Review article
DOI: /10.5513/JCEA01/27.2.5345
Journal of Central European Agriculture, 2026, 27(2), p.354-373

Insect and soybean meals as sustainable alternatives to fish meal in aquaculture: nutritional, growth, and health implications

Făina de insecte și soia ca alternative sustenabile la făina de pește în acvacultură: implicații nutriționale, de creștere și de sănătate

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Received: April 9, 2026; accepted: May 8, 2026

ABSTRACT

Sustainable aquaculture demands viable alternatives to traditional fish meal (FM), whose limited supply, high cost, and ecological impacts challenge its continued use in aquafeeds. This review synthesizes current knowledge on two promising protein sources - insect meal (IM) and soybean meal (SBM) - focusing on their nutritional profiles, digestibility, effects on fish growth performance, and implications for fish health and feed formulation. IMs, particularly from *Hermetia illucens* and *Tenebrio molitor*, offer high protein content, balanced essential amino acids (EAAs), bioactive compounds (e.g., chitin, antimicrobial peptides), and micronutrients that enhance gut health and immune responses at moderate inclusion levels. SBM, with its global availability and favorable economics, provides substantial protein but contains anti nutritional factors that require processing or supplementation to optimize utilization, especially in carnivorous species. Comparative analysis reveals that IM generally yields superior functional benefits and closer nutritional similarity to FM, while processed SBM remains an effective, cost efficient ingredient in aquafeeds. Challenges for large scale adoption include variability in IM composition, production costs, regulatory frameworks, and the need to balance essential fatty acids when replacing FM. Integrating IM and SBM with traditional ingredients and refining feed formulations can support sustainable, nutritionally balanced aquafeeds without compromising fish growth, health, or product quality, contributing to the long term viability of aquaculture industries. The findings offer practical guidance for fish feed formulators seeking sustainable alternatives to FM. This knowledge can help develop nutritionally balanced and cost-effective aquafeeds without compromising fish growth or health.

Keywords: fish feed formulation, protein digestibility, growth performance, gut health, immune response

REZUMAT

Acvacultura durabilă necesită alternative viabile la făina de pește tradițională (FP), a cărei disponibilitate limitată, costul ridicat și impactul ecologic reprezintă o provocare pentru utilizarea sa continuă în furajele acvatice. Acest articol sintetizează cunoștințele actuale despre două surse promițătoare de proteine - făina de insecte (FI) și făina de soia (FS) - concentrându-se pe profilurile lor nutriționale, digestibilitate, efectele asupra performanței de creștere a peștilor și implicațiile pentru sănătatea acestora și formularea nutrițională. Făina de insecte, în special de la speciile *Hermetia illucens* și *Tenebrio molitor*, oferă un conținut ridicat de proteine, aminoacizi esențiali echilibrați, compuși bioactivi (de exemplu: chitină, peptide antimicrobiene) și micronutrienți care îmbunătățesc sănătatea intestinală și răspunsurile imune la niveluri moderate de includere. FS, cu disponibilitatea sa globală și rentabilitatea economică, oferă proteine substanțiale, dar conține factori antinutriționali care necesită procesare sau suplimentare specifică pentru a optimiza utilizarea, în special la speciile carnivore de pești. Analiza comparativă arată că FI oferă, în general, beneficii funcționale superioare și o similaritate nutrițională mai mare cu FP, în timp ce FS procesată rămâne un ingredient eficient și rentabil în furajele acvatice. Provocările pentru adoptarea la scară largă includ variabilitatea compoziției FI, costurile de producție, regulile de reglementare și necesitatea de a echilibra acizii grași esențiali atunci când înlocuiește FP. Integrarea FI și FS cu ingrediente tradiționale și rafinarea formulelor de furaje poate susține furajele acvatice sustenabile și echilibrate din punct de vedere nutrițional, fără a compromite creșterea, sănătatea peștilor sau calitatea produselor, contribuind la viabilitatea pe termen lung a industriilor asociate acvaculturii. Acest articol oferă îndrumări practice pentru nutriționiștii din acvacultură care caută alternative sustenabile la FP. Aceste cunoștințe pot ajuta la dezvoltarea de rețete pentru acvacultură echilibrate din punct de vedere nutrițional și rentabile, fără a compromite creșterea sau sănătatea peștilor.

Cuvinte cheie: formularea hranei pentru pești, digestibilitatea proteinelor, performanța de creștere, sănătatea intestinală, răspuns imun

INTRODUCTION

Worldwide aquaculture has expanded rapidly over the past decades and now accounts for an increasing share of global fish production, which leads to a growing demand for the aquatic feed industry. Fish meal (FM) has long been considered the reference protein source in aquaculture due to its high quality and broad amino acid profile. However, it faces serious limitations: global supply becomes scarce, price volatility has increased significantly, and environmental concerns about forage fish stocks are growing (Macusi et al., 2023; FAO, 2024). The increasing cost and environmental impact of fishmeal have accelerated the search for alternative protein sources, including plant-based ingredients and insect meals (IMs) (Kontara et al., 2025). This has encouraged intensive research to identify sustainable and nutritionally adequate alternatives.

In this context, insects have attracted increased interest as an alternative protein source for aquaculture. They can be grown on various substrates, including agro-industrial wastes, transforming low-value resources into protein- and lipid-rich biomass. Species such as the black soldier fly (BSF) (*Hermetia illucens*) and the mealworm (*Tenebrio molitor*) have a protein content of 40-60% of the dry matter (DM) basis and an amino acid profile comparable to that of FM (Barroso et al., 2014). In addition, insects have a highly efficient feed conversion rate to transform food waste and can contribute to reducing pressure on marine resources (Makkar et al., 2014; Nogales-Mérida et al., 2019). On prices, the cost is still too high, the quality variability is also noticed, while the quantities produced are simply too low. Even so, the scientific interest has to investigate if the IM might be an alternative for FM (Hua et al., 2019).

Recent studies have shown that partial replacement of FM with IM, especially from *H. illucens* and *T. molitor*, does not negatively affect growth performance or fillet quality in species such as common carp, *Cyprinus carpio* Linnaeus, 1758 (Askale et al., 2022). Similarly, dietary inclusion of oil derived from *H. illucens* larvae has been shown to improve growth performance and survival in aquaculture species (Herawati et al., 2025). In addition, bioactive components such as chitin and antimicrobial peptides (AMPs) can support immune responses and gut health in fish (Abdallah et al., 2025). However, variability in nutritional composition, high production costs, and lack of uniform regulations remain important challenges for the widespread adoption of these ingredients (Henry et al., 2015; Nogales-Mérida et al., 2019).

In addition to animal protein sources, much research has also focused on plant-based ingredients, which can contribute to reducing pressure on marine resources. Among these, soybean meal (SBM) has long been the most widely used and studied protein source in aquatic feed formulations. Is cheap when compared with FM and IM, being a secondary product of the cooking oil industry, while the nutritional value is high, digestibility close to FM, and already proven as a core ingredient in various fish species intensive nutrition (Mondal, 2025). SBM is frequently used as a benchmark protein source in comparative feeding trials, showing favorable effects on growth performance, physiological parameters, economic efficiency (Vodounnou et al., 2026), immune response and intestinal development in fish species (Kontara et al., 2025).

SBM generally contains between 44-48% crude protein and offers an amino acid profile capable of supporting fish growth and good technological performances, although it is deficient in sulfur-containing amino acids such as methionine. In addition, SBM provides carbohydrates and minerals that contribute to nutritional balance, although vitamin levels may vary depending on processing (Mondal, 2025). Studies have confirmed the high digestibility of SMB in several aquaculture species, with protein apparent digestibility coefficients (ADCs) exceeding 90% in species such as Nile tilapia, *Oreochromis niloticus* (Linnaeus,1758), and catfish (*Siluriformes*) (Kurniasih et al., 2024). However, the presence of antinutritional factors (ANFs) - such as trypsin inhibitors, oligosaccharides and phytic acid - can reduce nutrient digestibility and affect gut health in some species, particularly in carnivorous fishes (Mondal, 2025). To mitigate these effects, various soy-derived products have been developed, such as soy protein concentrate (SPC) and fermented soybean meal (FSBM). The processes to obtain these products reduce ANFs and improve protein digestibility and palatability, allowing higher levels of SBM inclusion in aquatic feeds without adverse effects (Yun et al., 2018; Zhang et al., 2021). Recent studies have demonstrated that FSBM can further enhance growth performance and feed efficiency, particularly when combined with probiotics such as *Bacillus coagulans* (Arungamol et al., 2025).

Recent research has also shown that bioactive components of SBM, such as isoflavones and peptides generated during fermentation, can enhance immunity and antioxidant capacity in fish (Xu et al., 2022; Zhang et al., 2023). However, responses to SBM inclusion vary considerably between species and culture systems, highlighting the need for tailored nutritional strategies and a thorough understanding of the physiological and environmental impacts of SBM use (Yun et al., 2017).

Even if the FM offers the best productive results in aquaculture, the uncertainty of maintaining abundant and constant sources from natural areas might impose the replacement of such ingredients over time. But the replacements must have a strong testing period and a predictable abundance for decades to come.

Given the still high dependence of aquaculture on FM and the increasing concerns related to cost, availability, and environmental impact, the search for sustainable alternative protein sources has become a major research priority. Among these, IM and SBM have attracted particular attention due to their nutritional potential and production scalability. However, their variable composition, digestibility, and species-specific physiological effects require a comprehensive comparative evaluation. This review aims to synthesize recent findings on the use of IM and SBM as alternative protein sources in aquafeeds, focusing on their nutritional value, effects on fish growth and health, and implications for sustainable aquaculture.

FISH MEAL AND ITS LIMITATIONS

FM has been the cornerstone protein ingredient in aquafeeds for decades, owing to its balanced nutritional profile, high content of essential amino acids (EAAs), and long-chain omega-3 polyunsaturated fatty acids such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA). These compounds are crucial for optimal fish growth, organ development, reproduction, and immune resistance (Makkar et al., 2014). FM also provides essential vitamins and minerals that support metabolic and physiological processes, giving it a nutritional value that remains difficult to replicate using alternative sources (Henry et al., 2015).

However, several ecological and economic constraints limit its sustainable use. Global FM production is declining — estimates from IFFO indicate a 23% reduction in 2023 compared to 2022, mainly due to lower catches in Peru (IFFO, 2024). The reliance on finite marine resources exerts pressure on wild fish populations, disrupting trophic balance and biodiversity in marine ecosystems (Nogales-Mérida et al., 2019). Overfishing of small pelagic species not only threatens ecological stability but also diverts potential food resources from direct human consumption (FishFocus, 2024).

Economically, the growing demand for FM from aquaculture and livestock sectors drives price volatility, which complicates cost predictability for fish farms (Makkar et al., 2014; Nogales-Mérida et al., 2019). Production also depends heavily on external factors such as climatic variability and oceanic productivity, resulting in inconsistent supply and quality. According to OECD/FAO (2025), FM shortages could easily become critical by 2028 if alternative protein sources are not widely implemented. Additionally, FM production and transport contribute to greenhouse gas emissions, and its low conversion efficiency. Specifically, 4-5 kg of wild fish to produce 1 kg of FM increases pressure on marine ecosystems (OECD/FAO, 2025). These inefficiencies raise ethical and environmental concerns, particularly in regions where fish species used for FM are also important for human nutrition (Gougbedji et al., 2022). SBM has been widely used as an alternative protein source in aquafeeds, contributing to reduced reliance on marine resources; however, its use requires careful formulation due to nutritional constraints and anti-nutritional factors that may limit its efficiency in fish diets (Gatlin et al., 2007; NRC, 2011). IM is considered a promising alternative protein source due to its ability to convert organic by-products into valuable biomass, thereby contributing to reduced dependence on marine resources (Makkar et al., 2014). However, its production systems are still developing, and current limitations include restricted industrial scalability, cost constraints, and variability in composition, which must be addressed to fully assess its sustainability and applicability in aquafeeds (Hua et al., 2019; FAO, 2024).

In this context, the adoption of substitutes, such as SBM and IM, becomes increasingly relevant. Plant protein sources like fermented *Moringa oleifera* leaf flour have also been explored as sustainable feed ingredients to reduce reliance on fishmeal, offering acceptable growth performance in *O. niloticus* diets when processed adequately to mitigate anti-nutritional factors (Putra et al., 2025). For example, a systematic review shows that 50% of FM could be replaced with a meal from larvae of *H. illucens* and up to 25% with SBM without affecting growth performance in some aquatic species (Macusi et al., 2023). Of course, the use of plant-based proteins, such as soy, also involves nutritional and digestibility challenges (anti-nutritional factors, amino acid imbalances), which require these ingredients to be treated carefully (Gyan et al., 2019). Recent studies in aquaculture have highlighted that partial replacement of fishmeal with IM (*H. illucens*) and plant proteins such as SBM can maintain growth performance while reducing reliance on finite marine resources (Herawati et al., 2025).

Therefore, the introduction of FM substitutes represents a key strategic direction for modern aquafeed — offering the potential to reduce pressure on marine resources, stabilize costs, and advance sustainability, without significantly compromising the biological and nutritional performance of aquatic organisms.

NUTRITIONAL COMPARISON BETWEEN FISHMEAL, SOYBEAN MEAL, AND INSECT MEAL

FM is still considered the gold standard in fish nutrition, due to its high-quality protein content, balanced essential amino acid profile, and omega-3 polyunsaturated fatty acids (EPA and DHA), but alternative proteins have increasingly been the focus of studies on digestibility and nutrient value. However, production sustainability limitations and high costs have stimulated interest in alternative protein sources, especially IM (Henry et al., 2015) and SBM, with the second widely available and economically favorable, although it is limited by deficiencies in sulfur-containing amino acids and the presence of ANFs (Francis et al., 2001; Mondal, 2025).

Crude protein content and amino acid profile

FM is characterized by a high crude protein content (typically 60-73% on a DM basis) and an excellent balance of EAAs, notably methionine, lysine, and cysteine, which are crucial for optimal growth and health in aquatic species (Miles and Chapman, 2006). In comparison, IM shows considerable variability in protein content depending on species, rearing substrate, and processing method. For example, defatted *H. illucens* meal may contain up to 65-70% protein, while full-fat versions typically contain less than 40-50% (Jannathulla et al., 2022; Alvanou et al., 2023).

Although IM contains a reasonably balanced EAA profile, deficiencies in sulfur-containing amino acids, particularly methionine and cysteine, have been consistently reported, potentially limiting growth if not supplemented (Basto et al., 2023). Nevertheless, some species, such as silkworm pupae (*Bombyx mori*), present a closer match to FM in terms of methionine levels.

As a widely used plant-derived protein source in aquaculture, SBM typically contains around 44-48 % crude protein and exhibits a relatively balanced amino acid profile (Mondal, 2025). Studies indicate that, despite its good availability and cost-effectiveness, SBM utilization can be limited by the presence of already mentioned ANFs such as trypsin inhibitors, lectins, oligosaccharides, and phytic acid, which reduce digestibility and mineral bioavailability (Mondal, 2025). For example, in juvenile whiteleg shrimp, *Litopenaeus vannamei* (Boone, 1931), dietary inclusion of SBM beyond 28 % significantly reduced growth performance, ADCs, and digestive enzyme activities, mainly due to ANFs and amino acid imbalance (Peng et al., 2022). Moreover, methionine supplementation in diets where FM was replaced with SPC has been shown to restore growth performance and health indicators in hybrid sturgeon (*Acipenser baerii* × *A. schrenckii*) when soy derivatives were used (Li et al., 2025).

Therefore, although SBM can serve as a viable alternative protein source, its effective use often requires complementary formulations (e.g., amino acid supplementation, reduction of ANFs) to approach the nutritional quality of FM.

Digestibility and nutrient bioavailability

Digestibility is a major determinant of feed efficiency. FM is generally considered highly digestible in many farmed species. In contrast, IM may contain chitin, a structural polysaccharide that can reduce protein digestibility in some species. However, processing techniques such as defatting or enzymatic treatment have been reported to improve the ADCs of IM, bringing them closer to those of FM (Melenchón et al., 2022; Alvanou et al., 2023).

In juvenile totoaba, *Totoaba macdonaldi* (Gilbert, 1890), partial replacement of FM with defatted *H. illucens* meal up to 50% did not impair growth performance, although some reduction in DM digestibility has been reported (Carvajal-Soriano and Corvera, 2025). In European seabass, *Dicentrarchus labrax* (Linnaeus, 1758), replacement of FM with defatted *T. molitor* meal has been studied for its effects on nutrient metabolism and growth performance (Basto et al., 2023).

The digestibility of SBM in aquafeeds is influenced by multiple factors, including species, feed formulation, and processing conditions. In a recent feeding trial with *L. vannamei*, it has been demonstrated that apparent ADCs of DM, crude protein, crude lipid, and ash declined linearly as dietary SBM increased from 20 to 50 %. The same study reported that *L. vannamei* fed diets with SBM inclusion beyond 28 % experienced significant reductions in enzyme activities and feed utilization (Peng et al., 2022). Moreover, the quality of SBM in terms of protein dispersibility, fibre content, and urease activity has been shown to affect ADCs in species such as *O. niloticus* (Ma et al., 2022).

To enhance the digestibility and nutrient bioavailability of SBM, strategies such as microbial fermentation, heat treatment, and enzyme supplementation have been applied successfully to reduce ANF content and improve nutrient utilization (Xue et al., 2024; Mondal, 2025).

Lipid composition and fatty acid profiles

One of the most critical nutritional differences among FM, SBM, and IM lies in their lipid composition and fatty acid profiles, particularly regarding the presence of long-chain omega-3 polyunsaturated fatty acids (LC-PUFAs), such as EPA (20:5 n-3) and DHA (22:6 n-3) (Tocher, 2010; Sprague et al., 2016).

FM and fish oil are well recognized as the primary dietary sources of LC-PUFAs in aquafeeds, providing high levels of EPA and DHA that are essential for optimal growth, neural development, immune function, and fillet quality in marine fish species (Nobre et al., 2025). These fatty acids are biologically derived from marine algae and accumulate through the aquatic food chain, making marine ingredients uniquely rich in omega-3 lipids compared to terrestrial feed sources. In contrast, plant-based ingredients such as SBM are characterized by a lipid profile dominated by C18 fatty acids, particularly linoleic acid (18:2 n-6), with very low or negligible levels of EPA and DHA (Miles and Chapman, 2006). Although SBM is primarily used as a protein source, its lipid fraction can significantly influence the fatty acid composition of fish tissues. Diets relying heavily on soybean-derived lipids or plant oils tend to reduce the concentration of LC-PUFAs in fish fillets, unless supplemented with marine lipid sources (Nobre et al., 2025).

Similarly, IMs, especially those derived from species such as *H. illucens*, contain substantial lipid levels but are typically deficient in EPA and DHA, while being richer in saturated fatty acids and certain monounsaturated or omega-6 fatty acids (Karapanagiotidis et al., 2023). The fatty acid composition of insect-based feeds is largely influenced by the substrate used for insect rearing, but even under optimized conditions, LC-PUFA levels remain significantly lower than in marine ingredients (Truzzi et al., 2023). The replacement of FM and fish oil with plant- or insect-based ingredients therefore leads to a shift in the fatty acid composition of aquafeeds, which is directly reflected in fish tissues. Numerous studies have demonstrated that the fatty acid profile of fish closely mirrors that of their diet, meaning that reduced dietary EPA and DHA result in lower levels of these essential fatty acids in fillets (Fukada et al., 2020). This alteration does not always negatively affect growth performance in the short term, but it can significantly reduce the nutritional value of farmed fish for human consumption, particularly in terms of omega-3 content (Wright, 2018). From a nutritional and functional perspective, EPA and DHA play a crucial role not only in fish physiology but also in human health, contributing to cardiovascular protection, anti-inflammatory processes, and neural development. Consequently, maintaining adequate levels of these fatty acids in aquaculture products is a key objective in feed formulation (Nobre et al., 2025).

To address the limitations of SBM and IM as lipid sources, modern aquafeed strategies increasingly incorporate alternative sources of LC-PUFAs, such as fish oil supplementation, microalgae-derived lipids, or enriched phospholipid fractions. These approaches aim to restore the balance of essential fatty acids in feeds and ensure that the final product retains its nutritional quality for consumers (Fukada et al., 2020).

Overall, while SBM and IM represent sustainable alternatives to FM in terms of protein supply, their lipid profiles require careful nutritional balancing. Without appropriate supplementation, high inclusion levels of these ingredients can compromise the omega-3 content of farmed fish, highlighting the importance of integrated feed formulation strategies in sustainable aquaculture.

Vitamin and mineral content

FM contains essential micronutrients such as phosphorus, calcium, selenium, and certain vitamins. Insects, depending on species and diet, may be rich in minerals like iron, zinc, and manganese, and contain B vitamins (Alvanou et al., 2023). Yet, due to the presence of chitin and variation in gut content, the bioavailability of these nutrients in IM can be variable due to factors such as chitin content and diet composition (Basto et al., 2023;

Yadav et al., 2025). SBM contains key vitamins like choline, niacin, and riboflavin, alongside minerals such as potassium and phosphorus, but has lower levels of phosphorus compared to FM (Guo and Wang, 2025). While vitamins and minerals are micro-ingredients in fish feed formulations, their addition in the receipt fulfills the nutritional requirements. Anyhow, in intensive aquaculture systems, where fish do not have access to natural food (algae, insects, crustaceans), artificial feed is their only source of nutrients (Gatlin et al., 2007). If the feed is deficient in vitamins and minerals, the following problems quickly arise: decreased immunity - fish become vulnerable to bacterial and parasitic attacks; poor feed conversion rate - fish do not assimilate proteins properly and do not have proper gain weight; increased mortality and malformations - fish with deformed gills, eroded fins or a crooked spine, which cannot be commercially exploited (Lall, 2000; Halver and Hardy, 2002).

Anti-nutritional and functional compounds

IMs, especially those derived from *H. illucens*, contain distinctive antinutritional and functional components that set them apart from traditional protein sources such as FM and SBM. One of the most abundant non nutritive components in IMs is chitin, a polysaccharide forming part of the insect exoskeleton. Chitin is not digestible by fish but can act as an insoluble dietary fiber with prebiotic potential, being fermented by gut microflora and contributing to the production of metabolites such as short chain fatty acids that support intestinal health (Aragão et al., 2022; Hasan et al., 2023). Studies in rainbow trout, *Oncorhynchus mykiss* (Walbaum, 1792) and Atlantic salmon, *Salmo salar* Linnaeus, 1758 fed diets containing IM have shown shifts in gut microbiota composition, including increases in beneficial bacterial groups such as *Firmicutes* and *Actinobacteria*, which are commonly associated with fiber fermentation and gut homeostasis (Weththasinghe et al., 2022).

Beyond chitin, BSF larvae contain a range of bioactive molecules. For example, *H. illucens* is relatively rich in medium chain fatty acids, particularly lauric acid, which has documented antimicrobial properties against certain pathogenic bacteria, and has been proposed as a factor influencing the intestinal microbial balance (Rimold et al., 2019). Additionally, insect derived proteins include multiple AMPs that have been identified and characterized in *H. illucens*, and which are known to contribute to innate immune responses in insects and have broad antimicrobial activity (Xia et al., 2021).

In contrast, FM is widely recognized as a highly digestible protein source with very low levels of ANFs and a complete profile of EAAs. FM also supplies long chain omega 3 fatty acids such as EPA and DHA, as well as other functional nutrients, supporting growth performance, metabolism, and immune competence in cultured fish (Aragão et al., 2022).

SBM, while an important plant protein source, contains several antinutritional compounds, including trypsin inhibitors, lectins, saponins, and phytoestrogens, which can reduce nutrient digestibility and trigger inflammatory responses in sensitive fish species if not mitigated by processing methods such as heat treatment or fermentation (Aragão et al., 2022; Pascon et al., 2025). Processing methods have been shown to lower the content of these antinutrients and improve SBM's nutritional performance (Aragão et al., 2022).

Taken together, these differences highlight that IMs not only provide a sustainable alternative protein source but also deliver functional components, such as fermentable fibers, antimicrobial fatty acids, and AMPs, that can beneficially influence gut microbiota and fish health when appropriately included in aquafeed formulations. These functional effects are largely absent in traditional FM and SBM, underscoring the potential of IMs to support both nutrition and health in aquaculture diets (Xia et al., 2021; Hasan et al., 2023).

The comparative analysis of nutritional values and ANFs highlights the key differences between FM, IM, and SBM. FM remains the most digestible and complete protein source, with a full essential amino acid profile and high omega-3 fatty acids (EPA and DHA), and negligible ANFs. IM provides moderate-quality protein, often limited in methionine and cysteine, and contains chitin, which may reduce digestibility at high inclusion levels but also exerts beneficial functional effects on gut microbiota due to its prebiotic properties and AMPs. SBM is rich in plant protein but contains antinutrients such as trypsin inhibitors, lectins, saponins, and phytoestrogens, which can impair digestibility and intestinal health if not properly processed. Overall, selecting the appropriate protein source for aquafeeds requires consideration not only of protein and amino acid content but also of ANFs and functional compounds. IM offers a sustainable alternative with added gut health benefits, FM provides optimal nutritional performance, and SBM can be effective if processed to reduce antinutrients (Table 1).

INSECTS AND SOYBEAN MEAL AS AN ALTERNATIVE NUTRIENT SOURCE

In the context of FM natural limitations, edible insects have been proposed as one of the sustainable protein alternatives for fish feed formulations (Kattakdad et al., 2022). They have a high protein content, ranging from 35-70% on a DM basis, and an essential amino acid profile comparable to that of FM, including lysine, methionine, and threonine, critical nutrients for fish growth and development (Barroso et al., 2014; Nogales-Mérida et al., 2019; Melenchón et al., 2022). In addition, insects contain lipids, vitamins (B12, riboflavin), and minerals (iron, zinc, calcium), which contribute to balanced nutrition, reducing the need for additional supplements in formulated diets (Henry et al., 2015).

Table 1. Nutritional comparison between fishmeal, insect meal and soybean meal

Nutritional parameter	Fishmeal	Insect meal	Soybean meal	References
Crude protein (%DM)	60-72% (species- and processing-dependent)	35-70% (species-dependent; full-fat ~40-50%)	44-48% (dehulled); ~40-44% (standard SBM)	NRC, 2011; Jannathulla et al., 2022; Melenchón et al., 2022; Alvanou et al., 2023
Essential amino acid profile	Complete; rich in lysine and methionine	Good, but often limited in methionine and cysteine; species-dependent	Good lysine content but deficient in methionine; tryptophan moderate	Gatlin et al., 2007; NRC, 2011; Melenchón et al., 2022; Basto et al., 2023
Digestibility	High; >90% ADCs	Moderate to high; affected by chitin and processing	High protein digestibility (~85-92%), but affected by anti-nutritional factors	Francis et al., 2001; NRC, 2011; Alvanou et al., 2023; Basto et al., 2023
EPA/DHA content	High (marine origin; rich in LC-PUFAs)	Low or absent; higher in SFA and n-6 FA; substrate-dependent	Negligible EPA/DHA; rich in linoleic acid (18:2 n-6)	Tocher, 2010; NRC, 2011; Basto et al., 2023; Carvajal-Soriano and Corvera, 2025
Chitin content	Absent	Present (~0.5-10%; species and stage dependent)	Absent	Jannathulla et al., 2022; Alvanou et al., 2023
Vitamins and minerals	Well-balanced; high in Ca, P, Se, B12	Variable; often rich in Fe, Zn, Mn; depends on substrate	Moderate; good P (but partly as phytate), B vitamins present but variable	Francis et al., 2001; NRC, 2011; Jannathulla et al., 2022; Alvanou et al., 2023
Anti-nutritional factors	Very low; generally free of antinutrients	Chitin (fiber; may reduce digestibility at high inclusion), minor antinutritional peptides; functional compounds like AMPs present	Trypsin inhibitors, lectins, saponins, phytoestrogens; can reduce digestibility and trigger inflammation if unprocessed	Xia et al., 2021; Aragão et al., 2022; Hasan et al., 2023; Pascon et al., 2025

Note: ADCs: apparent digestibility coefficients; DM: dry matter; EPA: eicosapentaenoic acid; DHA: docosahexaenoic acid

Recent research has shown that additions derived from BSF larvae (such as insect oil) can significantly improve growth performance and survival in cultured fish species, underscoring the nutritional and functional potential of insect based ingredients in aquafeeds (Herawati et al., 2025).

Species such as *H. illucens* and *T. molitor* have attracted the most interest due to their growth efficiency (Gebremichael et al., 2021) and adaptability to various substrates (Gebremichael et al., 2022). They can be raised on agro-industrial waste or food residues, transforming low-value resources into high-quality fish feed (Barroso et al., 2014; Nogales-Mérida et al., 2019). This practice reduces the environmental impact associated with protein production and supports the circular economy. Still, the better the feeding substrate is, the higher the quality and crude protein content from IM. This leads to higher production costs; however, faster-growing insect species may still mitigate this effect. IM, especially those derived from *H. illucens*, *T. molitor*, house cricket (*Acheta domesticus*), and *B. mori*, contain moderate to high concentrations of EAAs (Jannathulla et al., 2022; Alvanou et al., 2023; Herawati et al., 2025; Khan et al., 2025).

Beyond their protein content, many insects provide functional lipids, micronutrients, and bioactive compounds. For instance, *H. illucens* larvae are rich in lauric acid and AMPs, while *T. molitor* contains high levels of B vitamins and trace elements such as iron and zinc. These attributes contribute not only to nutritional adequacy but also to enhanced immune responses and improved gut health in fish (Barroso et al., 2014; Bera et al., 2022).

Askale et al. (2022) showed that partial replacement (up to 50-65%) of FM with *H. illucens* or *T. molitor* meal in the diet of *C. carpio* did not significantly affect specific growth rate (SGR), fillet yield, or body composition. Similarly, Dogan and Turan (2021) reported favorable results for the same type of substitution in *C. carpio*, highlighting that growth performance and feed utilization remained comparable to the control diet based on FM when *H. illucens* larvae meal replaced up to 65% of FM. Recently, Gebremichael et al. (2022) evaluated the effects of feeding *C. carpio* with extruded diets containing *H. illucens* and *T. molitor* larvae meals. The results showed that fillet yield and flesh quality were not significantly affected compared to the control diet based on FM, suggesting that IMs can be viable alternative protein sources in aquafeeds for omnivorous species.

The following table summarizes the reported inclusion levels of *H. illucens* and *T. molitor* in various cultured fish species, along with their observed effects on growth performance and feed utilization.

Overall, these findings indicate that partial replacement of fishmeal with *H. illucens* or *T. molitor* meal is generally well tolerated across omnivorous and carnivorous species, supporting growth, feed conversion, and fillet quality, while highlighting species-specific inclusion thresholds.

Insects also provide additional functional benefits due to the presence of chitin, bioactive compounds, and lipids with immunostimulatory effects. Chitin can stimulate the innate immunity of fish and promote the development of a balanced gut microbiome, which contributes to disease resistance and improved overall health (Barroso et al., 2014; Bera et al., 2022). This is a significant advantage over plant proteins, which do not offer such bioactive effects. Challenges include variability in nutritional composition depending on growth substrate, affecting protein, lipid, and amino acid profiles (Nogales-Mérida et al., 2019; Alvanou et al., 2023). Insect lipids have lower omega-3 fatty acids than FM, so formulations must be adjusted to maintain fillet quality. Processing techniques such as defatting and enzymatic hydrolysis improve protein digestibility and nutrient availability (Barroso et al., 2014; Melenchón et al., 2022).

SBM has been widely employed as a primary protein source in aquafeeds for over 40 fish species, including carnivorous species, particularly *S. salar* and *O. mykiss*. (Sales, 2009; Collins et al., 2013; Mustofa et al., 2022). The percentages of inclusion into the combined fodder vary, but over 40% replacement of FM seems to alter the fish growth without amino acid supplementation of diets, mostly as crystalline methionine (Sales, 2009).

Table 2. Optimal inclusion levels of *Hermetia illucens* and *Tenebrio molitor* in some cultured fish species and their effects on growth and performance

Fish species	Trophic level	Insect meal inclusion (%)	Observed effect on growth/performance	References
Nile tilapia, *Oreochromis niloticus* (Linnaeus,1758)	Omnivorous	15-30	Maintained or improved growth performance, FCR, and immune parameters	Tran et al., 2015; Askale et al., 2022; Melenchón et al., 2022; Edea and Verkhoturov, 2023
Common carp (*Cyprinus carpio* Linnaeus, 1758)	Omnivorous	50-65	Partial replacement up to 50-65% did not significantly affect SGR, fillet yield, or body composition	Dogan and Turan, 2021; Askale et al., 2022; Gebremichael et al., 2022a
Atlantic salmon, *Salmo salar*, Linnaeus, 1758	Carnivorous	50%	Replacement beyond 20-30% may reduce growth; amino acid supplementation is required	Sahlmann et al., 2013; Ye et al., 2019
Rainbow trout, *Oncorhynchus mykiss*, (Walbaum, 1792)	Carnivorous	Up to 50	Partial substitution maintained growth performance; total replacement may reduce growth and protein digestibility	Nogales-Mérida et al., 2019; Caimi et al., 2021
Seabass, *Dicentrarchus labrax* (Linnaeus, 1758)	Carnivorous	15-50	Partial FM replacement with IM maintained growth, FCR, and fillet quality	Basto et al., 2023; Edea and Verkhoturov, 2023
Milkfish, *Chanos chanos* (Fabricius, 1775)	Omnivorous	Up to 50	Inclusion of insect-derived components improved growth performance and survival	Herawati et al., 2025

Note: FCR: feed conversion ratio; SGR: specific growth rate; FM: fish meal; IM: insect meal

Economically, every percent of SBM replacing FM in the formulation decreases the cost of the fodder. In omnivorous and herbivorous fish species, SBM may contribute to up to 70% as a FM replacer, but the amino acid and mineral optimization of the feed is also requested (Apines Amar et al., 2015). As a nutrient source, SBM has a lower digestibility than IM, while both are inferior to FM (Mohamad Zulkifli et al., 2019). IM might represent one of the future core ingredients of aquaculture feed, offering superior nutrition to soy without compromising fish growth, while also being an environmentally sustainable alternative to FM.

Overall, the comparison highlights the complementary roles of SBM and IM as alternative protein sources in aquaculture. While SBM provides a validated plant-based protein, it has limitations in digestibility, amino acid balance, and the presence of ANFs. In contrast, IM, particularly from *H. illucens* and *T. molitor*, offer high protein content, EAAs, beneficial lipids, and functional bioactive compounds such as chitin and antimicrobial peptides. These attributes not only support growth and feed utilization but also enhance gut health and immune function. Table 3 summarizes these differences, illustrating the nutritional and functional advantages of IM over SBM, and highlighting its potential as a sustainable and high-quality ingredient for fish feed formulations.

EFFECTS ON FISH GROWTH AND PERFORMANCE

Integration of IM into fish feed has been extensively studied to determine its impact on SGR, feed conversion ratio (FCR), and fillet yield, which are key indicators of economic and biological performance in aquaculture. Studies show that partial substitution of FM with IM, particularly up to 50%, can be successfully implemented in carnivorous and omnivorous fish species without negatively affecting growth performance or fillet quality (Tran et al., 2015; Askale et al., 2022; Melenchón et al., 2022; Edea and Verkhoturov, 2023).

Table 3. Soybean meal and insect meal nutritional comparison

Characteristic	Soybean meal	Insect meal (e.g., *H. illucens*, *T. molitor*)	References
Protein source	Plant-based	Animal-based (Invertebrate)	Barroso et al., 2014; Nogales-Mérida et al., 2019
Protein content	~40-48%	35-70% (species and substrate dependent)	Melenchón et al., 2022; Alvanou et al., 2023
Fats (lipids)	Low (~2% if defatted)	9-35%; rich in lauric acid	Barroso et al., 2014; Henry et al., 2015
Amino acids	Methionine and lysine may be limiting	Rich in essential amino acids (lysine, methionine, threonine)	Jannathulla et al., 2022; Alvanou et al., 2023; Khan et al., 2025
Digestibility	Moderate; may reduce growth if over 40% inclusion	High; slightly reduced by chitin; improved with processing	Barroso et al., 2014; Nogales-Mérida et al., 2019
Anti-nutritional factors	Phytic acid, trypsin inhibitors, saponins, phytoestrogens	Minimal; chitin has immunostimulatory effects	Aragão et al., 2022; Bera et al., 2022
Functional components	Generally absent	AMPs, lauric acid, and chitin are beneficial for gut health and immunity	Barroso et al., 2014; Bera et al., 2022
Sustainability	Requires high land/water input	Circular economy; can be reared on agro-industrial or food waste	Barroso et al., 2014; Nogales-Mérida et al., 2019

Recent feeding trials have demonstrated the feasibility of incorporating IMs in aquafeeds for a range of species, including *O. mykiss*, gilthead seabream, *Sparus aurata* Linnaeus, 1758, *O. niloticus*, and *T. macdonaldi*. Inclusion levels between 15-30% have generally been associated with stable or improved growth performance, FCRs, and immune parameters (Basto et al., 2023; Edea and Verkhoturov, 2023). In some cases, total replacement of FM was achievable when diets were supplemented to correct amino acid or fatty acid imbalances (Edea and Verkhoturov, 2023). Recent research demonstrated that the inclusion of insect-derived components, such as *H. illucens* larvae oil, can improve growth performance and survival parameters in aquaculture species such as milkfish, *Chanos chanos* (Fabricius, 1775), reinforcing the nutritional value and functional benefits of insect-based ingredients in formulated feeds (Herawati et al., 2025).

However, excessive inclusion (especially >50%) has occasionally led to reductions in growth or digestibility, likely due to increased chitin levels or nutrient imbalances (Hasnan et al., 2023). These findings underscore the importance of diet formulation and ingredient processing in maximizing the efficacy of IMs.

In *C. carpio*, Askale et al. (2022) reported that the inclusion of *H. illucens* or *T. molitor* meal up to 50% of the total protein diet did not modify SGR, FCR, or body composition compared to the FM control group. The same trend was observed by Panikar et al. (2018), who demonstrated that partial substitution of FM with *H. illucens* pre-pupae meal did not affect nutritional performance or feed efficiency in *C. carpio*. These results indicate that IMs can provide high-quality protein comparable to FM for omnivorous species.

In the case of carnivorous species such as *O. mykiss*, the effects of total substitution may be more pronounced. Some studies suggest that the complete replacement of FM with IM may reduce growth rate and protein digestibility, likely due to differences in lipid profiles and the digestibility of certain amino acids (Nogales-Mérida et al., 2019). Partial substitution of FM with IM in well-balanced diets can maintain growth performance and does not negatively affect body composition or fillet quality in *O. mykiss* (Caimi et al., 2021). In addition to the effects on growth, insects may influence fish health and disease resistance. These effects are considered additional benefits compared to plant proteins, which do not offer the same bioactive properties.

Another important aspect is the fillet yield and meat quality, which remain generally comparable to FM-fed groups, if the substitution does not exceed the critical threshold of 50% (Askale et al., 2022). This suggests that insects can be effectively integrated into fish feed without compromising the commercial and nutritional parameters of the final product.

SBM productive performance varies significantly depending on the fish species and inclusion levels (Howlader et al., 2023; Cai et al., 2025). Herbivorous and omnivorous species (like *O. niloticus* and *C. carpio*) tolerate higher SBM levels (up to 50-75% replacement) (Gatlin et al., 2007) better than carnivorous species (like *S. salar* or *O. mykiss*), which may show growth depression at levels as low as 20-30% (Table 4). Some authors suggested that FSBM could substitute 50% FM without affecting the growth, immunity and enzymatic indices of roho labeo, *Labeo rohita* (Hamilton, 1822) (Aslam et al., 2025). Performance of SBM can be optimized by supplementing limiting amino acids (methionine, lysine) or functional additives like taurine, allowing for higher FM replacement levels (Ye et al., 2019). Overall, the data indicate that omnivorous species, such as *O. niloticus* and *C. carpio*, can tolerate high levels of SBM without compromising growth, while carnivorous species are more sensitive to SBM inclusion and may experience reduced performance at lower levels. Similarly, partial replacement of FM with IM is generally well tolerated across both trophic groups, supporting growth, feed conversion, and fillet quality, whereas very high inclusion levels may lead to reduced performance due to factors like chitin or nutrient imbalances. These trends highlight the importance of species-specific diet formulation to optimize the nutritional and functional benefits of alternative protein sources (as summarized in Table 4).

Overall, the data indicate that raw SBM contains several anti-nutritional factors, such as trypsin inhibitors, phytic acid, and saponins, which can limit digestibility and affect growth and gut health in sensitive species. Fermentation effectively reduces these compounds, while producing smaller peptides and improving amino acid availability, leading to enhanced digestibility, growth performance, and intestinal function. These improvements underscore the nutritional and functional advantages of fermented SBM compared to raw SBM, as summarized in Table 5.

NUTRITIONAL ASPECTS IN RELATION TO FISH HEALTH

IM, in addition to protein intake, brings important changes in the nutritional composition of the fish diet, with effects on metabolism, intestinal health, and immunity. Insect proteins have moderate to high digestibility, based on species and processing, but the presence of chitin in the exoskeleton can slightly reduce the total digestibility (Barroso et al., 2014; Makkar et al., 2014). Furthermore, it has been shown that supplementation with digestive enzymes, such as phytase, can improve protein and mineral digestibility, as well as feed utilization efficiency and growth performance in aquaculture species such as striped catfish (*Pangasianodon hypophthalmus*) and Java barbel (*Barbonymus gonionotus*). That might provide practical strategies to mitigate the negative effects of ANFs from plant-based or alternative protein ingredients (Rachmawati and Amalia 2025; Rachmawati et al., 2025). Chitin and other bioactive compounds derived from IMs exhibit immunostimulatory properties, which contribute to the modulation of gut microbiota and enhancement of innate immune responses. Several studies have reported improved disease resistance and survival in fish fed IM-based diets (Barroso et al., 2014; Caimi et al., 2021; Rimoldi et al., 2021). To address issues such as health and production performance in replacing traditional fishmeal with alternative proteins, recent research has highlighted the use of IM and other novel sources in fish diets; these have been formulated to support not only growth, but also fish health overall, nutrient utilization, and performance (Kontara et al., 2025).

A critical aspect is the lipid profile of insects. Although insects contain fatty acids, the content of omega-3 is lower compared to FM.

Table 4. Inclusion percentages and productive performance of soybean meal on the performance of some fish species

Fish species	Trophic level	Soybean meal inclusion (%)	Impact on performance	References
Nile tilapia, *Oreochromis niloticus* (Linnaeus,1758)	Omnivorous	Up to 75	High tolerance; minimal impact on FCR and growth	Gatlin et al., 2007
Common carp (*Cyprinus carpio* Linnaeus, 1758)	Omnivorous	50-60	Good growth; methionine supplementation improves performance	NRC, 2011; Askale et al., 2022
Atlantic salmon, *Salmo salar*, Linnaeus, 1758	Carnivorous	20-30	Risk of distal enteritis or reduced growth above 30%	Sahlmann et al., 2013; Ye et al., 2019
Rainbow trout, *Oncorhynchus mykiss* (Walbaum, 1792)	Carnivorous	25-35	Slower growth if SBM is not heat-treated; total FM replacement may reduce digestibility	Collins et al., 2013; Nogales-Mérida et al., 2019; Caimi et al., 2021
Seabass, *Dicentrarchus labrax* (Linnaeus, 1758)	Carnivorous	20-25	Reduced palatability due to saponins; growth maintained at low inclusion	Wang et al., 2022
Multiple species (*O. niloticus*, *O. mykiss*, *C. carpio*, *D. labrax*) - IM diets	Omnivorous/ Carnivorous	15-50	Partial FM replacement with IM maintains growth, FCR, and fillet quality; >50% may reduce growth due to chitin or nutrient imbalance	Tran et al., 2015; Askale et al., 2022; Melenchón et al., 2022; Basto et al., 2023; Edea and Verkhoturov, 2023; Hasnan et al., 2023

Note: FCR: feed conversion ratio; FM: fish meal; IM: insect meal; SBM: soybean meal

Table 5. The main differences between fermented soybean meal and raw soybean meal as a feed ingredient for fish

Parameter	Raw soybean meal	Fermented soybean meal	References
Trypsin inhibitors	High	Very low	Aragão et al., 2022
Phytic acid	High	Low	Hasan et al., 2023
Saponins	Present; may reduce digestibility and trigger inflammation	Reduced by fermentation	Aragão et al., 2022; Pascon et al., 2025
Peptide size Protein hydrolysis	Large intact proteins; slower digestibility	Smaller peptides; higher digestibility	Basto et al., 2023
Amino acid availability	Moderate; methionine and lysine may be limiting	Improved; limiting amino acids are more bioavailable	Ye et al., 2019; Basto et al., 2023
Fish growth/ FCR	Baseline; sensitive species may show slower growth at high inclusion	Improved (10-20% increase in growth or FCR)	Basto et al., 2023; Aslam et al., 2025
Gut health/ Digestive enzymes	May cause mild inflammation or reduced enzyme activity	Enhanced enzyme activity; improved gut microbiota	Aragão et al., 2022; Basto et al., 2023

Note: FCR: feed conversion ratio

This fatty acid is considered essential to maintain the quality of fish tissues, physiological functions, and meat quality. Therefore, dietary formulations that substitute FM with IMs need to be adjusted; supplementation with marine source oils or other sources of omega-3 is suggested to maintain lipid balance and fillet quality (Nogales-Mérida et al., 2019; Basto et al., 2023). IMs provide compounds such as chitin, AMPs and specific lipids that may enhance resistance to pathogens. In *O. mykiss*, some studies showed reduced mortality and improved gut mucosa after pathogen challenge (Barroso et al., 2014; Caimi et al., 2021; Bera et al., 2022). In addition, IMs contain essential minerals and vitamins, such as iron, zinc, calcium, and B vitamins, which contribute to harmonious growth and efficient energy metabolism. These nutrients are often limited in plant proteins and need to be supplemented, making insects a more nutritionally complete alternative (Henry et al., 2015; Alvanou et al., 2023). Insect processing, including defatting and enzymatic hydrolysis, can increase protein digestibility and nutrient bioavailability, reduce the negative effects of chitin and optimize feed conversion (Barroso et al., 2014; Melenchón et al., 2022). Thus, continuing to optimize IM processing/production becomes essential to maximize nutritional benefits and fish health.

Several studies have demonstrated that moderate inclusion levels of IM can stimulate innate immune responses in fish. A recent meta-analysis showed that partial replacement of FM (approximately 40%) with IM leads to upregulation of immune-related genes such as IL-1β, TNF-α, and lysozyme in various teleosts (Chen et al., 2024). However, excessively high substitution levels (>85%) were associated with diminished immune gene expression, suggesting a dose-dependent response and the need to define optimal inclusion thresholds.

Moreover, dietary supplementation with *T. molitor* extract in zebrafish (*Danio rerio*) improved growth performance and immune indicators (e.g., lysozyme activity, phagocytic index), without negatively affecting hepatic enzyme function, which indicates the potential of insect-derived bioactives in modulating fish immunity (Abdolmanafi et al., 2025).

Substituting FM with IM also influences intermediary metabolism. In a long-term feeding trial with *D. labrax*, partial replacement (50%) of FM with defatted *T. molitor* meal maintained normal plasma metabolite levels and enzyme activities. In contrast, total replacement induced significant alterations in liver gene expression related to amino acid and lipid metabolism, potentially impairing nutrient utilization efficiency (Basto et al., 2023).

The gastrointestinal tract is a primary interface between nutrition and health. In sea trout, *Salmo trutta* Linnaeus 1758, diets incorporating *T. molitor* or superworm (*Zophobas morio*) meal as a partial replacement of FM showed no significant shifts in the abundances of the major bacterial phyla (*Firmicutes*, *Proteobacteria*, *Actinobacteria*) compared to FM-fed controls. However, genus-level composition was subtly altered, particularly in fish fed the *Z. morio* diet (Józefiak et al., 2023).

In Siberian sturgeon, *Acipenser baerii* Brandt,1869, inclusion of up to 15% IM maintains *villus* morphology and even promotes gut health via beneficial microbial shifts. A moderate IM inclusion did not compromise, but enhanced gut integrity and nutrient absorption in fishes (Józefiak et al., 2019).

SBM has specific and well-documented limitations on fish health (Table 6). High saponin content acts as the primary trigger for distal enteritis in carnivorous species, such as *S. salar*, by compromising the structural integrity of intestinal cell membranes (Krogdahl et al., 2010; Sahlmann et al., 2013). Lectins possess the ability to bind specifically to the gut mucosal lining, where they interfere with efficient nutrient absorption and can lead to reduced growth rates (Gatlin et al., 2007; NRC, 2011). Specifically, compounds like genistein (as phytoestrogens) can disrupt endocrine signalling and negatively impact the reproductive success and hormone levels of fish broodstock (Pavlopoulos et al., 2023).

Table 6. Impact of soybean meal on fish health

Health effect	Clinical description	Sensitive species	Reference
Distal enteritis	Inflammation of the posterior intestine, shortening of villi, and leucocyte infiltration.	*S. salar*, *O. mykiss*	Sahlmann et al., 2013
Enzyme inhibition	Trypsin inhibitors block protein digestion, leading to pancreatic hypertrophy.	Most species (especially fry/juveniles)	Krogdahl et al., 2010
Immune barrier breach	Soya saponins increase intestinal permeability, facilitating pathogen entry.	*D. labrax*, Salmonids	Knudsen et al., 2007
Oxidative stress	High SBM levels may reduce antioxidant capacity in the liver	*C. carpio*, *O. niloticus* (at >50% inclusion)	Barroso et al., 2014; Basto et al., 2023
Mineral malabsorption	Phytic acid binds phosphorus, zinc, and magnesium, causing skeletal deficiencies.	All species	NRC, 2011

ADVANTAGES AND CHALLENGES

The inclusion of IM in fish feed brings multiple advantages, which make it an attractive alternative to FM. Firstly, insects are a sustainable and renewable protein source that does not directly depend on limited marine resources, reducing pressure on ecosystems and contributing to the maintenance of biodiversity (Barroso et al., 2014; Henry et al., 2015). Secondly, insects allow the valorization of agro-industrial waste, transforming food scraps or agricultural by-products into high-value feed ingredients. This supports the circular economy and reduces the ecological impact of fish farms (Nogales-Mérida et al., 2019). Another advantage is represented by the bioactive properties of insects. Chitin, AMPs, and specific lipids can stimulate immunity, promote a balanced gut microbiome, and reduce mortality induced by intestinal diseases or oxidative stress (Barroso et al., 2014; Caimi et al., 2021; Bera et al., 2022). Thus, insects not only replace protein but can also bring additional functional benefits compared to other protein sources.

However, there are also challenges associated with the use of insects in fish feed. A first aspect is the variability of nutritional composition depending on the growth substrate, species, and developmental stage of the insect. This can affect the content of proteins, EAAs, and fatty acids, requiring careful standardization and monitoring (Nogales-Mérida et al., 2019). Production and processing costs are another challenge. Although insects can be raised efficiently, the initial investments for specialized farms, processing equipment, and diet optimization are high, which may limit large-scale adoption (Henry et al., 2015). Also, legal regulations for the use of insects in animal and fish feed are still incompletely defined in many countries. This may limit product commercialization and industrial adoption, requiring legislative clarification and food safety standards (Nogales-Mérida et al., 2019).

Although alternative protein sources such as IMs, single-cell proteins, and animal by-products show promise, their large-scale adoption still faces significant challenges: high production costs, regulatory limitations, species-specific acceptability issues, and limited long-term data on health and product quality outcomes (Chen et al., 2024). Additionally, current formulations often require supplementation with EAAs (e.g., methionine, lysine) to match the nutritional profile of FM, which can further complicate diet formulations and impact economic viability (Basto et al., 2023; Hasnan et al., 2023).

SBM has its specific advantages in fish nutrition. Unlike FM or IM, SBM has a stable global supply chain and consistent quality, giving it a consistent and durable availability. It is significantly cheaper per unit of protein than FM or IM prices (Arru et al., 2019). Once treated (e.g., with phytase), its phosphorus is more accessible than in many other plants (NRC, 2011). It is highly attractive to species like *O. niloticus* and *C. carpio*, promoting high feed intake (Hussain et al., 2024). Contains 44-48% crude protein with the best amino acid profile among all plant sources (Gatlin et al., 2007). Apart from

SBM, the most important processed forms with superior characteristics are SPC, soy protein isolate and FSBM, which all offer improved performances in fish nutrition. Those products are recommended to sensitive carnivorous species (SPC for *S. salar*, *O. mykiss*) (Sahlmann et al., 2013), or in starter diets for *larvae* or very small fry (SPI) (NRC, 2011), while in omnivorous species, they might improve digestive health (FSBM) (Barroso et al., 2014; Bera et al., 2022).

CHALLENGES AND FUTURE PERSPECTIVES

Despite their potential, several challenges must be addressed before IMs can be widely adopted:

Nutritional variability

The nutritional composition of IMs is highly dependent on insect species, developmental stage, diet, and processing methods; therefore, standardization is essential to ensure consistent nutritional quality in aquaculture feeds (Makkar et al., 2014; Henry et al., 2015).

Cost and scalability

IM remains more expensive than traditional protein sources due to limited production scale and infrastructure. Further technological improvements and policy support are needed to reduce costs (Bera et al., 2022).

Regulatory and safety concerns

Global regulation of insect-derived feed ingredients remains fragmented. Potential risks related to allergens (e.g., tropomyosin), contaminants, and microbiological safety must be rigorously assessed (Edea and Verkhoturov, 2023).

To fully leverage the benefits of insect proteins, future research should focus on optimizing, rearing and processing systems to improve nutrient digestibility and evaluate long-term effects on fish physiology and product quality. Moreover, integrating IMs with other alternative ingredients (e.g., plant proteins, microbial meals) may offer balanced, cost-effective solutions for sustainable aquaculture (Khan et al., 2025).

With respect to SBM, the advantages have already been proven in the past decades. Limitations are various, with the most common based on preparation, neutering ANFs and culture conditions. Under-processing: inadequate heat treatment can leave active enzymes that interfere with nutrient digestion in fish. Over-processing: if the temperature is too high, the Maillard reaction occurs. That "destroys" EAAs, such as lysine, making them impossible to be absorbed by the fish, even if the protein level appears high on the label. Stability in water: pellets with a high percentage of soy tend to disintegrate more quickly in water. If the pellet dissolves before it is eaten, feed is lost, and the aquarium/pond is polluted. Variation in the quality of raw materials: unlike marine ingredients, which are more constant, the quality of soy depends enormously on the geographical area of harvest, climatic conditions and storage (molds can produce mycotoxins which are fatal to fish). Another disadvantage can be the spatial variation in pesticide, herbicide, and fertilizer inputs across soybean-producing regions that may influence both the nutritional composition and residual contaminant burden of SBM incorporated into aquaculture diets. As perspectives, SBM and derivates will most likely remain a core ingredient for aquaculture feeding formulations.

CONCLUSIONS

IM, particularly from *Hermetia illucens* and *Tenebrio molitor*, represents a sustainable, high-quality protein alternative to FM. Partial FM replacement (up to 50%) supports growth, feed conversion, fillet yield, gut health, and immune responses, while total replacement may require amino acid and lipid supplementation, especially in carnivorous species. SBM offers cost-effective, widely available plant protein, tolerated at higher levels in omnivorous fish, though anti-nutritional factors and processing affect digestibility and performance. Combining IM and SBM allows for nutritionally balanced, environmentally sustainable aquafeeds. Optimized species-specific formulations and processing strategies are essential to maximize growth, health, and feed efficiency, supporting long-term sustainable aquaculture.

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