7%
- Thailand (9.9%)	59,514	+ 10.0%	+ 19.1%
- Indonesia (9.5%)	56,990	- 07.9%	+ 06.6%
- Taiwan (7.9%)	47,435	-17.0%	- 01.1%
Africa (6.4%)	**38,470**	**+ 10.8%**	**+ 09.3%**
- Egypt (4.2%)	25,214	+ 27.0%	+ 07.7%
Latin America & Caribbean (5.9%)	**35,164**	**+ 12.2%**	**+ 07.9%**
- Cuba (2.0%)	11,792	+ 01.8%	- 01.8%
Developing countries (97.8%)	**585,897**	**+ 08.1%**	**+ 12.5%**
Developed countries (2.2%)	**13,238**	**- 05.2%**	**+ 07.1%**
Low-Income Food Deficit Countries (74.1%)	**444,163**	**+ 10.4%**	**+ 16.3%**

[1/] Data compiled from FAO (1996)
[2/] Annual percent rate (APR) from 1984 to 1994 calculated using the compound-interest formula $P_t = P_o (1 + r)^n$, where n is the time interval in years, and r is the APR

Fagbenro (1988) found that *T. guineensis* (52g initial body weight) reared in fertilized outdoor ponds grew reasonably well when fed a diet based on the use of defatted cocoa cake as a replacement for a commercial diet containing 38.5% crude protein; economic analyses indicating that cocoa cake could be used as the sole nutrient source for these fishes. Similarly, the growth of *O. niloticus* fingerlings (2.5g body weight) fed up to 60% palm kernel protein was reported to be similar to that of fish fed a FM-based diet (Omoregie and Ogbemudia, 1993). Macadamia presscake, a by-product arising after the oil extraction of macadamia nut kernels, has also been found to have great potential for use as a protein source for tilapia. For example, Fagbenro (1993) found that monosex *T. guineensis* fed macadamia cake (33.4% crude protein) within concrete tanks for 180 days grew at a similar rate to fish fed a commercial diet (35.5% crude protein). In contrast, when macadamia cake was used as a replacement for SBM at levels exceeding 50% in feeds for *O. niloticus* fingerlings (10g body weight) reared within outdoor tanks over a 100-day test period, fish growth and protein digestibility were adversely affected (although feed efficiency was not ; Balogun and Fagbenro, 1995). However, once again, the low price of macadamia cake makes it an excellent alternative plant protein source for tilapia.

Aquatic plants

Relatively few studies have been conducted concerning the use of aquatic plants as feed ingredients within tilapia feeds. Moreover, as with the use of oilseeds, the results of feeding trials using aquatic plants often vary considerably and sometimes yield conflicting results. A good example can be seen concerning the use of the freshwater fern *Azolla* sp.; the latter having a unique symbiotic relationship with a nitrogen fixing cyanobacteria *Anabaena azollae*. For example, Almazan *et al.*, (1986) and El-Sayed (1992) reported extremely poor performance for *O. niloticus* fingerlings and adults fed *Azolla pinnata*-based diets, respectively. Similar results were reported by Micha *et al.,* (1988) for *O. niloticus* and *T. rendalli* fed *Azolla microphylla.* By contrast, Santiago *et al.*, (1988) found that *O. niloticus* fed rations containing up to 42% *A. pinnata* out performed fish fed the FM-based diet; see El-Sayed (1992) for a possible explanation of this discrepancy.

Duckweed *Lemna* sp. also has considerable potential for use a fishmeal replacer within tilapia feeds (Mbagwu *et al.,* 1990) or as a complete diet in its live form (Edwards, 1987; Journey *et al.,* 1990; Wee, 1991). For example, Mbagwu, Okoye and Adiniji (1990) reported that *Sarotherodon galilaeus* fed a diet (33% protein) containing duckweed *L. paucicostata* as a partial protein source exhibited better growth and feed efficiency than fish fed a standard (40% protein) diet. Appler (1985) found that up to 20% of FM could be replaced by *Hydrodictyon reticulatum* without any adverse effects on the growth performance *of O. niloticus* and *T. zillii.* Chiayvareesajja *et al.,* (1990) fed moist diets containing dry coontail *Ceratophyllum demersum*, rice bran and FM at combinations of 4:3:1 and 4:2:2 to *O. niloticus* (88-111g body weight) reared in floating net cages for 90 days, and found that the 4:3:1 combination was the most appropriate. In another study, three levels (ie. 20%, 30% and 40%) of Coontail and chuut-nuu (*Eleocharis ochrostachys*) were evaluated within rations for *O. niloticus* at three dietary protein levels (ie. 16%, 25%, and 35%) over an 11-week rearing period (Klinnavee *et al.,* 1990). At the same protein level, fish fed the plant-based diets grew at similar rates, with growth increasing as the level of dietary protein increased; the 35% crude protein plant-based diets displaying the best growth performance and lowest cost/kg fish produced. However, in another study juvenile and adult *O. aureus* lost weight when fed diets containing *Elodea trifoliata, Muyriophyllum spicatum* and *Potamogeton gramineous* at 15 or 25°C (Okeyo, 1988).

Single cell proteins

Single cell proteins (SCP) are micro-organisms and include the use of bacteria, yeasts, and algae. Under extensive and semi-intensive pond farming conditions micro-organisms constitute a natural food organism for tilapia in the form of periphytic mats and detrital biomass, with many commercially important tilapia species such as *O. niloticus* also being capable of directly filtering particulate matter and micro-organisms from the water column (Moriarty and Moriarty, 1973; Shrestha and Knud-Hansen, 1994; Dempster *et al.*, 1995).

Viola and Zohar (1984) reported that bacterial SCP (Pruteen, 70% crude protein) could replace up to 50% of the FM within a 30% crude protein diet with no loss in the growth of caged-reared tilapia hybrids (*O. niloticus* x *O. aureus*). However, fish performance was reduced when Pruteen completely replaced FM in the diets. Similar results were also obtained by Davies and Wareham (1988) with *O. mossambicus* fry who reported that SCP (Eurolysine Fodder Protein - EFP, 64% crude protein) could replace up to 40% of dietary FM with no loss in fish performance, but that at higher substitution levels growth and feed efficiency were adversely affected; the latter was attributed to either EAA deficiency or low feed intake. In contrast, the filamentous alga *Spirulina* sp. successfully replaced 20% of a commercial eel diet without adversely affecting the growth, appetite, and amylase/protease activities of *O. mossambicus* (Chow and Woo, 1990).

The biosynthesis and utilization of microbial protein by *O. aureus* in a recirculated (airlifting) water system was investigated by Avnimelech *et al.*, (1989); microbial production achieved through the use of protein-poor (10% crude protein) and carbon-rich cereal pellets as a nutrient substrate. The results indicated that fish fed the microbially produced SCP growth grew as well as fish a protein-rich (30% crude protein) pellet. Furthermore, the microbial assimilation of ammonium ions into the carbon-rich substrate also facilitated reduced inorganic nitrogen levels in the water. It follows from the above therefore that it may be possible to reduce the use of expensive protein sources with cheaper carbon and nitrogen nutrient sources.

Legumes and cereal by-products

With a few exceptions, the results reported concerning the use of leguminous and cereal plants and their by-products as FM-replacers have been promising. However, like the majority of most plant proteins, they may contain a wide variety of antinutrients which would require removal or inactivation through *processing* prior to usage within aquafeeds (for review see Tacon, 1995a).

A number of studies have been conducted on the use of *Leucaena* leaf meal (LLM) in tilapia feeds, with similar results. Jackson *et al.*, (1982) found that dietary levels exceeding 25% LLM within rations containing 30% crude protein resulted in reduced growth and feed efficiency of *O. mossambicus*. This is in agreement with the results of Wee and Wang (1987) and Santiago *et al.,* (1988a) with fingerling and broodstock *O. niloticus,* respectively; the latter studies of Santiago *et al.*, (1988a) indicating that the level of LLM should not exceed 40% in broodstock feeds. However, as mentioned previously, processing LLM prior to usage may greatly improve its quality. For example, Wee and Wang (1987) found that soaking LLM produced better results with *O. niloticus* than either sun-dried or commercial LLM. More recently, Osman *et al.*, (1996) reported that cooked or sun-dried LLM gave better results than sodium hydroxide or rumen liquor treated LLM when used within *O. niloticus* feeds. Although the subject matter for this review paper does not cover the use of unprocessed feed ingredients used in their fresh or natural state as supplementary feeds for tilapia, for information concerning the food preference of herbivorous tilapia species for different terrestrial plants see Chikafumbwa et al., (1991).

Similar results have also been reported with *O. niloticus* fed other legumes, including cassava leaf meal (CLM; *Manihot esculenta*), with increasing dietary CLM levels resulting in progressively reduced fish performance (Ng and Wee, 1989). However, fish growth was significantly improved when CLM-based diets were supplemented with 0.1 Met. Other legumes which have been successfully tested in tilapia feeds include the green gram (*Phaseolus aureus*; De Silva and Gunasekera, 1989) and the Jack bean (*Canavalia ensiformis*; Martinez-Palacios et al., 1988); the former authors reporting that the best growth response of *O. niloticus* was attained at the 25% dietary substitution level, and the latter authors that the jack bean was useful as a partial substitute for FM within *O. mossambicus* feeds, respectively. Leaf protein concentrate (LPC) is another FM-replacer with considerable potential; the studies of Olvera *et al.*, (1990) with *O. mossambicus* fingerlings indicating that the growth of fish fed alfalfa LPC as a dietary replacement of up to 35% of FM protein was better than that obtained with fish fed a control a FM-based diet.

Cereal by-products such as maize gluten meal, gluten feed, grain distillers and brewery waste have also been successfully used as dietary protein sources for tilapia. For example, the growth of *O. niloticus* fingerlings fed maize distillers grains with solubles, gluten meal and gluten feed as partial protein sources was better than that of fish fed a FM-based control diet (Wu et al., 1994, 1995; Tudor et al., 1996). Similarly, Pito brewery waste has been recommended as a full dietary replacement for FM for *T. busumana* , with considerable economic savings (Oduro-Boateng and Bart Plange, 1988). In contrast, Pouomogne (1995) reported that brewery draff could be included up to a level of 30% within feeds for *O. niloticus* without any significant adverse effect on fish growth.

Reported digestibility of fishmeal replacers

Numerous studies have been conducted so as to ascertain the digestibility of the major feed ingredients commonly used within tilapia feeds. For example, Table 2 shows the reported digestibilities for a variety of different feed ingredients for *O.*

niloticus. It is evident from the data presented that the majority of the protein sources tested are well digested by the tilapia species in question. However, little published information exists concerning the digestibility of different FM-replacers and feed ingredient sources for other tilapia species. Clearly, considerable further research is required in this key subject area, and in particular concerning the development of more refined and applied standardised techniques for measuring nutrient digestibility both *in-vivo* and *in-vitro* over a range of different dietary inclusion levels and different ingredient/feed processing methods.

Economic analyses

Although the majority of the above mentioned studies on FM-replacers have been evaluated from a biological or nutritional viewpoint, little or no attention has usually been given to economic analyses within these studies. Since aquaculture is usually operated as an economic activity it follows therefore that studies concerning the development of feeds and feeding regimes (which generally constitute the largest operating cost item of most semi-intensive and intensive fish farming operations) be also analysed from an economic viewpoint. For example, some workers showed that even though certain FM-replacers resulted in a reduced biological performance, cost-benefit analyses including incidence cost and profit indices indicated that many of the FM-replacers tested were more economical. Examples of studies were both economic and biological analyses were performed can be seen during the evaluation of cottonseed meal (El-Sayed, 1990), corn gluten feed and meal (Wu *et al.,* 1995), and animal by-product meal (Rodriguez-Serna *et al.,* 1996) for *O. niloticus*, brewery waste (Oduro-Boateng and Bart-Plange, 1988) for *T. busumana*, and cocoa cake (Fagbenro, 1988) for *T. guineensis*.

CLOSING REMARKS

It is evident from the above review that there exists considerable scope for small-scale farmers and feed manufacturers in the coming decade to completely replace FM within farm-made and commercial aquafeeds for tilapia. However, it is also clearly evident that the results obtained have sometimes been conflicting, even for same FM-replacer and species. To a large extent this has been due to the variability of processing methods and sources of the FM-replacers used, and the methodology employed by researchers for conducting and reporting their studies (ie. different feed preparation and feeding methods, indoor and outdoor experiments, different stocking densities and sizes, etc., Tacon, 1985b). In this respect it is essential that researchers clearly specify the name (including international feed number) and composition of the FM-replacer tested, including origin (country), source (species), processing and treatment methods prior to feeding, proximate composition, and antinutrients present (Tacon, 1993). In the final analysis it is important to remember that :

- FM-replacers should always be carefully defined and specified, be readily available at economic prices, and be evaluated both biologically and economically;

Table 2. Reported digestibility of different feed ingredients for Nile Tilapia *Oreochromis niloticus*

Source	Reference					
	1a	2b	3a	4a	5c	6a
Plant sources:						
Azolla					75	
Brewers grains			62 (42)	63 (30)		
Copra meal		1.56			56	
Corn gluten meal	90.7					
Cottonseed meal			31 (-24)			
Groundnut meal		4.29	79 (72.5)			
Palm kernel meal		0.41	-26 (-89)			
Rapeseed meal		2.54				
Shea butter seed			-97 (32)			
Soybean meal	90.9	4.45		91 (55)	93	
Sunflowerseed meal		0.86				
Wheat germ meal	95.5					
Animal sources:						
Chicken manure			-82 (-130)			
Fishmeal	92.2	3.88	72 (58)	86 (80)	92	
Fish silage						85 (83)
Meat and bone meal	96.2	2.18				
Poultry offal meal		4.40		74 (59)		
Shrimp meal					87	
Silkworm pupa meal	91.1					

Reference 1 - Watanabe et al., (1996), 2 - Anderson et al., (1991), 3 - Luquet (1989), 4 - Hanley (1987), 5 - Lorico-Querijero and Chiu (1989), 6 - Fagbenro and Jauncey (1994); where a - % protein and (organic matter) digestibility, b - digestible energy expressed as kcal/g, and c - % true digestibility

- the optimum dietary inclusion level of FM-replacers will be affected by dietary crude protein and energy levels, feeding rate and frequency, and natural food availability;
- tilapia appear to gain little or no benefit from dietary supplementation with crystalline EAA. In this respect better response might be gained from the use of coated or protected EAA and/or continuous feeding methods;
- many other factors apart from EAA may be limiting within potential FM-replacers and therefore need to considered, including minerals, carbohydrates, lipids, and antinutrients;
- consideration should be given to the blending of complementary FM-replacers so as to obtain the ideal or required overall dietary nutrient specification; and
- long terms studies need to be conducted under realistic farming conditions (ie. tanks, cages, pens or ponds) with fish growing at maximum rates for each phase of the life cycle (ie. fry, fingerling, juvenile, grower, brood), and biological and economical analyses complemented with histological examinations of fish tissues and an assessment of fish quality with market sized fish.

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