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Future demand and supply of aquafeed ingredients: Outlines to commercialize non-conventional protein ingredients to enhance aquaculture production for food security in sub-Saharan Africa

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Aquaculture, being the fastest growing food sector, is expected to provide the highly needed animal protein for about 9.7 billion people globally by 2050. The world population is likely to consume 178 million tons of food fish/aquatic animals by 2028, whereby 58% of fish will likely be from aquaculture. Growth of food fish production is expected to increase overall production of aquafeeds to over 87 million tons by 2025. Aquafeed production relies largely on fishmeal which is getting expensive due to its multiple use and scarcity. A remedy to this situation is the use of non-conventional protein sources, which may be of plant (leaves, cereals, pulses etc.) or animal (insects, worms, etc.) origin. This paper demonstrates the potential of non-conventional ingredients for aquaculture. It was found that crude protein levels of selected non-conventional plant ingredients ranged from 25-71% while those of animal origin were from 66-72%. Inclusion levels of 5-40% and 25-66% were recommended in aquafeeds, respectively, from ingredients of plant and animal origin. Performances of fish fed aquafeeds containing selected non-conventional ingredients have been reviewed. Presence of anti-nutrients, chitin and high lipid in feed ingredients, and shortcomings in processing and mass production technologies, have been identified as the main challenges limiting the commercialization of the selected feed ingredients. To remove the unwanted factors and to enhance inclusion of non-conventional ingredients in aquafeeds, authors suggested varied strategies. The strategies such as defatting, heat treatment, extrusion cooking, solvent extraction, dehulling, fermentation, ensiling, genetic modification and inclusion of enzyme are identified as some of the most efficient methods. Effective and affordable technologies to improve nutritional value should be validated through research for adequate and consistent supply of aquafeed in Sub-Saharan Africa. Consequently, provision of sufficient, quality and affordable aquafeeds will promote sustainable aquaculture production and reduce fishing pressure and pollution in natural aquatic ecosystems.

Keywords: alternative aquaculture protein, fishmeal, plant-based protein, animal-based protein

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Introduction

By 2050, the human population is likely to rise to about 9.7 billion (United Nations, 2019). Aquaculture is expected to provide a major part of the animal protein source for the human population, since it is the fastest growing food production sector. The growth in demand for food fish will largely be from developing countries, especially Asia and Africa. Food fish provides more than 20% animal protein for over 200 million Africans in about 20 countries (Obiero et al., 2019). Fish consumption in countries of sub-Saharan Africa (SSA) is growing. Interestingly, some countries in SSA such as Zambia, South Africa, Kenya, Nigeria, Ghana and Uganda, have embraced commercial aquaculture to meet the existing demand. This is reported to have led to 21% average annual growth of aquaculture in SSA during the last decade (FAO, 2017).

Drivers of demand and supply for non-conventional protein sources for aquafeed

Global food fish production is projected to reach 196.3 million tons by 2028 (OECD/FAO, 2019), an increase of about 10% from 2018 (178.5 million tons) (FAO, 2020). The amount of food fish for human consumption is expected to rise to 178 million tons by 2028 from about 156.4 million tons in the year 2018 (FAO, 2020). Further, it is predicted that by 2028, global aquaculture production will grow to about 102.2 million tons, an increase of about 24.5% over 2018 (82.1 million tons), implying an average annual increase of about 2.0 million tons (OECD/FAO, 2019). About 90% of the fish production (178 million tons) will be consumed as human food whereas about 18.3 million tonnes are to be used as fishmeal and fish oil (OECD/FAO, 2019). Due to innovation and technology adoption, aquaculture production has experienced consistent growth. As a result, aquafeed production rose from 7.6 million tons in 1995 to 49.7 million tons in 2015 (Tacon and Metian, 2015). Overall production of aquafeeds is projected to increase from about 50 million tons in 2015 to slightly above 87 million tons in 2025 (Tacon and Metian, 2015). The cost of aquafeeds remain the most expensive input in aquaculture, accounting for about 50-70% of the operational expenses (Craig et al., 2017). Regardless of the cost, all major ingredients such as protein, lipids, carbohydrates, vitamins and minerals should be incorporated in the right proportions during feed formulation to attain optimum growth and health (Lucas et al., 2019). Sustainability in aquaculture relies on feed ingredients that are locally available, less costly and nutritious, for target fish species. In order for fish to benefit from an ingredient source, feeding habits and nutritional requirements need to be taken into consideration before selection of the ingredients (Davis, 2015). In evaluating particular feed ingredients, their nutritional effects on fish should be well understood before they are incorporated into commercial fish feeds.

Protein supply in aquafeed has traditionally been relying on fishmeal (FM) due to its high protein content (65% to 72%). Further, fishmeal has all the ten essential amino acids in right proportions, that meet the requirements of all fish (Jackson, 2012). Fishmeal and fish oil are generally derived from forage fish. The rapid growth in aquaculture production has over the years exerted intense pressure on the small pelagic fish stocks (Froehlich et al., 2018) which are steadily declining (Shepherd and Jackson, 2013). In the 1980s, aquafeeds used approximately 8-10% of annual fishmeal production which increased to 35% in the year 2000, and 70% by 2010 (Jackson, 2012). Despite the increased demand, fishmeal production has been on the decline over the years (Han et al., 2016). Moreover, besides the use of forage fish as fishmeal in aquafeed production, they are also used as human food and in production of terrestrial animal feed including that of livestock and pets. Consequently, there is an obvious gap between the limited availability of fishmeal to the needs of a growing aquaculture sector.

Cognizant of the situation, fish nutritionists have over time preferred to partially or completely replace fishmeal using conventional or commercial animal and plant protein sources (Munguti et al., 2012; Ogello et al., 2014). Nevertheless, alternative conventional protein sources used in aquafeeds production, are also facing competition from human consumption and terrestrial animal feed industry, hence increasing aquafeed cost (Moutinho et al., 2017). Thus, the present review aims to identify relatively cheap and locally available feed ingredients of plant and animal origin which can be used as alternative protein sources for aquafeeds. Further, this paper presents information on the chemical composition of the ingredients, their optimum inclusion levels in fish diets, growth performance and feed utilization of farmed fish species fed on diets in which non-conventional protein sources have been incorporated. Factors that hinder the commercial use of the non-conventional ingredients as protein sources in aquafeeds and possible commercialization strategies have been outlined.

Methodology

Selection of non-conventional plant ingredients as protein source in aquafeeds

When selecting suitable ingredients, one should consider their availability at a local scale, collection and processing cost. It has been observed that most of the potential ingredients of plant origin for aquafeeds, in many developing countries, are collected without any additional or marginal costs (Lucas et al., 2019). Despite the wide variety of non-conventional plant ingredients which have been evaluated over time to establish their potential for use in aquafeeds, this review has selected a total of twelve (12) feed ingredients of plant origin, based on their local availability, crude protein level and possibility for cultivation. Amongst non-conventional plant protein sources, this paper presents five most commonly available feed ingredients of aquatic origin and seven of terrestrial origin (Table 1).

Selection of non-conventional animal ingredients as protein source in aquafeeds

The selection of insects as potential protein sources for aquafeeds was guided by their nutritional profile, especially the high levels of protein and richness in amino acids. Other factors included: acceptability, simplicity of culture techniques that promote mass production, short culture periods among others. Further, they present a low risk of transmitting zoonotic diseases whereas use of organic wastes during their culture is a climate smart way of producing aquafeeds which at the same time help in sanitizing the environment. In this paper, nine animal protein sources have been presented (Table 2).

Results and discussion

Chemical composition of selected non-conventional ingredients

The crude protein for selected aquafeed ingredients of animal origin, in this review, ranged from 25.0 to 71.1%, an average of 48.1%. When compared to conventional protein sources such as fishmeal or soybean meal (SBM), the ingredients of animal origin have protein content lower than that of fishmeal (66–72%) but similar or higher than soybean meal (44–50%). On the other hand, some of the evaluated dietary plant ingredients have lower levels of crude protein compared to most conventional ingredients of animal origin. However, it is likely that some non-conventional aquafeed ingredients of plant origin have a higher level of crude protein than some conventional aquafeed ingredients of plant origin; on the contrary, some may have similar levels and others may have lower levels. For instance, water hyacinth, duckweed, Amaranthus among others, have higher crude protein levels than other conventional legumes like chickpea and cowpea. Moringa leaves provide protein, vitamins and amino acid such as methionine, cystine, tryptophan that can improve the growth and health of fish (Makkar and Becker, 1996) more than most other conventional ingredients. In the present review only crude protein of the selected ingredients have been shown in Tables 1 and 2. Further, this review confirmed the availability of amino acid, micronutrient and macronutrient data for all selected ingredients of animal origin as reviewed elsewhere (Jabir et al., 2012; Makkar et al., 2014; Henry et al., 2015; Tran et al., 2015; Belghit et al., 2019; Hua et al., 2019; Musyoka et al., 2019) except for termites, *Macrotermes* spp., where data was not available.

Performance, replacement, and recommended inclusion levels

From the summaries provided in Table 1, most plant-based feed ingredients could only replace fishmeal or animal protein in aquafeeds

Table 1. Chemical composition, substitution/inclusion level, nutrient utilization and performance of fish fed diets containing selected non-conventional plant ingredients.

Common Name	Scientific name	Parts used	Crude protein	Fish species	Substitution %	Recommended inclusion level %	Fish growth	Reference
Amaranth [t]	*Amaranthus spinosus*	Leaf	31.9	North African Catfish *(Clarias gariepinus)*	0-20	5	1.83 ± 0.23%/ day	Adewolu and Adamson (2011)
Amaranth [t]	*Amaranthus hybridus* LPC	Leaf	36.42	Nile Tilapia (*Oreochromis niloticus*)	0-100	80	SGR: 1.66 ± 0.10	Ngugi et al. (2017)
Azolla [a]	*Azolla pinnata*	Whole plant	19-30	Nile Tilapia (*Oreochromis niloticus*)	50–100	na	na	Hasan and Chakrabarti (2009)
Cassava [t]	*Manihot esculenta* Crantz	Leaf	16.5-31.7	Nile Tilapia and Catfish (*Clarias gariepinus*)	10-100 0-100 (Substituting maize meal)	10.0-66.7	Digestibility: dry matter -50%; protein-50%	Heuzé et al. (2016) Bichi and Ahmad (2010)
Duckweed [a]	*Lemna minor*	Entire plant	35-45	Common Carp (*Cyprinus carpio*)	0-50	40	TWG: 83% of control diet	Hasan and Chakrabarti (2009)
Water Hyacinth [a]	*Eichhornia crassipes*	Leaf, aerial parts, whole plant	34.9	Nile Tilapia, Catfish and other species	20-50	5-10	SGR: 110%, 93% and 64% of control diet for 20, 30 and 40% inclusion levels	Hasan and Chakrabarti (2009) Heuzé et al. (2015)
Red algae/ marine macroalgae [a]	*Gracilaria bursa-pastoris*	Whole plant	25-50	Nile Tilapia and other species	5- 10 of fishmeal replacement	10	DWG (% IBW): 3.37 ± 0.28	Valente et al. (2006)
Green algae-seaweed [a]	*Ulva rigida*	,,	29.5	European Seabass (*Dicentrarchus labrax*) juveniles	-	10	DWG 2.54 ± 0.32 SGR: 1.01 ± 0.09	Valente et al. (2006)
,,	,,	,,	,,	Nile Tilapia	0 and 5	5	SGR: 0.81 ± 0.02	Ergün et al. (2009)
,,	,,	,,	,,	Nile Tilapia	0-15	5	SGR (%): 1.1 ± 0.03	Güroy et al. (2013)
Prosopis [t]	*P. juliflora*	Seed	30	Nile Tilapia	25-100	< 50	SGR (%):2.8 FCR: 1.71	Ondiba (2016)
Sweet potato [t]	*Ipomea batatas*	Leaf	18.8-35.3	Nile Tilapia	na	na	na	Adewolu (2008)
Arrowroot [t]	*Maranta arundinacea*	Leaf	33.5	Nile Tilapia	na	na	na	Munguti et al. (2006)
Papaya [t]	*Carica papaya*	Leaf	20.9-32.6	Barramundi (*Lates calcarifer*) Nile Tilapia	13-18	na	Poor growth	Munguti et al. (2006)
Moringa [t]	Moringa oleifera	Leaf/ foliage	17.5-33.5	Nile Tilapia and North African Catfish	10-12 25	10 20	Low SGR, Nutrient utilization and digestibility.	Munguti et al. (2012)

Notes: SGR: specific growth rate, TWG: total weight gain, DWG: daily weight gain, IBW: initial body weight; na: not accessed; ingredients of aquatic origin are denoted by superscript [a] while those of terrestrial origin are denoted by [t]

Table 2. Chemical composition, substitution/inclusion level, nutrient utilization and performance of selected non-conventional animal ingredients in aquafeeds.

English/ common name	Scientific name	Crude protein (%)	Fish species	% inclusion	Recommended inclusion (%)	Performance	References
Earthworm	*Eisenia foetida*	50.9- 71.1	Nile Tilapia (*Oreochromis niloticus*) and 18 other species	0-100	50	SGR=4.21 FCR=1.58	Musyoka et al. (2019)
Black Soldier Fly	*Hermitia illucens*	25- 50	Atlantic Salmon (*Salmo salar)* and 6 other species	0-100	66	SGR=0.9 FCR=1.1	Tran et al. (2015) and Belghit et al. (2019)
Super worm	*Zophobas morio*	25- 50	Nile Tilapia	0-100	25-50	SGR: 1.01 ± 0.29 FCR: 1.25- 1.50	Jabir et al. (2012); Tran et al. (2015)
Termite	*Macrotermes* spp	25-55	North African Catfish (*Clarias gariepinus*)	10-50	40	SGR: 0.0041 FCR: 1.98	Henry et al. (2015)
Locust	*Schistocerca Gregaria/ Locusta migratoria*	57.3 (62.6)	North African Catfish (*Clarias gariepinus*)	25 & >25	25	No adverse effect on growth and nutrient utilization at up to 25% inclusion.	Makkar et al. (2014); Tran et al. (2015)
Silkworm pupae	*Bombyx mori*	60.7-75.6 (81.7)	Common Carp (*Cyprinus carpio*) and 10 other species	100	50	Up to 50% inclusion, no adverse effect on growth and flesh quality	Tran et al. (2015)
Mealworm	*Tenebrio molitor*	52.8 (82.6)	Rainbow Trout (*Oncorhynchus mykiss*) and 3 other species	25-50	Up to 50	No negative effect on growth up to 50% inclusion	Tran et al. (2015) and Hua et al. (2019)
Housefly	*Musca domestica*	50.4 (62.1)	Nile Tilapia and North African Catfish	15-68	25	Better specific growth rate and survival; for inclusion >30, there was decreased performance	Tran et al. (2015) and Hua et al. (2019)
Cricket	*Gryllus bimaculatus*	63.3 (76.5)	North African Catfish	0-100	100	FCR decreased, while SGR and PER increased with increased inclusion of CM	Tran et al. (2015) and Taufek et al. (2018)

Notes: EAA: essential amino acids, SGR: specific growth rate, FCR: feed conversion ratio, CM: cricket meal

from 5-40%, without adverse effects on growth, feed utilization and health performance of fish. For instance, when *Sarotherodon galilaeus* fingerlings were fed on a 33% crude protein diet where *duckweed* replaced blood meal at 10%, they exhibited better growth and feed utilization than those fed a 40% CP diet, where blood meal was used as the sole protein source (Mbagwu et al., 1990). Further, Nile Tilapia fed diets where methanol-extracted moringa leaf meal replaced fishmeal at 11, 22 and 33 % had similar growth performance as fish fed fishmeal-based diet (Afuang et al., 2003). In an eight-week experiment, similar growth and nutrient utilization were reported for *Tilapia zilli* fed diets where sweet potato leaf meal replaced protein ingredients (fishmeal, groundnut cake and soybean meal) at 0, 5,10 and 15% (Adewolu, 2008). When solar-dried duckweed was used to replace fishmeal in Nile Tilapia diet at 5, 10, 20, 30 and 100%, growth performance and feed utilization of fish fed diets containing up to 20% duckweed inclusion was similar to that of fish fed control diet (0% duckweed inclusion). On the other hand, fish fed diets with 30 and 100% duckweed inclusion had reduced growth performance and nutrient utilization compared to those fed control diet (Fasakin et al., 1999). Inclusion of azolla up to 40% in the diet of *Labeo fimbriatus* was found to be ideal for growth and survival during fry-to-fingerling stages (Gangadhar et al., 2015). Higher inclusion of Azolla protein concentrate beyond 50% reduced protein utilization in the diet of *Labeo rohita* (Dorothy et al., 2018). However, exceptional findings have been reported in cases where plant-based ingredients were used singly or contributed >50% of the protein requirements in fish diets. For example, complete replacement of freshwater shrimp meal (FSM) with papaya leaf meal did not compromise growth of *O. niloticus* reared in hapas (Benson, 2010). In another study, where Amaranth leaf protein concentrate (ALPC) replaced fishmeal up to 100% in *O. niloticus* diets, growth performance was good and similar to that of fish fed control diet for up to 80% replacement (Ngugi et al., 2017).

In the case of animal-based feed ingredients, replacement levels ranging from 25-66 % (Table 2) have been recommended to support healthy growth of fish. Earthworm, *Eisenia fetida* has been reported to support growth, feed utilization and reproduction, among different fish species, when used to replace fishmeal and other conventional protein source ingredients at <50%, except for guppy (*Poecilia reticulate*) where safe inclusion was up to 100% (Musyoka et al., 2019). zebrafish (*Danio rerio*), fed fishmeal/fish oil based-control diet and those fed diet with 25% black soldier fly (BSF) full-fat pre-pupae meal inclusion, had similar wet weight after 6 months of feeding whereas zebrafish fed diets with 50% BSF full-fat pre-pupae inclusion had significantly low wet weight (Zarantoniello et al., 2019). Generally, use of insects is gaining prominence as a source of protein in aquafeeds. Apart from BSF, locusts, silkworm, mealworm, crickets, housefly and super worm have been used in aquafeeds at experimental levels with different species of fish (Table 2).

Limitations to commercialize non-conventional protein sources from plant and animal feed ingredients

There are a number of challenges when non-conventional protein sources of fish feed ingredients are used. These problems include poor understanding of the nutritional profiles of some of the feedstuffs, presence of anti-nutritional factors, stigma and prejudice, adverse environmental effects of the ingredients, legislation, supply imbalance, lack of skills on proper processing, insufficient information on large-scale production and commercialization and lack of specific target species. Poor nutritional value of many potential sources of protein may be due to presence of anti-nutrients which lead to unavailability, poor or low digestibility of protein or amino acids, or because the amino acid profile is not suitable for the target species. Anti-nutritional factors such as phytic acid, trypsin inhibitor, tannins, saponins, oligosaccharides etc are present mainly in plant proteins (Francis et al. 2001). The reduced growth rate of fish fed with plant protein may be due to presence of anti-nutritional factors inherent in most plant ingredients (Francis et al. 2001). For example: moringa leaves have anti-nutritional factors such as saponins, phenols (Egwui et al., 2013), tannins and polyphenols that were reported to reduce growth performance of *Tilapia rendalli* at 25% inclusion (Hlophe and Moyo, 2014). Sweet potatoes contain anti-nutritional factors such as invertase and protease inhibitors (Adewolu, 2008).

For animal based aquafeed ingredients of protein source, the major challenge observed, especially when using insect meal in fish feed is their high chitin content. Chitin a component of the insect exoskeleton which is poorly digestible by fish has been reported in a number of insect species (Henry et al. 2015). Results on the use of insect meal in aquaculture species are primarily influenced by the type and condition of insect larvae used (fresh or dried, whole, ground, defatted), method of nutrient isolation, processing (sun drying, thermal treatments, lipid extraction methodologies) and the target fish species. The insect larvae with high fat content (15–50%) can cause problems when included as protein source. The high fat content can generate problems in formulation, storage and pellet stability. The efficacy of using earthworm meal was reported to be hindered by presence of coelomic fluid (Musyoka et al., 2019); its slimy, sticky and moisty nature and presence of chitin. In addition, cultural stigma and sensory appeal have been identified as reasons that hinder the use of some insect meals (Musyoka et al., 2019).

Strategies towards commercializing non-conventional ingredients

Some procedures which have been suggested to commercialize non-conventional feed ingredients of protein source include reduction of anti-nutritional factors through processing techniques such as drying, soaking, grinding, steaming or boiling, dehulling, mechanical extraction, solvent extraction, fermentation, ensiling etc. For instance, drying, soaking and grinding of moringa leaf meal have been suggested to assist in reduction of anti-nutrients (Lochmann et al., 2011). Heat treatment has been suggested to reduce or inactivate hemagglutinins, protease inhibitors, phytates and goitrogens. In order to attain a higher substitution of fishmeal with *Moringa oleifera* in *O. niloticus* diet, heat treatment was recommended (Tagwireyi et al., 2014). Further, drying, boiling and grinding brings positive results when it is done to potato leaf meal before its inclusion in aquafeeds. Increased palatability and removal of invertase and protease inhibitors were reported (Adewolu, 2008) upon heat treatment. Mechanical extraction and solvent extraction are recommended in processing of non-conventional ingredients. Fermentation is an important method in fish feed detoxification, it helps in reducing anti-nutrients and improves nutritional quality. Fermentation was reported to inactivate anti-nutrients in duckweed leaf meal used in preparing diets for feeding *Labeo rohita* fingerlings (Bairagi et al., 2002). Fermentation is encouraged before use of water hyacinth in aquafeeds. Ensiling by use of lactic acid was reported to eliminate presence of flavonoids, phenols and saponins in *Prosopis juliflora* seed meal (Ondiba, 2016). Dehulling has also been used to prepare seeds of plant species for commercialization (Olagunju et al., 2018).

Extrusion, a process whereby raw feed material is exposed to controlled conditions of high temperature, pressure and moisture can be used to improve the quality of some legume seeds and blended ingredients. Nutrient supplementation is also a technology used to ensure supply of all nutrients necessary to enhance good health and fast growth of culture species. Deficient amino acids, vitamins, minerals, medication, prophylactics, fatty acids etc can be added to aquafeeds as additives. Genetic modification is a modern technology that will ensure cultivation/culture of highly nutritious, palatable and less toxic species for aquafeed production. Defatting by physical and chemical extraction has been considered by insect producers as an appropriate strategy of processing high fat insect larvae for aquafeed production. In the case of chitin, extraction method can be used to reduce chitin levels (Sánchez-Muros et al. 2014). Alternatively, enzyme inclusion in aquafeeds can be used to enhance chitin digestibility (Henry et al. 2015). To address the presence of coelomic fluid, chitin and the slimy, sticky and moisty nature in earthworm, cleaning, blanching in hot water and oven drying (Musyoka et al., 2019) are recommended. In the case of sensory appeal and cultural stigma for black soldier fly, improved nutrition and campaign to change perception among potential users is suggested to enhance commercialization efforts. Development of cultivation and culture protocols for mass production of non-conventional ingredients is a strategy that is likely to greatly promote commercialization of most feed ingredients of protein source for aquafeed production.

Conclusions and way forward

This review demonstrates that there are a number of non-conventional feed ingredients of protein source whose chemical compositions have been evaluated, partly or fully. As a result, there are several plant and animal protein sources that have been characterized and tested on fish with variable outcomes. Inclusion levels recommended for most evaluated plant-based feed ingredients for protein source in aquafeeds is below 50% whereas those of animal origin ranges between 25-66%. This suggests that ingredients of animal origin can be used to replace fishmeal at higher levels than plant ingredients. However, processing techniques and other technologies like genetic manipulation can lead to enhanced inclusion for both animal and plant based proteinous ingredients, without negative effects on growth and health of fish. There is need for further research focusing on validation of innovative technologies meant to promote commercialization of potential ingredients. Further, any efforts should prioritize simple, cost-effective and ease to adapt technologies that can help improve palatability, digestibility, availability and acceptability. Consequently, increased use of non-conventional aquafeed ingredients of protein source will reduce demand and use of fishmeal and other traditional protein ingredients, which are highly needed for human consumption and terrestrial animal feed. Ultimately, this will reduce pressure, associated with fishmeal, on water bodies and promote conservation and sustainable aquaculture production for food and nutrition security in SSA.

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