***Suitability of Hermetia illucens* Larvae Meal and *Moringa leifera* Leaf Meal to Replace Fishmeal in *Clarias gariepinus* Diet: A Mini-Review**

# Abstract

Across the globe, African catfish (*Clarias gariepinus*) is increasingly recognized as a vital species in aquaculture, renowned for its complex biology and adaptability to varying

environmental conditions. As demand for sustainable aquaculture feeds grows, the need for alternative protein sources to replace conventional fishmeal becomes more pressing. This review explores the multifaceted biology and nutritional needs of African catfish,

emphasizing its dietary protein requirements during various growth stages and the impact of alternative protein sources on its development. Among these alternatives, Black Soldier Fly

larvae (*Hermetia illucens*) and Moringa leaf meal (*Moringa oleifera*) emerge as promising contenders, offering significant potential in both cost-effectiveness and sustainability. The review also investigates the ecological implications of using these alternative proteins, alongside their economic benefits and challenges in large-scale implementation. By

examining the core aspects of African catfish nutrition, alternative feed ingredients, and their influence on growth and reproductive performance, this review aims to provide a comprehensive framework for advancing aquaculture practices and promoting

environmental sustainability.

*Keywords: Clarias gariepinus, Hermetia illucens, Fishmeal, Moringa oleifera leaf, sustainability*

1. **Introduction**
	1. **The African Catfish (*Clarias gariepinus*)**

*Clarias gariepinus*, commonly referred to as the African catfish, has garnered significant attention in aquaculture due to its exceptional morphological and physiological traits that enhance growth, adaptability, and production efficiency. Its rapid growth rate, a result of targeted selective breeding programs, has yielded remarkable improvements in growth by 10- 40% and productivity gains of 15-70%, while simultaneously shortening the growth cycle (Srimai *et al.,* 2019; Imron *et al.,* 2020; Srimai *et al.,* 2020). The species' low feed conversion ratio (FCR) further enhances its economic viability, as it efficiently converts feed into body mass, a critical factor in reducing operational expenses dominated by feed costs (Imron *et al.,* 2020; Naorbe, 2021). Feeding trials, such as those involving raw chicken entrails at 4% of body

weight, demonstrate optimal growth rates, feed conversion, and survival, showcasing the species' dietary adaptability (Naorbe, 2021). This resilience extends to disease resistance and high survival rates under pathogenic stress, such as exposure to *Aeromonas hydrophilia*, which underscores its robustness in intensive farming systems (Imron *et al.,* 2020). Furthermore, the species thrives across diverse aquaculture systems, including earthen ponds and polyethylene tanks, with minimal genotype-environment interactions affecting growth traits. Morphological variability within the species facilitates selective breeding efforts aimed at enhancing traits like size uniformity and carcass quality, without compromising reproductive performance despite the low heritability of reproductive traits (Mikaheel *et al.,* 2022; Michael & Olubunmi, 2021). Collectively, these attributes, first explored in foundational research by Huisman and Richter (1987), solidify *C. gariepinus* as a cornerstone of sustainable aquaculture.

# Taxonomy of African catfish

Taxonomically, *C. gariepinus* occupies a chief position within the *Clariidae* family, belonging to the *Siluriform* order, a diverse group of freshwater catfishes. It shares close mitochondrial DNA similarities with species like *Clarias camerunensis*, though phylogenetic analyses confirm distinct genetic identities (Kundu *et al.,* 2023). Other related species, including *Clarias platycephalus, Clarias gabonensis, Clarias buthupogon*, and *Clarias angolensis*, display significant ecological diversity, particularly in regions like the Lower Congo and Pool Malebo. Morphological studies, such as those comparing *C. gariepinus* with *Clariallabes melas*, reveal evolutionary adaptations, including cranial variations, which reflect the species' ability to exploit varied ecological niches (Cabuy *et al.,* 1999). These phylogenetic insights underscore the biological significance of *C. gariepinus* as both an aquaculture model and a representative of ecological dynamics within freshwater ecosystems (Kundu *et al.,* 2023).

# Diverse Physiological Adaptabilities of African catfish

* + 1. **Water parameters**

The African catfish (*C. gariepinus*) exhibits exceptional adaptability to a wide range of water quality parameters, including temperature, pH, and dissolved oxygen, which ensures its resilience and suitability for diverse environments. The species thrives optimally at temperatures around 28°C, where efficient metabolic processes and growth are supported, with stability in temperature being critical for survival (Nchegang *et al.,* 2024). Additionally, it shows a preference for neutral to slightly alkaline pH levels, with optimal larval survival recorded between pH 6.7 and 7.5, as this range promotes proper osmoregulation and ion balance (Marimuthu *et al.,* 2019). In suboptimal pH conditions, the fish employs adaptive

physiological mechanisms, enabling survival amidst fluctuating water chemistries (Samuel and King, 2024).

Despite its remarkable tolerance, dissolved oxygen levels below 3 mg/L hinder growth and survival, although *C. gariepinus* can tolerate short-term hypoxia by utilizing atmospheric oxygen through specialized structures, provided regular oxygenation occurs (Nindum *et al.,* 2023). Poor water quality, characterized by high ammonia levels and low dissolved oxygen, reduces growth rates and survival, necessitating adaptive physiological responses such as enzyme activity modifications to cope with these stressors (Nindum *et al.,* 2023). These physiological adaptations help the species maintain homeostasis, showcasing its resilience across diverse aquatic environments (Latief *et al.,* 2023).

# Feeding strategy

Feeding habits further highlight the adaptability of *C. gariepinus*, as it is an omnivorous species consuming phytoplankton, zooplankton, insects, detritus, macrophytes, and small fish, ensuring survival across reservoirs, rivers, and lakes (Dessie *et al.,* 2024). Seasonal variations significantly influence its diet, with zooplankton and phytoplankton dominating during dry seasons and detritus and macrophytes prevailing in wet seasons (Dessie *et al.,* 2024). Ontogenetic dietary shifts also optimize resource utilization across life stages, as smaller fish primarily consume insects and zooplankton, whereas larger individuals shift to diets dominated by fish and detritus (Dadebo *et al.,* 2014).

Carnivorous tendencies further highlight the ecological flexibility of *C. gariepinus*, with fish and invertebrates forming significant dietary components in ecosystems such as Lake Babogaya and Lake Sibaya (Bruton, 2010). The species employs feeding strategies like bottom foraging and surface feeding, enabling it to exploit different ecological niches and adapt to environmental fluctuations (Bruton, 2010). Its ability to switch dietary preferences based on food availability underscores its dietary flexibility, a critical survival mechanism in habitats with fluctuating resources (Dessie *et al.,* 2024). This adaptive behavior establishes *C. gariepinus* as both a predator and a scavenger, ensuring ecological success across diverse aquatic systems (Dessie *et al.,* 2024).

Feeding practices also play a critical role in balancing growth performance and cost-efficiency. Feeding fingerlings three times daily at 5% of their body weight enhances growth and survival, while feeding at 6% of body weight per day offers optimal growth, though 2% feeding may improve feed utilization, striking a balance between cost and growth outcomes (Okomoda *et al.,* 2019). These strategies collectively demonstrate that precise protein levels, balanced amino

acid compositions, strategic feeding regimens, and innovative protein alternatives are indispensable for supporting the early growth stages of African catfish fingerlings.

* 1. **Nutrient Requirements of *C. gariepinus***

Achieving optimal growth in *C. gariepinus* requires a diet that meets its precise macronutrient and micronutrient requirements. Studies have shown that a high protein content of 40-45% in the diet is essential for promoting growth, with significant growth improvements observed at protein levels of 40% (Hassan, 2023) and 45% (Oparah *et al.,* 2011). Similarly, a crude fat content of approximately 12% has been identified as beneficial for enhancing growth performance (Oparah *et al.,* 2011). Minimal fiber content, at 1.5%, and an ash content of 9.5% are also recommended to support optimal growth rates (Oparah *et al.,* 2011). Carbohydrates are another key component, with research indicating that up to 50% of maize in the diet can be replaced with sweet orange peel without negatively affecting growth performance (Yusuf *et al.,* 2022). Additionally, micronutrients and natural additives have shown to significantly enhance growth and survival, with ginger and garlic improving these metrics and microalgae such as *Phaeodactylum tricornutum* increasing nutrient utilization (Nyadjeu, 2020). Alternative protein sources such as *Boscia senegalensis* seeds and baobab seed meal have also proven effective, with 50% and 10% inclusion levels, respectively, yielding positive growth outcomes (Hassan, 2023).

Protein and lipid sources play primary roles in the diet of *C. gariepinus*, directly impacting growth, feed utilization, and body composition. Optimal protein levels of 30-35% crude protein are widely regarded as ideal for growth and feed efficiency (Ahmad, 2008). Alternative protein sources such as *Hermetia illucens* larvae, microalgae, and bacterial protein have been explored as sustainable substitutes for fishmeal, with studies demonstrating that these alternatives maintain or even enhance growth performance and nutrient utilization (Fawole *et al.,* 2020). Lipids are equally crucial, with an optimal dietary inclusion of 9-12% shown to maximize growth and feed efficiency while promoting protein utilization through a protein-sparing effect (Ahmad, 2008). The balance between protein and lipid levels is also critical, with a protein-to- lipid ratio of 34.62% protein to 12.12% lipid yielding superior growth results. Furthermore, animal-based lipids such as pork lard have been shown to be more effective for growth and feed utilization compared to plant-based lipids like soybean oil, although the latter offers improved cholesterol profiles in fish (Nwakaji *et al.,* 2021).

# Protein requirement of African catfish fingerlings

The protein requirements of African catfish (*Clarias gariepinus*) fingerlings during early growth stages are critical for optimal growth, efficient feed conversion, and nutrient retention. Research highlights that dietary protein levels between 34.4% and 39.6% are essential for maximizing growth potential, improving live weight gain, protein efficiency ratio, and protein retention efficiency (Farhat & Khan, 2011). These protein levels provide the building blocks necessary for tissue development and metabolic processes, emphasizing their importance during rapid growth phases. Adequate inclusion of essential amino acids, such as 2.06% methionine and 8.11% lysine, further enhances growth rates and nutrient digestibility, highlighting the critical role of a balanced amino acid profile in supporting fingerling development (Hamid *et al.,* 2017).

Feeding strategies complement these dietary formulations by optimizing nutrient utilization. Studies suggest that feeding fingerlings at 5% of their body weight, divided into two daily meals, significantly improves growth and nutrient uptake (Hamid *et al.,* 2017). Moreover, dividing daily rations into three portions administered at regular intervals further enhances growth performance and survival rates, underscoring the importance of consistent and frequent feeding patterns. Additionally, protein sourcing is a key factor; the partial substitution of fishmeal with alternative protein sources such as black soldier fly larvae meal at a 50% replacement level has been shown to sustain robust growth performance and nutrient utilization, offering a sustainable and cost-effective solution (Fawole *et al.,* 2020).The quality of protein, particularly the balance and availability of essential amino acids, directly influences growth and nutrient utilization in African catfish fingerlings (Hamid *et al.,* 2017). High levels of protein-bound methionine and lysine have been associated with optimal weight gain and specific growth rates, emphasizing their indispensable role in diet formulation (Hamid *et al.,* 2017). Furthermore, the choice of protein source and substitution levels significantly impact growth performance. For instance, while black soldier fly larvae and African yam bean meal can partially or wholly replace fishmeal, imbalanced amino acid profiles in alternative sources may reduce growth and nutrient utilization (Fawole *et al.,* 2020; Okeke *et al.,* 2017). Nonetheless, achieving balanced amino acid profiles remains crucial, even in locally formulated feeds, to optimize growth and nutrient retention (Magouz *et al.,* 2019).

Suboptimal protein levels in diets can hinder growth and survival rates in African catfish fingerlings, demonstrating the necessity of precise protein formulations. Dietary protein levels of 35% to 45% have been identified as optimal for growth, with 35% crude protein supporting the best growth performance, while 45% protein diets maximize weight gain and specific growth rates (Ronald *et al.,* 2021). In contrast, diets containing lower protein levels, such as

25% or 30%, yield poorer growth outcomes and higher feed conversion ratios, reflecting inefficient nutrient utilization (Magouz *et al.,* 2019). Higher protein diets also improve survival rates, with the best outcomes observed at 45% protein levels, while lower protein diets compromise survival and overall health (Ronald *et al.,* 2021). Protein efficiency ratios and feed conversion ratios are likewise optimized with higher protein diets, confirming the importance of adequate dietary protein for effective feed utilization and growth (Ronald *et al.,* 2021).

Sustainable aquaculture practices increasingly emphasize alternative protein sources to replace fishmeal in the diets of African catfish fingerlings. Black soldier fly larvae (BSFL) meal, for instance, supports a 50% substitution level, maintaining superior growth performance and nutrient utilization while preserving physiological parameters such as blood health and oxidative stress markers (Fawole *et al.,* 2020). Other insect-based proteins, such as cricket and mealworm meals, also demonstrate viability, with cricket meal enabling up to 100% fishmeal replacement without adverse effects on growth or body composition, though minor deficiencies in essential amino acids have been noted (Taufek *et al.,* 2018). Mealworm meal can replace fishmeal at levels up to 80%, sustaining excellent growth and feed efficiency, further reinforcing its promise as an alternative protein source.

Plant-based proteins, including soybean and sunflower meal, effectively replace up to 50% of fishmeal, maintaining immune responses and antioxidant status. However, higher inclusion levels may negatively impact globulin levels and increase mortality rates, necessitating careful formulation (Reda *et al.,* 2021). Conversely, African yam bean meal exhibits limitations, with replacement levels exceeding 50% reducing growth and compromising gonad development (Okeke *et al.,* 2017). Animal by-products such as feather, blood, tilapia, and maggot composite meals have emerged as cost-effective alternatives, enabling full fishmeal replacement with commendable growth and feed utilization outcomes (Emmanuel *et al.,* 2022). Algae-based proteins like Spirulina and Chlorella also demonstrate efficacy, with inclusion levels around 68-69% significantly enhancing growth and feed efficiency (Raji *et al.,* 2019).

# Some Alternative Animal Protein Ingredients and their Limitations

The assumption so far is that alternative fish feeds can supply adequate essential nutrients requirements for fish growth and health (Matanda, 2017). Non-conventional fish feeds are prospective feed components, which are rarely used in fish feed processing, due to insufficient knowledge on their protein content during manufacture with a view to commercializing them (Matanda, 2017). The expectation is that they are readily available and cheaper since they are from plants or animals not regularly used as food by humans (FAO 2014). The use of unconventional feeds has been reported to promote growth and have cost effective value. Focus

has been placed on the use of insects, worms, garden snails and tadpoles among others as alternative protein sources for cultured fish (Abowei *et al.,* 2011). The plant protein sources of fish diets comprise, leaf protein, leaf meal, aquatic macrophytes, cultivable pulses such as Mucuna bean, yam beans, bread beans, winged beans and any legume that can yield pods with seeds (Abowei *et al.,* 2011). Animal waste, mainly droppings from pig and poultry can be used to enrich ponds for growth of plankton or when uncontaminated, as a direct source of fish feed (Matanda, 2017). Some farmers have used poultry manure without further artificial feed with good results (Mahboob and Al-Ghanim, 2014). Earthworms (*Lumbricus terrestris* and *Allobophora long*) have been used as food for fish in artisanal fisheries and thus may be a potential source of protein. Studies have shown that insects such as desert locusts, cockroaches, black soldier fly larvae and worms such as polychaetae have high nutritional value in terms of proteins, fatty acids and mineral salts (Matanda, 2017). But sustainability is paramount in looking for cheaper alternative feeds for fish. The high fecundity of insects makes them nearly inexhaustible and perhaps the best candidates.

In this regard, scientists in many parts of the world have proposed using insect biomass as an excellent feed for animal feed such as poultry, swine, and fish. Insects, especially fly larvae, can feed on low-grade organic matter that is converted into proteins and fats. Insect meals and whole insect diets are used in fish farming and animal nutrition (FAOb, 2012; Cohen, 2015) and their use in animal nutrition needs to be increased (Cappellozza *et al.*, 2019). Insect meals are rich in essential amino acids particularly lysine, methionine, and leucine, and do not have any anti-nutritional factors (Spranghers *et al*., 2017). Insects are also very high in crude protein, over 60% in some species (Matanda, 2017), and vary widely in fat content.

# The Black Soldier Fly

The Black Soldier Fly (*H. illucens*) is a biologically and ecologically significant insect, recognized for its remarkable ability to convert organic waste into valuable resources (Liu *et al.,* 2019; Surendra *et al.,* 2020). Munsch-Masset *et al.,* (2023) notes that the reproductive system of the Black Soldier Fly exhibits sophisticated adaptations to sexual selection, with females possessing specialized sperm storage organs capable of holding a large number of spermatozoa, facilitating multiple matings. Males, on the other hand, produce long sperm that align with this reproductive strategy, enabling successful fertilization (Munsch-Masset *et al.,* 2023). Genomic studies reveal that *H. illucens* has an expanded genome in areas related to septic adaptation, particularly immune system factors and olfactory receptors, enhancing its survival and efficiency in waste conversion (Zhan *et al.,* 2019). Additionally, the larvae exhibit

specialized mouthparts, akin to a "tunnel boring machine," enabling them to process a wide variety of organic materials efficiently (Bruno *et al.,* 2020).

Ecologically, the larvae of *H. illucens* play a critical role in waste management by digesting organic waste and converting it into proteins, lipids, and other valuable compounds. This process reduces waste, produces animal feed, and supports biodiesel production (Liu *et al.,* 2019; Surendra *et al.,* 2020). The larvae's capacity to thrive on diverse organic substrates positions them as a sustainable option for waste management, aligning with circular economy principles by transforming waste into recyclable materials and by-products (Giannetti *et al.,* 2022). However, the presence of bacteria in their gut microbiome, which aids digestion and waste conversion, necessitates safety measures to mitigate potential health risks, particularly in their application as animal feed (Khamis *et al.,* 2020).

# Suitability of BSFL in Aquaculture

The integration of Black Soldier Fly (BSF) production into aquaculture systems offers a sustainable approach to enhancing resource utilization and reducing environmental impact, as BSF larvae can be used as an alternative protein source in aquafeeds and as a nutrient recycler in aquaponics (Zarantoniello *et al.,* 2020; Hoc *et al.,* 2021; Zarantoniello *et al.,* 2019). In aquafeeds, BSF larvae meal can replace a significant portion of fishmeal without compromising fish growth or health, with studies showing that substituting up to 50% of fishmeal with BSF meal in diets for species like zebrafish and rainbow trout can maintain growth performance (Zarantoniello *et al.,* 2020; Hoc *et al.,* 2021; Zarantoniello *et al.,* 2019). Additionally, BSF meal enriched with spirulina has been shown to have no negative effects on fish welfare or quality traits in European seabass (Zarantoniello *et al.,* 2023). In aquaponics, BSF larvae frass serves as an effective organic fertilizer, supporting plant growth without negatively affecting water quality or plant yield (Nguka *et al.,* 2024), and BSF meal can replace up to 30% of fishmeal in tilapia-spinach aquaponics systems, supporting both fish and plant growth (Tadesse, 2023). The integration of BSF into aquaculture promotes a circular bioeconomy by converting organic waste into valuable nutrients, reducing reliance on marine-derived fishmeal, and sparing significant amounts of pelagic fish from ocean catch (Yakti *et al.,* 2024; Shaw *et al.,* 2023; Moore *et al.,* 2024).

The Black Soldier Fly (BSF) has been successfully implemented as a feed component in several regions worldwide, primarily due to its ability to convert organic waste into high-nutrient biomass suitable for animal feed (Alagappan *et al.,* 2021). In the European Union, Australia, Canada, and the USA, specific regulations allow the trade and manufacture of BSF as feed under certain conditions, facilitating its use in animal feed production (Alagappan *et al.,* 2021).

Indonesia has also explored the nutritional value and production potential of BSF, particularly in the context of ruminant feed, with studies showing that it can be used as a substitute for traditional feed components like soybean meal in goat diets without adverse effects on growth or health (Astuti & Wiryawan, 2022). In West Java, Indonesia, BSF larvae have been integrated into sustainable farming systems, particularly for organic waste management and animal feed production, demonstrating successful application in quail farming (Sinaga *et al.,* 2024). Additionally, BSF meal has been used as a direct replacement for complex fish feed in regions where fish farming is prevalent, such as for African catfish and rainbow trout, showing no negative impact on growth or survival rates (Bartucz *et al.,* 2023). The successful implementation of BSF as a feed component in these regions highlights its potential to support sustainable agriculture practices by converting organic waste streams into valuable feed (Miranda *et al.,* 2020), while also providing a high-protein and lipid-rich feed option, making it a viable alternative to traditional feed ingredients (Mangindaan *et al.,* 2022).

The widespread adoption of Black Soldier Fly larvae (BSFL) as aquaculture feed is limited by several factors, including nutritional composition, production challenges, and awareness among farmers (Ewald *et al.,* 2020; Ido *et al.,* 2021). One of the primary nutritional limitations is the fatty acid profile of BSFL, which is rich in saturated fatty acids, such as lauric acid, but lacks sufficient unsaturated fatty acids like EPA and DHA, crucial for replacing fish oil in aquaculture feeds (Ewald *et al.,* 2020). Additionally, the fat content in BSFL can negatively impact the growth of certain fish species, suggesting that defatting the larvae meal may be necessary to improve growth outcomes (Ido *et al.,* 2021). Production challenges also hinder the adoption of BSFL, including the influence of diet and environmental conditions, such as pH and feeding systems, on the growth and nutritional quality of the larvae, which require optimization for mass production (Liland *et al.,* 2023). Furthermore, the accumulation of heavy metals like arsenic and mercury in BSFL grown on certain substrates poses a safety risk, exceeding legal limits for feed ingredients (Liland *et al.,* 2023). Awareness and economic factors also play a significant role, with farmer awareness in regions like Kenya influenced by socioeconomic status, distance to feed sources, and knowledge about feed components (Ouko *et al.,* 2023). The economic competitiveness of BSFL as a feed alternative depends on its availability and ability to produce larvae at scale (Tegtmeier *et al.,* 2021).

# Suitability of BSFL to Replace Fishmeal

Black Soldier Fly larvae meal (BSFLM) has emerged as a promising alternative to fishmeal in aquaculture diets due to its ability to replace a substantial portion of fishmeal without compromising fish performance. The substitution of fishmeal with BSFL in aquaculture diets

represents a promising avenue for reducing dependence on traditional fishmeal, which is often expensive and environmentally unsustainable (Madibana *et al.,* 2020). Studies indicate that BSFL can replace fishmeal in the diets of various fish species, including Atlantic salmon, dusky kob, barramundi, Nile tilapia, Japanese eel, and zebrafish, without compromising growth performance, feed efficiency, or overall health (Madibana *et al.,* 2020; Tippayadara *et al.,* 2021; Kuo *et al.,* 2022). In certain cases, partial replacement of fishmeal with BSFL has even improved growth metrics, highlighting its potential as a nutritionally rich and economically viable alternative (Wachira *et al.,* 2021). The nutritional composition of BSFL, which is high in protein, lipids, and essential nutrients, enhances immune responses and mucosal barrier functions in fish, further solidifying its role as a sustainable protein source (Tippayadara *et al.,* 2021; Liu *et al.,* 2024). The ability of BSFL to convert organic waste into high-quality protein not only reduces environmental impact but also lowers costs associated with feed production, particularly in regions where fishmeal is scarce or prohibitively expensive (Wachira *et al.,* 2021; Liu *et al.,* 2024). Optimal replacement levels for fishmeal with BSFL typically range from 20% to 50%, ensuring a balance between nutritional adequacy and cost-effectiveness (Madibana *et al.,* 2020; Liu *et al.,* 2024).

The replacement percentage varies depending on fish species and specific dietary requirements (Tippayadara *et al.,* 2021; Kuo *et al.,* 2022). For instance, BSFLM can fully replace fishmeal in Nile Tilapia diets (up to 100%) without adverse effects on growth, feed utilization, or survival rates, while enhancing mucosal immune responses (Tippayadara *et al.,* 2021). Similarly, replacement levels of 47% in Juvenile Tench, 30% in Japanese Eel, and 14% in Juvenile Turbot have shown optimal results, with higher levels feasible without significant growth impacts (Kuo *et al.,* 2022; Zhao *et al.,* 2023). In Atlantic Salmon, complete replacement (100%) of fishmeal with BSFLM maintains growth, nutrient digestibility, and sensory qualities of the fillet (Belghit *et al.,* 2019), whereas a 25% replacement is economically optimal for Asian Seabass (Liu *et al.,* 2024). Additional studies report that Dusky Kob and Zebrafish can tolerate up to 20% and 100% BSFLM replacement, respectively, without adverse effects on growth or feed utilization (Madibana *et al.,* 2020). In African catfish, a 25% BSFLM replacement optimizes growth and profitability, enhancing profit indices and reducing incidence costs compared to diets without BSFLM (Mundida *et al.,* 2023).

Incorporating BSFL into African catfish diets also positively influences growth performance, nutrient utilization, and health outcomes. Diets with 25% BSFL replacement yield significant improvements in final body weight and specific growth rate compared to other replacement levels (Mundida *et al.,* 2023; Fawole *et al.,* 2020). Furthermore, diets with a 50% BSFL

replacement achieve the best feed conversion ratio (FCR), although weight gain is comparatively lower than control diets (Maranga *et al.,* 2022; Fawole *et al.,* 2020). Economically, BSFL diets reduce feed costs and increase profit indices, with 25% BSFL inclusion providing the highest economic benefits (Mundida *et al.,* 2023). From a nutritional perspective, diets with 50% BSFL inclusion enhance whole-body protein content, indicating efficient nutrient utilization (Fawole *et al.,* 2020). Health parameters remain stable, with no significant adverse effects on blood profiles or oxidative stress biomarkers, despite minor variations in serum biochemistry across inclusion levels (Gebremichael *et al.,* 2023; Fawole et al., 2020). These findings underscore the metabolic and immunological stability of African catfish fed BSFL-based diets, further validating the potential of BSFL as a sustainable fishmeal replacement (Gebremichael *et al.,* 2023; Fawole *et al.,* 2020). The use of Black Soldier Fly (BSF) larvae in aquaculture feeds raises several safety and quality concerns, primarily related to heavy metal and contaminant accumulation, microbial safety, and microbiota and fungal contamination (Liland *et al.,* 2023; Swinscoe *et al.,* 2019; Boccazzi *et al.,* 2017). BSF larvae can accumulate heavy metals such as cadmium, lead, mercury, and arsenic when grown on substrates enriched with seaweed or aquaculture sludge, with concentrations potentially exceeding European Union maximum levels for feed ingredients (Liland *et al.,* 2023). Additionally, the larvae can accumulate unwanted elements like arsenic and mercury, which can exceed legal limits when grown on high sludge inclusion levels (Liland *et al.,* 2023). Microbial safety is also a concern, as pathogenic bacteria and faecal indicator organisms (FIOs) can be present in substrates like seaweed, posing a risk of contamination (Swinscoe *et al.,* 2019; Swinscoe *et al.,* 2020; Were *et al.,* 2021). Furthermore, the presence of pathogens like *Listeria spp.* and *E. coli* can be influenced by the feed and processing methods, with blanching shown to significantly reduce microbial counts (Bessa *et al.,* 2021). The substrate used for rearing BSF larvae also affects the fungal communities present in the larvae, with different substrates leading to diverse yeast and mold genera, which may impact feed safety (Boccazzi *et al.,* 2017). To mitigate these risks, strategies such as pretreatment of substrates, post-treatment of larvae, and careful management of feed sources are necessary to reduce microbial and heavy metal contamination, although these treatments can affect larval growth and the quality of the final product (Shelomi, 2024).

# Moringa Leaf Meal

*Moringa oleifera*, commonly referred to as the "Miracle Tree," exhibits a diverse range of biological and morphological characteristics, rendering it a valuable resource in various sectors, including nutrition, medicine, and agriculture (Gandji *et al.,* 2020; Trigo *et al.,* 2020).

# Nutritional Properties of MLM

*Moringa oleifera,* a plant renowned for its rich nutritional and medicinal properties, is utilized in various industries, with different parts of the tree being employed across multiple sectors (Atreya *et al.,* 2023; Trigo *et al.,* 2020). The leaves, for instance, are highly nutritious, containing proteins, vitamins, and minerals, and are used in human food, animal feed, and aquaculture to improve the growth and health of fish (Atreya *et al.,* 2023; Trigo *et al.,* 2020). Additionally, the leaves have therapeutic applications, such as treating malnutrition and enhancing breast milk production (Kushwaha & Bhatt, 2022). *Moringa oleifera* leaves have been extensively studied for their nutritional potential, particularly their protein content, which ranges from 21% to 32% crude protein, positioning them as a viable alternative to traditional protein sources like fishmeal (Suharman *et al.,* 2022). Although this protein content is significant, it remains lower than that of fishmeal, which typically exceeds 60% crude protein, making the latter a more concentrated protein source (Egwui *et al.,* 2013). However, advancements in processing techniques have enabled Moringa protein concentrates to achieve up to 55.7% protein, with improved digestibility and a balanced amino acid profile, further enhancing their nutritional value (Benhammouche *et al.,* 2020). *Moringa oleifera* leaves are a rich source of various bioactive compounds that significantly contribute to their nutritional value, including a diverse range of phenolics, vitamins, and minerals (Fejér *et al.,* 2019). The leaves are abundant in phenolic compounds such as flavonoids and phenolic acids, with key phenolics including quercetin, kaempferol glycosides, caffeoylquinic acid, feruloylquinic acid, and chlorogenic acid, which contribute to their antioxidant properties (Fejér *et al.,* 2019). Additionally, the leaves contain significant amounts of vitamins, including vitamin C and β- carotene (a precursor of vitamin A), which are essential for various bodily functions and contribute to the antioxidant capacity of the leaves (González-Castellano *et al.,* 2019; Burgos *et al.,* 2021). Moringa leaves are also rich in proteins and essential minerals, making them a valuable nutritional resource, with essential amino acids and minerals like calcium, potassium, and iron (González-Burgos *et al.,* 2021). Furthermore, the leaves contain glucosinolates and carotenoids, which are noted for their health-promoting properties, including anti- inflammatory and anti-cancer effects (Kashyap *et al.,* 2022). The high phenolic content in Moringa leaves provides strong antioxidant activity, reducing oxidative stress and protecting against cellular damage (Hassan *et al.,* 2021; Fejér *et al.,* 2019), while the bioactive compounds

in Moringa leaves exhibit anti-inflammatory and antimicrobial effects, contributing to their use in traditional medicine (Kashyap *et al.,* 2022; Hassan *et al.,* 2021).

* 1. **Suitability of *Moringa oleifera* in aquaculture**

The potential of Moringa leaf meal in aquaculture has been widely recognized, with studies consistently demonstrating its efficacy in improving fish growth and health indices (Zhang *et al.,* 2020; Elabd *et al.,* 2019; El‐Kassas *et al.,* 2020; Faisal *et al.,* 2024; Tabassum *et al.,* 2021). For instance, partial replacement of fishmeal with fermented Moringa leaves, up to 40%, significantly enhanced growth metrics such as final body weight, weight gain rate, and specific growth rate in juvenile gibel carp (Zhang *et al.,* 2020). Similarly, dietary supplementation with 1.5% Moringa leaf meal improved growth indices in Nile tilapia, including body mass gain and specific growth rate (Elabd *et al.,* 2019). A 5% inclusion of Moringa leaf powder was found to enhance growth performance in mono-sex Nile tilapia (El‐Kassas *et al.,* 2020), while a 10% substitution of fishmeal with Moringa leaf meal yielded the highest growth performance in *Cirrhinusmrigala* (Faisal *et al.,* 2024; Tabassum *et al.,* 2021). Beyond growth performance, Moringa leaf meal supplementation has been associated with improved stress indices, enhanced antioxidant enzyme activities, stronger immune responses, increased disease resistance, and better nutrient digestibility and mineral absorption in various fish species (Zhang *et al.,* 2020; Shahzad *et al.,* 2021). However, optimal inclusion levels are suggested to be around 10%, as higher levels may negatively impact growth performance due to the presence of anti-nutritional factors (Faisal *et al.,* 2024; Richter *et al.,* 2003; Al-Dubakel & Taher, 2021).

# Suitability of MLM to Replace Fishmeal

Various studies have demonstrated that Moringa leaf meal can partially replace fishmeal in fish diets without significantly affecting growth performance. Nevertheless, higher substitution levels have been associated with reduced growth, primarily due to the anti-nutritional factors inherent in Moringa leaves (Richter *et al.,* 2003; Hlophe & Moyo, 2014; Faisal *et al.,* 2024). One of the challenges with Moringa leaves is their high crude fiber content, which can impede nutrient digestibility. However, fermentation with *Aspergillus niger* has shown promise in improving both the protein and fiber quality of Moringa leaves, making them more suitable for animal feed (Suharman *et al.,* 2022). Additionally, the presence of compounds such as saponins and phenols, while beneficial in moderation, can adversely affect growth performance when present in high concentrations in fish diets (Egwui *et al.,* 2013; Hlophe & Moyo, 2014). The amino acid profile of *Moringa oleifera* leaves contributes significantly to their nutritional value. They are a rich source of essential amino acids, which play crucial roles in various physiological processes and must be obtained through diet since the body cannot synthesize

them (Natsir *et al.,* 2019; Abbas *et al.,* 2018). These amino acids include threonine, essential for protein synthesis and immune function (Natsir *et al.,* 2019; Abbas *et al.,* 2018); lysine, which is vital for growth and tissue repair (Natsir *et al.,* 2019; Abbas *et al.,* 2018); and leucine, a key contributor to muscle protein synthesis and repair (Natsir *et al.,* 2019; Abbas *et al.,* 2018). Other notable amino acids include isoleucine, involved in muscle metabolism and energy regulation (Natsir *et al.,* 2019; Abbas *et al.,* 2018); phenylalanine, a precursor for neurotransmitters (Natsir *et al.,* 2019; Abbas *et al.,* 2018); valine, necessary for muscle growth and tissue repair (Natsir *et al.,* 2019; Abbas *et al.,* 2018); and methionine, important for metabolism and detoxification processes due to its sulfur content (Natsir *et al.,* 2019; Abbas *et al.,* 2018). Tryptophan, although present in lower concentrations, serves as a precursor for serotonin (Natsir *et al.,* 2019). Histidine, sometimes considered semi-essential, is crucial for growth and tissue repair (Abbas *et al.,* 2018). The presence of these essential amino acids highlights the potential of Moringa leaf meal as a valuable resource in both animal feed and human nutrition.

The optimal inclusion level of MOLM in the diets of various fish species has been established at around 10%, supporting growth performance and health without adverse effects (Tabassum *et al.,* 2021; Faisal *et al.,* 2024; Richter *et al.,* 2003; Afuang *et al.,* 2003). For instance, in studies on *Cirrhinusmrigala* fingerlings, a 10% inclusion of MLM resulted in superior growth performance, nutrient digestibility, and hematological indices compared to higher inclusion levels, which demonstrated a decline in these parameters (Tabassum *et al.,* 2021; Faisal *et al.,* 2024). This optimal level can be attributed to the nutrient richness of MLM, containing essential proteins, vitamins, and minerals that enhance fish growth and development. Similarly, in Nile tilapia, MLM inclusion at 10% is considered optimal, as higher levels (e.g., 20% and 30%) have been associated with reduced growth due to the presence of anti-nutritional factors such as phenolics and saponins (Richter *et al.,* 2003; Afuang *et al.,* 2003).

A similar trend has been observed in Asian sea bass, where MLM inclusion at 10% has been found effective for growth and feed efficiency, with higher levels leading to reduced growth rates and protein efficiency ratios (Ganzon-Naret, 2014). However, in the case of common carp, studies suggest that a lower inclusion level, around 5%, is more appropriate, as higher percentages negatively affect growth performance and feed conversion ratios (Al-Dubakel & Taher, 2021). Research on other species, such as *Heterobranchus longifilis* and *Megalobramaambly cephala*, indicates that inclusion levels of 5-10% and 4.4%, respectively, can yield significant growth and nutritional benefits (Mo, 2020; Jiang *et al.,* 2023). Moreover, the processing and treatment of MLM, such as fermentation, can enhance its nutritional value

by reducing anti-nutritional factors, thereby allowing for higher inclusion levels without adverse impacts on fish health or performance (Jiang *et al.,* 2023; Zhang *et al.,* 2020). These findings highlight that the optimal inclusion level of MLM depends on several factors, including species-specific dietary requirements, processing techniques, and the presence of anti-nutritional compounds, necessitating further research to refine its application in aquaculture systems.

Replacing fishmeal with MLM in the diets of African catfish (*C. gariepinus*) offers promising potential, provided that inclusion levels are carefully managed to avoid compromising growth and health (Adekilekun *et al.,* 2022; David-Oku *et al.,* 2018). Research demonstrates that MLM can replace up to 30% of fishmeal without detrimental effects on growth performance, with optimal results often achieved at lower inclusion levels of around 10% (Adekilekun *et al.,* 2022; David-Oku *et al.,* 2018). Fish fed diets containing 10% MLM exhibited improved growth performance, including enhanced weight gain and length, compared to diets with higher MLM inclusion levels (David-Oku *et al.,* 2018). Additionally, these fish showed elevated crude protein and fat content, comparable to control diets, highlighting the nutritional quality of MLM-based feeds (David-Oku *et al.,* 2018). Notably, the highest protein content in fish carcasses was observed with a 30% MLM inclusion, suggesting that MLM can enhance protein accumulation in fish (Adekilekun *et al.,* 2022). MLM inclusion at 1.5% has also been linked to improved hematological parameters, which are vital indicators of fish health and immune function, without significant deviations from control diets (Eyiwumi *et al.,* 2018). Nevertheless, addressing the anti-nutritional factors inherent in MLM remains a priority to allow for higher inclusion levels without compromising fish health or performance (Adekilekun *et al.,* 2022). Economically, MLM-based diets present a cost-effective alternative to conventional fishmeal-based diets, enhancing the sustainability of aquaculture production (Avwemoya & Eze, 2019).

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