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Nutritional requirements and effect of culture conditions on the performance of the African catfish (*Clarias gariepinus*): a review

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ABSTRACT

Aquaculture is crucial for global food and nutrition security due to the inability of wild harvests to meet increasing demand. Africa's contribution to aquaculture is generally low, despite its potential for economic development, food security, and reduced unemployment. The study focuses on the African catfish (*Clarias gariepinus*) a freshwater fish species that is widely farmed for food in Africa and other parts of the world. Proper nutrition is essential for the growth and development of the fish, and understanding their nutritional requirements is critical for producing healthy and high-quality fish. This review article provides an overview of the knowledge on the nutritional requirement of the African catfish, including protein, lipids, carbohydrates, vitamins, minerals, and amino acids. The recommended protein content for juvenile fish is between 40 and 50% and for adult fish is between 30 and 40%. Based on the reviewed studies, the recommended amount of methionine in *C. gariepinus diets* ranges from 18.7 to 29.7 g/kg of protein while the lysine requirement ranges from 44.9 to 62.2 g/kg protein). The recommended lipid content in the diet is between 5–15% for juvenile fish and 5–10% for adult fish. The African catfish requires a low-carbohydrate diet, with recommended carbohydrate content between 26 and 32%. They require a variety of vitamins, including vitamin A, vitamin D, vitamin E, and vitamin C, as well as minerals, such as calcium, phosphorus, and potassium. *Clarias gariepinus* also require a variety of essential and non-essential amino acids. Besides the nutritional requirements, culture conditions also have a significant effect on the feed performance. The recommended conditions include temperature ranging from 28 to 32 °C, Light intensity of 150 Lx, 12D:12L photoperiod, and stocking density in earthen of 7 fish m^{-3}. Overall, understanding the nutritional requirements of *C. gariepinus* is crucial for the successful fish farming and sustainable aquaculture. Information in this review will be built to further guide the development of feeds for *C. gariepinus*.

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1. Introduction

Aquaculture is an important food production sector for meeting global food and nutrition security needs to curb the challenges of hunger and malnutrition. There is a consensus that the increasing global demand for aquatic products is unlikely to be met by harvests from the wild owing to several factors, including overfishing, climate change, pollution, and poor management of fisheries resources (FAO, 2022; Maulu et al., 2021). On the other hand, aquaculture production and its contribution to global food fish have continued to increase significantly reaching 122.6 million tonnes, of which 87.5 million tonnes were aquatic animals and 35.1 million tonnes of algae (FAO, 2022). Further, aquaculture production has more than tripled in the last 20 years with numerous advances toward sustaining the sector (Naylor et al., 2021). Currently, aquaculture's contribution to global food fish exceeds 50%, surpassing that of

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capture fisheries whose production has generally declined over the years (FAO, 2022).

Despite the continued global increase in aquaculture production, Africa's contribution has remained generally low due to a limited number of culture species, low investments, and poor advancement in key aspects of aquatic animal culture, such as breeding technology and feeding practices. Furthermore, there are some coordination and policy challenges that hamper the creation of conducive environments for aquaculture development (Satia, 2017), although some improvements have been reported (Adeleke et al., 2020). In Africa, the aquaculture sector holds the potential to drive economic development, improve food and nutrition security, and reduce high unemployment rates (Adeleke et al., 2020; Hasimuna et al., 2019; Khalil et al., 2023). Several studies show that aquaculture expansion has enabled consumers from low-income countries to have all-year-round access to aquatic products that are rich in proteins and macronutrients (Belton et al., 2020; Belton & Thilsted, 2014; Béné et al., 2016; Maulu et al., 2022). Realizing the full potential of aquaculture in Africa will require significant improvements in science and technology developments besides improved policy reforms (Maulu et al., 2019).

Finfish farming has continued to increase globally and its current total production from aquaculture is estimated at 66%, representing the largest share of the sector's production (FAO, 2022). The African catfish (*Clarias gariepinus*) is one the major aquaculture species accounting for 75% of the global aquaculture output (Naylor et al., 2021). *Clarias gariepinus* is endemic throughout Africa and in the Middle East and remains an important aquaculture species for food security in developing countries (Ouma et al., 2022). Around 81% of catfish globally rely on some form of commercially formulated diet as a supplement to natural food produced in the culture systems to attain optimal fish performance (Naylor et al., 2021; Tacon, 2019). However, in catfish farming, the formulation of quality and relatively cheaper feeds is one of the leading factors confronting sustainable production of the species in most developing countries (Mbokane et al., 2022). Over the years, many studies have attempted to investigate the nutritional requirement of the African catfish to improve the species' culture. However, there lacks a synthesis of such studies to provide a detailed summary of recent developments in catfish nutrition as well as highlighting gaps in existing studies to guide future studies and promote sustainable production of the species. Therefore, the present study attempted to compile recent advances in the nutritional requirements of the African catfish (*C. gariepinus)*. The study further highlights major gaps in existing literature for future studies.

2. Methodology

This review was developed using a systematic and comprehensive literature review of peer-reviewed publications. Available published data were collected and compiled using online databases, Google Scholar, ScienceDirect, PubMed, Scopus, and Web of Science. Keywords, such as 'nutrient requirements', 'growth performance', 'catfish', 'feed utilization', and '*C. gariepinus*' were used individually or in combinations to generate matches. Peer-reviewed, published articles and online documents available in the English language were selected. Apart from the primary articles that fulfilled the search criteria, further articles were obtained by scanning through the relevant cross-references contained therein.

3. Digestive system of the African catfish

The digestive system of the African catfish, *C. gariepinus*, has been receiving special attention, mainly due to the importance that this species occupies in aquaculture. *Clarias gariepinus* is considered as carnivorous but it shows an omnivorous behaviour and feeds on large quantities of different food (Dadebo et al., 2014). Several studies have been conducted to provide a well-adapted system for its omnivorous feeding habits which includes both plant and animal matter. The catfish's digestive system starts with the mouth, which is equipped with sharp teeth for biting and grinding food, followed by a short pharynx that leads to a straight and cylindrical oesophagus. The oesophagus leads to the J-shaped stomach, which is lined with glandular mucosa for secreting digestive juices and enzymes (Ikpegu et al., 2014; Verreth et al., 1992). It has been speculated that the J-shape of the stomach helps extend the time feed stays in the organ, thereby ensuring a greater degree of digestion by gastric enzymes. The majority of nutritional absorption occurs in the small intestine, which has microscopic projections that resemble fingers and improve the surface area for absorption (Hamlin et al., 2000). The large intestine is responsible for reabsorbing water and electrolytes and compacting undigested material, which is eventually eliminated as waste (Hamlin et al., 2000).

The development of the catfish digestive system from the larval stage has been found to follow a time-course similar to that described by other researchers (Hamlin et al., 2000; Ikpegu et al., 2014; Kozarić et al., 2008; Nattabi, 2018; Verreth et al., 1992) developing from a rather undifferentiated system into distinct organs with accompanying cells. According to Nattabi (2018), the stomach in *C. gariepinus* appears 4–5 days after hatching (dph), confirming the idea that early development is dominated by alkaline protease digestion before transitioning to a more acidic digestive mode after the development of the stomach. This suggestion is probably an effect of the diet switching from zooplankton to the omnivorous diet of the species during the development state. As the fish develop the gastric glands develop in the pyloric region (Ikpegu et al., 2014) in which rare goblet cells are sometimes observed. The muscularis sheet is particularly thick at the level of the pyloric sphincter (Ikpegu et al., 2014). The stomach is followed up by the intestine which has mucosal folds with honey comp-like appearance. It is hypothesized that, most probably, the shortness of the intestine of the African catfish may be compensated for by an increase in mucosal folding complexity (Al-Hussaini, 1949). This specialization is also a compensation for the absence of pyloric caeca which increases the effective absorptive area of the proximal intestine. Other organs of the digestive system of catfish include the liver and pancreas, producing digestive enzymes (pepsin and trypsin) and bile. The bile helps in the breakdown of fats, while the pepsin and trypsin aid in the digestion of proteins (Al-Hussaini, 1949). Additionally, the catfish has a muscular gizzard, which is responsible for grinding and mashing food before it enters the digestive system.

4. African catfish diet composition

Feeds used in aquaculture are designed to satisfy the dietary requirements of fish species while ensuring the ratio of protein, carbs, and fats (Geay & Kestemont, 2015). The optimal balance in nutrients not only depends on the fish species but also on its life stages (The Fish Site, 2007). Feeds must be nutritionally complete as the fish do not get supplementary nutrients from nature in. intensive aquaculture systems. A shortage of published data on the nutritional requirements of *C. gariepinus* for the different life stages is a hindrance to the development of low-cost feeds.

4.1. Energy

Balance of dietary energy is critical for determining feeding standards for fish. Energy is released by the metabolism of lipids, carbohydrates, and amino acids (proteins) (Robinson & Li, 2015). In fish feeds, the main source of energy is the carbohydrates and lipids, as these are cheaper than proteins. Typically, dietary energy level determines the feed intake which could affect growth and utilisation. For instance, it has been reported that lower dietary energy causes higher feed intake for fish feed to meet their dietary energy requirement (Aderolu et al., 2018; De Silva & Anderson, 1995). However, in the case of catfish this might not necessarily be the case as feed intake maybe linked to what the fish can consume (Robinson et al., 2006; Robinson & Li, 2015). Alternatively, higher dietary energy could result in lower feed intake subsequently leading to reduced intake of essential nutrients and growth. Excess energy level has also been reported to lead to higher fat deposition in the body and inhibition of nutrient utilization. Careful consideration should be made to ensure that the dietary energy to protein ratio is optimal during feed formulation. This is because dietary energy and protein not only influence growth but also the activities of digestive enzymes and plasma metabolites. Additionally, low level of non-dietary protein energy sources (lipids and carbohydrates) in the diet, leads to more expensive protein being utilised for energy instead, thus increasing the cost of fish feeds.

The energy requirements for catfish which are frequently expressed in literature as a ratio of digestible energy (DE) to crude protein (DE/P) range from 7.4 to 12 kcal/g (Robinson & Li, 2015) although a range of 8.5–9.5 kcal/g has been reported as adequate for commercial feeds (Robinson et al., 2006; Robinson & Li, 2015). A similar DE/P range of 8.24–9.19 kcal/g was reported for catfish in the grow-out phase by FAO (2023). African catfish juveniles (51 ± 0.56 g) were fed diets containing 35% crude protein (CP) and graded levels of energy ranging from 2.8 kcal/g in the control diet to 3.6 kcal/g energy in a feeding trial to assess the nutritional energy requirements of the fish (Aderolu et al., 2018). Fish fed feeds with dietary energy level of 3.0 kcal/g had the best FCR while those given feeds with dietary energy level of 3.2 kcal/g had the best PER. The dietary energy requirements reported by Aderolu et al. (2018) are lower than those reported by FAO (2023), Robinson and Li (2015), and Robinson et al. (2006). These changes could be caused by a variety of variables including temperature and production systems.

4.2. Protein and amino acid requirements

Proteins are large organic, nitrogen-containing compounds formed by linkages of individual amino acids (Alberts et al., 2002). Protein requirement information is one of the most important aspects of fish nutrition because proteins, which are synthesized from amino acids are essential for fish growth, tissue repair (Keremah & Beregha, 2014; Miles & Chapman, 2006), and if in excess for energy (Craig & Helfrich, 2017). Since feed is the single biggest expense in fish culture, proteins, being the most expensive component of fish feed, present a significant financial expenditure. Therefore, using proteins as a dietary energy source is equally unfeasible.

A summary of the dietary protein requirements is indicated in Table 1. The amount of protein required in the diet varies depending on life stage, temperature, calorie content of the meal, feeding level, protein digestibility, and the quality of the protein used (Geay & Kestemont, 2015; Keremah & Beregha, 2014). The average minimum protein level of catfish has been reported to range between 28 and 32%, with no detrimental effects on feed efficiency, weight gain, or dressed yield (Craig & Helfrich, 2017). However, other studies have reported a minimum requirement of 40–43% crude protein (Hecht, 2013; Van Weerd, 1995), or a range of 30–35% crude protein (Hecht, 2013) for fish in the grow out phase. However, the dietary protein level for the larval and nursery phase estimated at >50% is higher than that of adult fish (FAO, 2023) as shown in the study by Sinyangwe et al. (2017) where *C. gariepinus* fry (IBW 0.01 g) stocked at 80 fish/m^3 and fed diets containing 52.5% CP had better weight gain and survival compared to those fed diet with 38.8% CP. Since fish require less energy to maintain normal bodily processes than warm-blooded animals like chickens, swine, cattle, horses, and other terrestrial animals, it is acceptable to use higher protein levels in fish meals. Additionally, several fish species get their energy from protein and lipids rather than carbohydrates (Miles & Chapman, 2006). Protein level also depends on the dietary energy because unbalanced dietary protein to energy ratio due to low non-protein energy has been reported to cause reduced growth and PER (Ali & Jauncey, 2005; Taj et al., 2023). This is because the dietary protein may be broken down and utilised as a source of energy to meet the maintenance needs before being utilized for growth purposes (Ali & Jauncey, 2005). The vice versa is true as excess dietary energy provided may inhibit fish feed consumption and limit protein intake (Ali & Jauncey, 2005).

Keremah and Beregha (2014) recommended CP level of 35% for catfish fingerlings (IBW 0.56 g). Although the fish growth was optimal, the protein

Table 1. Effects of dietary protein level on growth performance of African catfish (*Clarias gariepinus*).

Duration	Rearing facility	Protein level (%)	Lipid level (%)	Digestible energy (kJ/kg)	Initial body weight (g)	Final body weight (g)	Specific growth rate (%/day)	Feed conversion ratio	Protein efficiency ratio	References
42 days	Glass aquaria tanks	35	–		0.60	1.7	2.34	4.06 ± 1.38	0.03	Keremah & Beregha, 2014
3 months	Earthen ponds	37	12.3		10.7 ± 0.4	174.4	3.18	1.32	0.26	Kemigabo et al., 2018
78 days	Indoor containers	40	12.7		11	4.26%	1.90	0.93	2.66	Degani et al., 1989
8 weeks	Aquarium tanks	25	12	19,250.17	9.9 ± 0.06	68.7 ± 1.77	1.85 ± 0.05	1.64 ± 0.02	2.60 ± 0.09	Ahmad, 2008
8 weeks	Aquarium tanks	30	12	20,192.82	9.9 ± 0.06	75.8 ± 1.49	1.94 ± 0.04	1.58 ± 0.02	2.28 ± 0.05	Ahmad, 2008
8 weeks	Aquarium tanks	35	9	20,665.19	10.1 ± 0.09	77.4 ± 1.72	1.94 ± 0.03	1.58 ± 0.02	1.97 ± 0.06	Ahmad, 2008
40 days	Tanks	52.5	–	–	0.01 ± 0.0	2.07 ± 0.13	1.99	1.62 ± 0.12	–	Sinyangwe et al., 2017
56 days	Tanks	34	7.5	18,955.61	9.12 ± 0.09	129.60 ± 9.09	4.73 ± 0.12	0.83 ± 0.05	4.73 ± 0.12	Siagian & Nugroho, 2017
56 days	Aquarium tanks	35	–	12,550	51.51 ± 0.18	157.50 ± 20.15	1.99 ± 0.02	1.33 ± 0.17	–	Aderolu et al., 2018
56 days	Aquarium tanks	35	–	13,390	51.50 ± 0.18	163.16 ± 0.58	2.06 ± 0.02	1.35 ± 0.07	–	Aderolu et al., 2018
76 days	Cylindrical tanks	46	16.58	23,750	152.83 ± 54.59		0.60	1.19	1.81	Pantazis, 1999

was utilised inefficiently independent of the CP level in the diet hence indicating that the quality of protein used was poor. Temperature is another factor that affects protein nutrient requirements for catfish. When compared to 25 or 23 °C, a temperature of 27 °C was found to be a better for growth and protein gain of *C. gariepinus* fingerlings (10–12 g) (Degani et al., 1989). In their study, higher protein levels in the diet (40%) led to better growth and feed utilisation than lower protein levels (25, 30, and 35%) (Degani et al., 1989). At all temperatures, fish fed low protein diets retained less protein presumably because a major portion of the protein was used for energy, instead of for growth. For cultured *C. gariepinus* to grow to its full potential, protein synthesis, and sufficient energy intake through feeds are required. However, it was clear that the source of protein contributed to the performance as fish fed diets composed of fishmeal grew better than those fed a diet with high level of soybean meal (Degani et al., 1989). In this study, the gross energy level of the diets ranged from 2.5 to 3.0 kcal/g which is line with dietary reported by Aderolu et al. (2018) although the dietary energy range lower than reported by FAO (2023), Robinson and Li (2015), and Robinson et al. (2006).

Carnivorous fish may experience adverse effects on their growth and well-being due to the consumption of plant-based protein sources, which are characterized by an imbalanced amino acid profile, low palatability, the presence of anti-nutritional factors (Zhou et al., 2018) and the presence of complex, indigestible carbohydrates (Gaudioso et al., 2021). Another study by Kemigabo et al. (2018) reported better performance of *C. gariepinus* fed diets containing 37% CP from plant sources but supplemented with 1200 FTU/kg of phytase. Because fish cannot produce phytase, dietary phytase must be added to their plant-based diets to increase the availability of minerals and nutrients. Thus, the incorporation of phytase had a positive impact on the protein utilisation and growth of *C. gariepinus*.

To enhance the protein sparing action and promote fish growth, it is possible to incorporate either lipids or carbohydrates in the diets. However, an improper balance of dietary protein and energy levels, as well as their ratios, can have negative consequences, such as reduced fish performance, increased production costs, and degraded water quality caused by wasted feed. Therefore, it is crucial to establish appropriate levels of lipid and protein in fish diets, as an imbalance in nonprotein energy sources or levels can negatively affect growth, nutrient utilization, and lipid deposition in the body (Ahmad, 2008). In a study by Ahmad (2008), catfish fingerlings (IBW 9.5–10.3 g) were fed nine diets containing three protein levels (25, 30, or 36% CP) and three lipid levels (6, 9, and 12% lipids). At each respective CP level, the fish performance based on FBW, FCR, and PER was best at 25% CP + 12% lipid, 30% CP + 12% lipid, and 35% CP + 9% lipid. The PER of fish at 30% CP + 12% lipid was higher than that of fish fed the diet with 35% CP + 9% lipid, although FBW, FCR, and PER were not significantly different (Ahmad, 2008). Therefore, it can be said that the lipid had a protein sparing action at 30% CP + 12% lipid and led to better protein utilisation for growth.

4.3. Amino acid

Fish require a sufficient balance of both essential and non-essential amino acids rather than a specific quantity of protein (Miles & Chapman, 2014). Hence, diets that are formulated solely based on protein content may not meet the required levels of all amino acids, particularly the essential ones (Nhu et al., 2021). An imbalance in essential amino acids (EAA) can potentially lead to a decline in growth performance and increased discharge of metabolic nitrogen compounds into the environment (Miles & Chapman, 2014). Although there are more than 200 different types of amino acids present in nature, only 10 of them are considered essential (or indispensable) for fish. These essential amino acids include methionine, arginine, threonine, tryptophan, histidine, isoleucine, lysine, leucine, valine, and phenylalanine cannot be synthesized by fish in sufficient quantities to meet the cellular demand, hence they must be obtained through the diet (Craig & Helfrich, 2017; Miles & Chapman, 2006). Lysine and methionine are often the first limiting amino acids as discussed in sections 4.3.1 and 4.3.2. When protein is digested, its constituent amino acids are released and absorbed into the body thereby facilitating growth. For optimal performance and maximum growth (e.g. size, yield, and body composition), an ideal protein source should have an optimum balance of amino acids. The EAA requirements for African catfish are not well understood. Amino acid requirements are determined by determining the amino acid profile in the body of the fish when limited information is available for new species (Elesho et al., 2021) or by dose response. In other instances, the EAA requirements for some aquaculture species are presumed for African catfish (Fagbenro et al., 1999). Lysine and methionine are the most extensively covered as discussed in sections 4.3.1 and 4.3.2. However, the other EAA requirements available in literature are summarized in Table 2.

4.3.1. Methionine

A majority of ingredients used for least cost fish feed formulation like soybean meal, brewer's yeast, hydrolysed feather meal, groundnut cake, and cotton seedcake are low in methionine (Fagbenro et al., 1999). Methionine is an amino acid that contains sulphur and is used in the process of protein synthesis (Wang et al., 2016), serves as a precursor of carnitine, succinyl-CoA, cysteine, homocysteine, and creatine (Martínez et al., 2017). Its deficiency has been linked to anorexia (Fagbenro et al., 1999), reduced growth and feed efficiency (Elesho et al., 2021), reduced survival, and negatively impacting several metabolic pathways and physiological processes (Wang et al., 2023). In one of the earliest studies in literature, Pantazis (1999) estimated that the dietary methionine content for African catfish (IBW 122–134 g) was 2.6 g/kg protein following whole body amino acid determination. However, the fish had previously been fed on purified diets with high protein content (46% CP) (Pantazis, 1999). Fagbenro et al. (1999) conducted the first known study to quantify the optimum dietary methionine requirement in the absence of cystine for African catfish fingerlings (IBW 18.7 ± 1.8 g). The fish were fed diets containing 400 g/kg protein from purified ingredients and 3.0 Kcal/g gross energy with graded increments of methionine ranging from 20 to 40 g/kg protein. Weight gain, feed conversion ratio, and specific growth rate improved with increasing levels of methionine upto an optimum 32–36 g methionine/kg protein beyond which growth declined (Fagbenro et al., 1999). Based on the growth response curve, the optimum methionine requirement for catfish fingerlings was recommended at 31.6 g methionine/kg dietary protein (12.6 g methionine/kg diet) (Fagbenro et al., 1999). Anorexia was observed for one week in fish fed diets with 20–24 g methionine/kg protein (Fagbenro et al., 1999) which could possibly be due to methionine deficiency. A study by Ovie and Eze (2010) showed that the methionine requirement of African catfish fingerlings (2.97 ± 0.03 g) was 2.97 g/100 g of protein. This finding which was slightly higher than that observed by Fagbenro et al. (1999) could be attributed to several variables, such as fish size, culture protocols, basal diet composition, or models used. More recently, Elesho et al. (2021) quantified the optimum methionine requirement for catfish juveniles (IBW 78 g) fed low methionine legume based diets supplemented with methionine. The authors came to the conclusion that the African catfish required 18.7–21.4 g/kg protein of digestible methionine, which is also much lower than estimates by Fagbenro et al. (1999). Elesho et al. (2021) argued that the use of quadratic regression model for nutrient requirement estimation led to over-estimation of the requirements compared to linear plateau and broken line regression. Additionally, fish fed diets with no methionine supplementation displayed poor feed efficiency and reduced growth (Elesho et al., 2021). Based on the reviewed studies, the recommended amount of methionine in *C. gariepinus diets* ranges from 18.7 to 29.7 g/kg of protein.

4.3.2. Lysine

Lysine is another key limiting EAA in feed ingredients for fish. It plays a significant role in protein synthesis (Madrid et al., 2019), the synthesis of carnitine for mobilization of long-chain fatty acids into hepatocytes that are catabolised for energy generation (Fagbenro et al., 2010; Yang et al., 2011). Generally, catfish fingerlings perform better with increasing

Table 2. EAA requirements (except methionine and lysine) of African catfish (*Clarias gariepinus*).

EAA	CP (%)	Protein sources	EAA requirement level (g/kg dietary protein)	Fish IBW (g)	References
Tryptophan	40	Casein and gelatin	11	11.5 ± 1.1	Fagbenro & Nwanna, 1999
Tryptophan	46	Casein and gelatin	25.9	122–134	Pantazis, 1999
Arginine	40	Casein and gelatin	45	16.6 ± 1.8	Oyedapo et al., 2008
Arginine	46	Casein and gelatin	19.7	122–134	Pantazis, 1999
Histidine	40	Casein gelatin	10–10.5	0.22 ± 0.03	Khan et al., 2009
Histidine	46	Casein and gelatin	13.9	122–134	Pantazis, 1999
Threonine	40	Casein and gelatin	6.8		Olaoluwa, 2017
Threonine	46	Casein and gelatin	20.4	122–134	Pantazis, 1999
Isoleucine	46	Casein and gelatin	15.6	122–134	Pantazis, 1999
Leucine	46	Casein and gelatin	48.7	122–134	Pantazis, 1999
Valine	46	Casein and gelatin	20.8	122–134	Pantazis, 1999
Phenylalanine	46	Casein and gelatin	45.6	122–134	Pantazis, 1999

levels of lysine in the diet. Fish fed lysine levels of 21.8–22.0 g/kg diet (61.7–62.2 g/kg protein) had better growth performance that those fed diets with 13.3–13.8 g/kg diet (Ozório et al., 2001). Catfish fingerlings (IBW 15.4 ± 1.6 g) were fed diets containing 40% crude protein from casein and gelatin, gross energy 12 KJ/g dry matter, 170 g/kg of a mixture of crystalline amino acids, and graded levels of lysine ranging from 40 to 65 g/kg protein. An increase in dietary lysine upto 55–60 g/kg protein resulted in improved fish growth as shown in a study by Fagbenro et al. (2010). Based on the dose-response curve, the lysine requirement was estimated at 57 g/kg of dietary protein corresponding to 22.9 g lysine/kg diet (Fagbenro et al., 2010). The reduced growth of fish beyond the optimal lysine requirement might have led to dietary imbalance. This is similar to the dietary lysine requirement of 44.9 g/kg protein estimated for catfish (IBW 122–134 g) following whole carcass amino acid determination (Pantazis, 1999). Based on the literature reviewed, the recommended range of lysine is 44.9–62.2 g/kg protein).

EAA determination done by Pantazis (1999) was based on analysis of EAA in whole carcass after feeding experiment, unlike the others which were dose-response studies.

4.4. Lipids

Lipids should be given in the proper quantities to maximize the utilisation of dietary protein for growth since they are an essential source of non-protein energy for fish, particularly carnivorous species (Ali & Jauncey, 2004). Compared to carbohydrates, lipids contain higher energy content and are easily digested (Robinson et al., 2006). Besides being energy sources, lipids supply essential fatty acids and help to absorb fat soluble vitamins (Robinson et al., 2006). Triacylglycerols, wax esters, phosphoglycerides, sphingolipids, and sterols are the main types of lipids (Halver & Hardy, 2003). The fatty acids (FA) in these lipid classes are classified according to their degree of unsaturation, position of double bonds, and chain lengths (Halver & Hardy, 2003). Therefore, FA can be saturated, monosaturated, or polyunsaturated (Halver & Hardy, 2003). The polyunsaturated FA includes Fish oil is the key source of lipids in fish feeds (Geay & Kestemont, 2015). Fish oil is mainly comprised of triglycerides and some fat-soluble vitamins (Geay & Kestemont, 2015). The minimum inclusion level of lipids for ranges from 10 to 12% (Hecht, 2013), 4–6% as in commercial feeds (Robinson & Li, 2015). There are several factors that affect the lipid requirements of fish for example the type of lipid, carbohydrate to lipid ratio.

The impact of different dietary sources on the growth and fatty acid composition of the African catfish fingerlings (IBW 9.03 ± 0.01 g) was investigated by Ng et al. (2003). In their study, fish fed diets containing 10% of sunflower oil or various palm oils performed better than fish fed diets containing 10% cod liver oil suggesting that plant-based lipid sources are appropriate for catfish. Therefore, substantial quantities of vegetable oils could potentially replace fish oil, which is expensive, thus contributing to lowering the cost of fish feeds. In addition, there was a favourable link between the fatty acid composition in the lipid sources and the fish muscle. Inclusion of 8% crude palm oil or 8% of refined, bleached, and deodorized palm oil (corresponding to 13.5% lipid and 35% CP in diet) has also been reported to improve the performance of African catfish fingerlings (IBW 7.01 ± 0.05 g) (Lim et al., 2001). However, Ochang et al. (2007) observed reduced performance of catfish fingerlings (IBW 22–25 g) fed diets with 12.26% lipid level in which the only source of lipids was palm oil which corresponded to total fish oil replacement. Instead, they findings of their study showed that recommended that the lipids in the diet contain both cod liver oil and palm oil at a ratio of 1:3.

There is some controversy about whether catfish utilise lipids better as an energy source compared to carbohydrates, and this consequently affects the requirement. In an eight week growth trial, Ali and Jauncey (2004) observed that fish fed 27% CHO and 16% lipids performed better than those fed 38% CHO and 11% lipids. They recommended a CHO:L g/g ratio of 1.7–3.4 for catfish fingerlings (IBW 12.32 ± 0.04 g). As described in section 1.1, lipid requirement depends on the protein level in the diet. It was observed that there was no significant difference in FBW, SGR, PER, and FCR of catfish fingerlings (IBW 9–10 g) fed diets with lower protein and higher lipid (30% CP + 12% lipid) compared to high protein and low lipid (35% CP + 9% lipid) (Ahmad, 2008). High lipid levels have been reported to have negative effects on the fish growth. In a study by Yilmaz et al. (2006) catfish fingerlings (IBW 10–15 g) were fed diets with 35% CP and increasing energy levels. Fish Fed diets with 12.73 MJ/kg feed had the best growth. Fish fed diets with caloric content of 10.85 MJ/kg feed (3.6% crude lipid) and 11.82 MJ/kg feed (7.0% crude lipid) had similar growth to those fed diets with 13.69 MJ/kg feed (15.4% crude lipid) and 15.06 MJ/kg feed (20.5%

crude lipid). However, it is important to note that Yilmaz et al. (2006) observed hepatic lipidosis in fish fed 11.82 and 13.69 MJ/kg feed thus indicating that crude lipid level should be lower than 15% at 35% CP for catfish fingerlings. In the same study, the authors recommended a dietary energy level of 12.73 MJ/kg feed (11% crude lipid) for optimal growth, healthy liver, and optimal blood parameters of catfish fingerlings. From the reviewed studies, the minimum recommended inclusion level of lipids in *C. gariepinus* diets is 11%.

4.5. Carbohydrates

Fish can obtain inexpensive non-protein sources of energy from carbohydrates like sugars and starches (Robinson & Li, 2015). For growth, fish do not require carbohydrates in their diet. They serve a protein-sparing effect in diets when included in the right quantities, maximizing the usage of dietary protein for growth (Orire & Sadiku, 2014). Fish performance based on the incorporation of carbohydrates is variable and depends on the natural feeding habits of the fish, type of carbohydrate, complexity of carbohydrate. Besides the dietary benefit to the fish as an energy source, carbohydrates act as binding agents which is beneficial for better water stability of manufactured feed pellets. In commercial feeds, digestible carbohydrate levels range from 27 to 40% (FAO, 2023; Pantazis, 2005; Robinson & Li, 2015).

The source of the carbohydrates and the amount of protein in the food affect the amount of carbohydrates that African catfish needs. In an eight-week growth trial, Orire and Sadiku (2014) showed that fish (IBW = 8.32 ± 0.04 g) fed diets with the corn fibre performed better than those fed corn starch and glucose at comparable, lower, or higher inclusion levels. In another study by Zaid and Sogbesan (2010), 25% replacement of maize meal with cocoyam as a carbohydrate source led to better performance of catfish fingerlings (IBW 9.86 g) in comparison to the control diet (100% maize meal). However, further replacement of maizemeal with cocoyam led to reduced growth and feed utilisation of the catfish fingerlings (Zaid & Sogbesan, 2010).

Carbohydrates included in catfish diets (IBW 150–171 g) at a level ranging from 26 to 32% have also led to better utilization of proteins due to better lipid and carbohydrate utilization (Pantazis, 2005). Based on the reviewed literature the carbohydrate requirement ranges from 26 to 32%.

4.6. Vitamins

Vitamins must be supplied in the diet of the fish because they are either not synthesized or not synthesized fast enough to cover the fish needs (Geay & Kestemont, 2015). There are few studies investigating the quantitative vitamin requirements of African catfish, particularly through dose response investigations. Vitamin premixes are typically added to commercial catfish feeds to supply all the vitamins required to meet requirements and offset losses resulting from feed processing. Although there are limited published studies, Monje et al. (1996) showed that the inclusion level of vitamin premixes at 2% improved the survival of *C. gariepinus* fingerlings compared to 0 and 3% inclusion levels. Ascorbic acid is the most studied vitamin in relation to *C. gariepinus* growth performance. The impact of supplemental vitamin C (Ascorbic acid) on the health status and growth performance of African catfish was examined by Okhionkpamwonyi and Edema (2017). The fish were fed diets formulated using readily accessible local ingredients that contained 37.4% CP with graded levels of supplementary ascorbic acid (AA) ranging from 0 to 92 mg/kg. Even though fish fed 0 mg/kg AA had higher PER than those in the other treatments, fish fed 42 and 92 mg/kg AA had higher weight gain and had a healthy body experience (Okhionkpamwonyi & Edema, 2017). Fish fed diets containing 0 and 23 mg/kg AA displayed clear deficiency symptoms like visible sutures, nodules on the neck and skin lesions. Although the exact AA requirement was not determined, it can be said that AA requirement for African catfish is ≥42 mg/kg (Okhionkpamwonyi & Edema, 2017). Adewolu and Aro (2009) also fed diets containing graded levels of AA ranging from 0 to 1500 mg L-ascorbic acid/kg diet to catfish fingerlings (IBW 10.12 ± 0.7 g). Compared to the control group, fish fed AA supplemented diets showed better SGR, FCR, PER (Adewolu & Aro, 2009). Additionally, fish fed diets with no supplementary AA showed deficiency signs like skin darkening, reduced growth, flashing, and erratic swimming (Adewolu & Aro, 2009). Although a dose of 1500 mg/kg AA achieved maximum growth performance and feed utilisation efficiency, the authors recommended that 50 mg/kg AA in diet was sufficient to prevent the fish from showing deficiency indications (Adewolu & Aro, 2009). Kuczynski (2002) recommended a 500 mg AA/kg diet for catfish larvae while Erazo-Pagador and Din (2008) recommended range of 1–7 g AA/kg dry diet for wound repair of catfish juveniles (IBW 80–110 g). Baker and Davies

(1997) fed fish diets containing graded levels of all-rac-α-tocopheryl acetate ranging from 0 to 100 mg/kg to evaluate the α-tocopherol requirement for African catfish. Based on broken line analysis, 30–40 mg/kg dry diet was needed to suppress lipid peroxidation. As a fat soluble vitamin, retinol (Vitamin A) is essential in bone growth, cell division, and vision. Udo (2017) recommended that diets for catfish fingerlings (IBW 15.9 ± 0.27 g) should contain vitamin A level ranging from 833 to 1666 IU/kg diet for optimal growth and feed utilization efficiency.

4.7. Minerals

Mineral requirements of African catfish are poorly understood. The key macro minerals are calcium, phosphorus, potassium, magnesium, sodium while the key micro minerals are iron, sulphur, chlorine, copper, manganese, iodine, chromium, zinc, fluorine, cobalt, selenium and molybdenum (FAO, 2023). Phosphorus (P) is a major element that pays a role in bone mineralisation (Schwarz, 1995), growth, and regulating pH in the blood (Nwanna et al., 2009). The gross requirement of phosphorous depends on diet composition and form of phosphorous. For example phosphorous in plant ingredients exists as phytate and can only be released by phytases for increased digestibility (Olugbenga et al., 2019; Schwarz, 1995). Following a dose response growth trial, Nwanna et al. (2009) suggested a range of 6.70–8.20 g P/kg diet as the requirement for catfish fingerlings (IBW 10.2 g). Fish fed the control diet deficient in phosphorous had the least SGR indicating that the existing phosphorus level in the formulated diet was poorly utilised by the fish (Nwanna et al., 2009). Provision of phosphorous beyond the optimal requirement led to reduced growth of the fish which could be attributed to pollution problems in the culture environment. The absorption of P is affected by the antagonistic effect of dietary calcium (Ca) (Nwanna et al., 2009). Therefore, it can be said that the dietary P requirement for catfish is dependent on the dietary calcium level. Both calcium and phosphorous make up 70% of mineral elements in the fish's body. A study by Nwanna and Oni (2018), suggested a Ca/P ratio of 2:1.5 as optimal for catfish fingerlings (IBW 7.60–7.70 g).

Zinc (Zn) is a micro/trace element with the highest concentration in the whole body of fish (Schwarz, 1995). It plays a role in growth, and antioxidant response in fish (Mahboub et al., 2020). Zinc deficiencies result in a reduced growth rate. Dietary supplementation of zinc using nano zinc oxide at 20 mg/kg improved the growth and antioxidant status of catfish (Mahboub et al., 2020). Potassium (K) plays a crucial role in acid-base balance, nerve functioning, and enzyme activities. Potassium concentrations ranging from 200 to 400 mg/L were recommended for improved welfare and growth of African catfish (IBW 29.5 g) grown in aquaponics systems (Wenzel et al., 2021). In aquaponics systems, the welfare of both the plants and fish has to be considered.

5. Nutritional requirement and growth performance changes with culture conditions

5.1. Effect of temperature

Fish are cold-blooded animals, and the water temperature plays a significant role in their survival and growth. Each fish species has an ideal temperature range, and any deviation from this range can adversely affect their growth and health (Fatma & Ahmed, 2020). In a study by Degani et al. (1989) *C. gariepinus* fingerlings (10–12 g) showed better growth and protein gain at a temperature of 27 °C compared to 25 or 23 °C. Fish fed higher protein diets (40%) grew better and had better feed utilization than those fed lower protein diets (25, 30, and 35%) at all temperatures. However, at all temperatures, fish fed lower protein diets retained less protein, presumably because more protein was used for energy than for growth. According to Conceição et al. (1998), higher temperatures led to increased absorption and depletion rates of amino acids, in addition to higher retention efficiency of yolk nutrients in African catfish larvae. This suggests that temperature could have induced the synthesis of different proteins or change in the proportions of the proteins being synthesizes during larval growth. Hien et al. (2022) reported similar findings in red hybrid tilapia (*Oreochromis mossambicus* × *Oreochromis niloticus*) where higher temperature and salinity increased the energy and protein maintenance requirements. In a study by Singh et al. (2009) final body weight of Asian catfish (*C. batrachus*) fry had higher final body weight when fed diets containing 36% CP at 28 and 32 °C, with higher weight gain observed at 32 °C.

5.2. Effect of light

While it is unclear whether light and darkness have a direct effect on the nutritional requirements, Almazán-Rueda et al. (2004) showed that husbandry conditions influenced the agnostic behavior and swimming activity of African catfish fingerlings (IBW

55 g). Their research found that the fish's swimming activity increased with a higher light intensity of 150 lx, and those under continuous light were more aggressive and had more scars on their body than those under 12D:12L photoperiod. Since swimming demands more energy, higher light intensity, and continuous lighting likely increased the energy requirements. In another study by Appelbaum and Mcgeer (1998), continuous darkness in the culture tank also enhanced the growth of catfish fingerlings. However, a study by Mukai and Seng Lim (2011) reported no significant differences in the ingestion rates and behavior of African catfish larvae under dark and light conditions, although survival rates were higher under dark/dim conditions with adequate access to food. Additionally, Solomon and Okomoda (2012a, 2012b) found that that photoperiod had no effect on condition factor, and total darkness in the fish culture tank could improve feed conversion efficiency and reduce cannibalism.

5.3. Tank color and shape

African catfish have been reported to perform better in dark colored tanks compared to lighter ones (Okomoda et al., 2017). In a study by Ninwichian et al. (2022), hybrid catfish (*C. macrocephalus* × *C. gariepinus*) fry reared in red tanks had the best growth, survival, and feed uttilisation performance compared to those reared in blue, green, white, and blank tanks. Krasteva et al. (2020) made a similar recommendation for European catfish (*Silurus glanis*) fingerlings as dark colored tanks were reported to resemble natural fish habitats. Tank shape has also been reported to have not significant effect on the growth performance of catfish fry however, fish in circular tanks has the highest weight gain and specific growth rate compared to those in rectangular and square tanks (Akinwole & Akinnuoye, 2012; Amponsah et al., 2021).

5.4. Stocking density

Catfish growth and performance have been reported to be affected by stocking densities. High stocking densities have resulted in stress and subsequently, negative impacts on fish growth and health. Stocking density is dependent on several factors including fish age, the production system, and its effect vary throughout the production cycle. In a commercial RAS system, fish stocked at 100 kg m^{-3} had a significantly higher final body weight compared to those stocked more intensively at 200 and 400 kg m^{-3} (Baßmann et al., 2023). In another study, van de Nieuwegiessen et al. (2009) showed that both low and high stocking densities could negatively affect the growth of African catfish. For early juveniles of weight ranging from 10 to 100 g, low stocking densities were characterized by higher aggression and increased plasma cortisol whereas, the effect of stocking density on welfare indicators for larger fish weighing 1044.6–1455.4 g was less apparent (van de Nieuwegiessen et al., 2009). As such, fish farmers should put a stronger emphasis on avoiding lower stocking densities, especially at juvenile stages. Wenzel et al. (2022) also reported the highest African catfish fry aggression at lowest stocking densities (10 fish L^{-1}). While the authors recommended an optimal stocking density of 30 fish L^{-1} combined with self-grading it was noted that stocking densities did not affect survival and growth of the larvae. Studies have also been carried out to investigate the effect of stocking density in ponds. Fish stocked in earthen ponds at density of 7 fish m^{-3} had the highest profitability index, growth, and feed utilization parameters compared to those stocked at higher or low densities (Oké & Goosen, 2019). While higher stocking densities 10 fish m^{-3} had higher net return, there were significant environmental tradeoffs that consequently affected production.

5.5. Salinity

Britz and Hecht (1989) investigated the effect of salinity on the growth and survival of African catfish larvae (10 ± 2 mg). In their study, larvae in treatments whose salinity ranged from 0 to 5.0 ppt showed no significant differences in growth rate although there was a decline in condition factor from salinity level 2.5 ppt upwards. Similar results were reported by Zidan et al. (2022) in catfish juveniles exposed to treatments with salinity levels ranging from 0 to 20 ppt. In their study, the fish also exhibited increased stress behavioral responses and feed conversion with increasing salinity levels.

6. Conclusions and perspectives

In conclusion, the African catfish is a valuable freshwater fish species that is widely farmed for food in Africa and other parts of the world. Proper nutrition is critical for the growth and development of the fish, and understanding their nutritional requirements is essential for producing healthy and high-quality fish. A balanced and complete commercial feed can meet the nutritional requirements of African catfish, but it is important to monitor the growth and development of the fish and adjust the diet accordingly. The recommended protein content for juvenile fish is between 40 and 50% and for adult fish is between 30 and 40%. Based on the reviewed studies, the recommended amount of methionine in *C. gariepinus diets* ranges from 18.7 to 29.7 g/kg of protein while the lysine requirement ranges from 44.9 to 62.2 g/kg protein). The recommended lipid content in the diet is between 5–15% for juvenile fish and 5–10% for adult fish. The African catfish requires a low-carbohydrate diet, with recommended carbohydrate content between 26 and 32%. They require a variety of vitamins, including vitamin A, vitamin D, vitamin E, and vitamin C, as well as minerals, such as calcium, phosphorus, and potassium. *Clarias gariepinus* also requires a variety of essential and non-essential amino acids. Besides the nutritional requirements, culture conditions also have a significant effect on the feed performance. The recommended conditions include temperature ranging from 28 to 32 °C, Light intensity of 150 Lx, 12D:12L photoperiod, and stocking density in earthen of 7 fish m^{-3}. Overfeeding should be avoided, and nutrient imbalances and other health problems should be addressed promptly. Overall, successful fish farming and sustainable aquaculture depend on understanding the nutritional requirements of African catfish and providing a balanced and appropriate diet.

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Author contributions

SM and SL conceptualised the idea and defined the objectives of the manuscript. SL, SM, OJH, VKK, and MT participated in writing of original draft. SL coordinated the writing, review, and submission of the manuscript. All the authors read and approved the final version of the manuscript.

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Data availability statement

The data supporting this review are from previously reported studies and datasets, which have been cited.

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