Aquafeed Innovation: Utilization of Insects for Sustainable Fish Nutrition: A Review

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ABSTRACT

Rapid global population growth has increased food demand, placing pressure on conventional agriculture and highlighting the need for sustainable protein sources. Aquaculture contributes significantly to global food security by supplying animal protein, yet its expansion is constrained by the high cost and environmental impact of traditional feed ingredients such as fishmeal and soybean meal, which are associated with overfishing and deforestation. These challenges have encouraged the exploration of alternative, environmentally responsible feed resources. Insects have emerged as a promising ingredient in aquaculture diets due to their high-quality protein, balanced amino acid profile, and beneficial lipid composition. Insect-based meals offer economic advantages while reducing reliance on conventional feed sources, potentially improving both sustainability and resource efficiency within the sector. This review evaluates the nutritional benefits and environmental implications of incorporating insect-derived ingredients into aquafeeds and examines their potential to enhance sustainable aquaculture production. The review also discusses key barriers to large-scale adoption, including regulatory limitations, cultural acceptance, production scalability, and logistical challenges. Safety considerations such as microbial risks, allergenic potential, and the accumulation of undesirable substancesare analyzed within current regulatory frameworks. Additionally, existing knowledge gaps, species-specific responses, digestibility concerns, and optimal inclusion levels are addressed, alongside consumer perception and market acceptance. Overall, continued research, investment, and supportive policy development are essential to facilitate the integration of insect-based feeds into mainstream aquaculture. Advancing these efforts can support environmentally sustainable aquaculture practices while helping meet the growing global demand for protein.

Keywords: Aquaculture, Aquafeeds, Cost-effective nutrition, Insect-based feeds, Sustainable protein

INTRODUCTION

The rapid expansion of the global population, currently increasing at an annual rate of around 1.8–1.0%, is expected to reach nearly 10 billion by 2050, placing significant pressure on global food production systems according to the Technical and Economic Committee for Fisheries (STECF, 2020. This growing demand necessitates advancements in agricultural and animal protein production to ensure food security (Maulu *et al*., 2020). Among various animal production sectors, aquaculture has emerged as the fastest-growing, playing a crucial role in meeting protein demands efficiently. Its ability to produce aquatic food sustainably positions it as a key solution to the limitations of traditional agriculture. However, the industry faces multiple challenges, including environmental concerns, economic constraints, and the pressing need for sustainable feed ingredients to support continued growth (Food and Agriculture Organization of the United Nations, FAO, 2020;

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Maulu *et al*., 2021). One of the primary challenges in aquaculture is the "food-feed-fuel" competition, which, along with climate change, has impacted the availability and cost of essential feed ingredients (Voulgari-Kokota *et al*., 2023; Abozaid *et al*., 2024; FAO, 2024). The dependence on these conventional feed sources presents sustainability issues related to resource depletion, fluctuating market prices, and environmental degradation. Additionally, plant-based proteins in aquafeeds have been associated with negative effects on aquaculture production, including compromised gut health and reduced growth performance due to the presence of anti-nutritional compounds (Gaudioso *et al*., 2021). Rising feeding cost pose a major economic burden on the sector. Heavy reliance on fishmeal and fish oil exacerbates these financial pressures, while environmental concerns related to overfishing, depletion of wild fish stocks, and contamination with microplastics further highlight the need for alternative protein sources (Dawood, 2022).

To address these challenges, researchers have explored innovative protein substitutes, with insects emerging as a promising new alternative due to their nutritional values, rapid growth, and minimal environmental impact. Insects provide a high protein content (34–74% dry matter), along with lipids, vitamins, and minerals, making them suitable candidates for aquafeeds. Additionally, insect farming requires fewer resources, generates lower greenhouse gas emissions, and can transform organic waste into high-quality protein, promoting sustainable aquaculture practices (Alfiko *et al*., 2022). Beyond their nutritional benefits, insects contribute functional properties to aquafeeds, as bioactive compounds such as chitin, fatty acids, and antimicrobial peptides have shown prebiotic and health-enhancing effects (Veldkamp *et al*., 2022). These properties make insect-based proteins not only a viable replacement for fishmeal and fish oil but also an effective solution to some of the limitations associated with plant-based feeds. However, variations in insect composition based on species, rearing conditions, and processing methods necessitate further research to optimize their application in aquaculture nutrition (Jeyasanta *et al*., 2024).

Recently, many studies have reported that, due to the increasing scarcity of fishmeal, there has been extensive exploration of alternative protein sources that can offer comparable nutritional benefits (Fantatto *et al*., 2024; FAO, 2024) to ensure aquaculture production remains green, profitable, and sustainable (GPS) in the long term, identifying new aquafeed protein sources such as insects, seaweed, distiller's grain and bacteria rather than conventional protein sources according to Chary *et al*. (2024).

Despite their potential as a sustainable alternative protein source, several research gaps remain in using insects for fish nutrition. The nutritional composition of insect meals, particularly black soldier fly (*Hermetia illucens*) and yellow mealworm (*Tenebrio molitor*), varies widely with substrate, processing, and developmental stage, highlighting the need for standardized production protocols. Limited studies exist on processing methods and their effects on digestibility and palatability, and most feeding trials are short-term, leaving long-term impacts on growth, immunity, gut health, and reproduction unclear. Safety concerns, including heavy metal accumulation, microbial contamination, allergenicity, and pathogen transfer, require further assessment. Species-specific guidelines are insufficient, with most research focusing on tilapia and salmonids, while marine carnivores and shrimp remain under-studied. Economic feasibility, large-scale production, and circular economy integration need further exploration, alongside comprehensive environmental assessments to quantify carbon footprints, water use, and resource efficiency. Finally, consumer acceptance and market dynamics of insect-fed fish are poorly understood. Addressing these gaps requires multidisciplinary research to unlock the full potential of insects in sustainable aquafeeds.

OBJECTIVES

This review explores the potential of insect-based proteins as a sustainable feed ingredient in aquaculture. It highlights recent advancements, addresses existing challenges, and discusses future directions for integrating insects into aquafeeds, contributing to the sector's long-term sustainability and productivity.

LITERATURE REVIEW METHODOLOGY

The literature review was conducted by synthesizing recent, peer-reviewed studies and authoritative reports on insect-based proteins in aquafeeds, focusing on nutritional composition, processing effects, fish performance outcomes, safety considerations, regulatory frameworks, and environmental impacts (including life cycle assessment where available). A targeted search was performed using Scopus, Web of Science, and Google Scholar with keywords such as "insect meal", "aquafeed", and "fishmeal replacement". The search covered publications from 2010 to 2024 and was restricted to English-language sources, prioritizing peer-reviewed articles. Studies were included if they addressed aquaculture-relevant species and provided experimental evidence or review-level synthesis; non-aquaculture and non-peer-reviewed sources were excluded unless essential for regulatory guidance or global reference reports. After removing duplicates and screening titles/abstracts, the final selection comprised the most relevant studies for qualitative synthesis.

RESULTS

Growth trends and economic impact of aquaculture

The global fishing and aquaculture industry had an estimated total value of USD 406 billion in 2020, with aquaculture contributing USD 277 billion (FAO, 2022). In the same year, global aquatic animal production reached approximately 178 million tonnes (MT), projected to rise to 202 MT by 2030. About 157 MT were used for human consumption, while approximately 20 MT were designated for non-food applications, including 16 MT for fishmeal and fish oil production. FAO (2024) forecasts a 10% expansion in aquaculture production by 2032, reaching 205 MT. The global aquaculture market, valued at USD 229.02 billion in 2023, is expected to reach USD 355.66 billion by 2033 (CAGR: 4.5% during 2024–2033). These trends highlight the need for sustainable and cost-effective feed alternatives, as feed quality directly influences health, growth, and productivity (Xiao *et al*., 2018). Overexploitation of wild fish stocks has intensified concerns over resource depletion, emphasizing the need for alternative aquafeed ingredients (Daniel, 2018; Stankus, 2021).

Global insect farming: Production, scale, and constraints

Insects have emerged as a sustainable solution for aquafeeds due to their high protein content, efficient resource utilization, and relatively lower environmental footprint (Voulgari-Kokota *et al*., 2023). Insect farming involves breeding and raising insects in controlled environments, with applications across aquaculture, poultry, swine, and pet food industries (Desjonquères *et al*., 2024). While some insects are cultivated for byproducts, others are farmed specifically as protein sources. Major farming regions include Asia (China, Thailand, Vietnam, South Korea), Europe (Netherlands, France, Belgium, Germany, Spain), the Americas (USA, Canada, Brazil, Mexico, Colombia), Africa (South Africa, Kenya, Ghana), and the Middle East (UAE, Saudi Arabia) (Omuse *et al*., 2024). In Europe, insect-based aquafeeds have been permitted since 2017, but adoption remains limited due to industry hesitancy and regulatory constraints (Rumbos *et al*., 2021). Key farmed species include black soldier fly, yellow mealworms, and house crickets (*Acheta domesticus*).

Global insect production is increasing, with approximately 42 European companies producing about 6,000 tonnes of insect meal annually, which is expected to rise to 0.5 million tonnes by 2030 (Mancuso *et al*., 2019; IPIFF, 2020). However, production costs remain high due to limited automation; in Europe, black soldier fly larvae prices range from USD 2.32–10.44 kg^{-1} (Mancuso *et al*., 2019). Increased automation and investment are needed to improve cost-efficiency and sustainability (Van Zanten *et al*., 2015).

The estimated number of insects farmed worldwide annually is significant. Rowe (2020) reported that global production was 1 to 1.2 trillion insects farmed per year, with 560–680 billion insects slaughtered and 180 to 230 billion sold as live insects (Table 1). Although data coverage is

Table 1. Global scale Estimatatio for insect farming and utilization, including insects slaughtered numbers, sold live, and farmed annually, with selected regional estimates according to Rowe, 2020).

Type	Number
Insect slaughtered	560 billion to 680 billion
Insects sold live	180 billion to 230 billion
Insects dead prior to processing	250 billion to 300 billion
Insects farmed annually	1 trillion to 1.2 trillion
US and Canada	4.500 to 5.500
Asia	26.000 to 28.000
Middle East+ Africa	19.000 to 21.000
Latin America	4.500 to 6.000
Total production (tonne)	60.000 to 67.000

relatively robust for Europe, the United States, and Canada, production estimates for Asia, the Middle East, Africa, and Latin America remain less comprehensive (Kim *et al*., 2022). Nonetheless, the edible insect market is projected to grow at a CAGR of 28.3% from 2022 to 2030, potentially reaching USD 9.60 billion by 2030 (Fuso *et al*., 2024). According to Kim *et al*. (2022), hundreds of startups and established companies are involved globally in producing and selling insect-based products, including whole insects, insect-based flour, and insect protein powder. Overall, the expansion of insect farming presents a promising opportunity for sustainable food production, though further research is required to optimize production methods and enhance regulatory frameworks worldwide.

Advantages of using insects in aquaculture feeding

According to FAO (2022), approximately 16 million metric tonnes (MMT) of fish are processed into fishmeal annually. Due to increasing demand, concerns over the sustainability of forage fish stocks have been raised since the early 2000s. Fishmeal production remains inconsistent due to fluctuating environmental and climatic conditions, fishing quotas, and rising fuel costs. For example, fishmeal supply in 2023 was 23% lower than in 2022 due to multiple contributing factors (IFFO, 2024). In addition to environmental concerns, the volatility and rising costs of fishmeal have driven interest in alternative protein sources. However, plant-based proteins such as soybean meal present limitations, especially for high-value carnivorous fish, such as salmon. Gasco *et al*. (2018) reported that the growing demand for sustainable and cost-effective protein sources in aquaculture has intensified interest in insect-based feed ingredients. Insects offer high nutritional value, with crude protein levels ranging from 42% to 74%, depending on processing methods. They are rich in lipids, amino acids, bioavailable minerals (e.g., iron and zinc), and vitamins (e.g., B12), making them promising substitutes for fishmeal and soybean meal. One of the most studied insect species for aquaculture is the black soldier fly.

Black soldier fly larvae exhibit exceptional reproductive efficiency, adaptability, and the capacity to thrive in high-density populations (Yu *et al*., 2024). They can efficiently convert organic waste into nutrient-dense feed components, offering a scalable and environmentally friendly solution (Melenchón *et al*., 2022).

Their nutritional profile aligns with the natural diets of many fish species, which frequently consume insects and invertebrates. Despite these advantages, challenges remain. Standardizing rearing substrates is essential, as the nutritional composition of insect meal is influenced by the inputs used. Moreover, determining species-specific inclusion levels and balancing production costs

with market demands are critical (Melenchón *et al*., 2022). Borrelli *et al*. (2021) emphasized that economic feasibility and accessibility depend on production techniques, substrate selection, and regional conditions. Insects provide a rich source of proteins, fats, minerals, and vitamins. Their high protein content (50–80% dry matter basis), ability to upcycle low-value agri-food waste into valuable products, and low resource requirements (less water, land, and time) contribute to their sustainability. This circular food system approach helps address food waste challenges, shorten feed supply chains, and support local production (Alfiko *et al*., 2022; Fantatto *et al*., 2024).

Insect-based feeds: a sustainable alternative for aquaculture

Insects are increasingly recognized as a sustainable and efficient protein source for aquaculture. As noted earlier, they offer a solution to the growing demand for feed ingredients with reduced environmental impact (Gómez *et al*., 2019; Alfiko *et al*., 2022; Fantatto *et al*., 2024). Sogari *et al*. (2023) highlighted that research primarily focuses on carnivorous fish species in both freshwater and marine environments, such as trout, salmon, seabass, tilapia, and largemouth bass. Commonly studied insect meals include those from black soldier fly, yellow mealworms, and housefly (*Musca domestica*). Their effectiveness depends on factors such as insect species, developmental stage, processing methods (whole vs. defatted), and inclusion levels. Most studies used iso-lipidic and iso-proteic diets, with a few focusing solely on iso-proteic diets (e.g., Nile tilapia). For instance, diets with 18% whole black soldier fly or yellow mealworm meal improved growth of rainbow trout and seabass, with yellow meal worm showing superior final body weight, specific growth rate (SGR), and feed conversion ratio (FCR), likely due to higher protein digestibility (Reyes *et al*., 2020; Melenchón *et al*., 2022). However, reducing black soldier fly to 12% in largemouth bass diets resulted in poorer growth (Fischer *et al*., 2022). Similarly, 9.2% house fly meal (25% fishmeal replacement) reduced performance. Renna *et al*. (2017) demonstrated that partially defatted black soldier fly larvae meal could replace fishmeal in trout diets up to 40% without compromising growth. Sealey *et al*. (2011) found that black soldier fly larvae raised on fish offal outperformed those fed standard diets. Trout fed enriched black soldier fly meal (50% fishmeal replacement) performed comparably to controls, while non-enriched black soldier fly meal at 25% replacement lowered growth. Belforti *et al*. (2015) observed no significant growth differences in trout diets with up to 50% full-fat yellow meal worm meal, though feed intake declined at higher inclusion. Doğankaya (2017) tested superworm (*Zophobas morio*) meal in trout diets and found performance declined only at 100% fishmeal replacement. Kroeckel *et al*. (2012) found growth in turbot at inclusion levels above 33%, likely due to low palatability and chitin digestibility issues. Nevertheless, black soldier fly raised on greenhouse waste showed sustainability benefits. Saowakoon and Saowakoon, 2007 and Araki *et al*., 2008 noted that increasing black soldier fly meal levels in gilthead seabream diets reduced feed intake and final body weight, though SGR, and FCR and protien efficiency ratio (PER) remained stable.

Nutritional composition of insects

Over the past decade, the importance of optimal nutritional composition in enhancing aquaculture production has been widely recognized. Recently, there has been a growing interest in incorporating insects into aquafeeds. Extensive research highlights the exceptional nutritional potential of insects as an alternative feed source. Their nutritional profiles, though varying by species, developmental stage, and diet, consistently demonstrate high levels of essential nutrients, making them a valuable component of fish diets (Sogari *et al*., 2023; Fantatto *et al*., 2024). Like other animals, insects are rich sources of protein, fat, vitamins, and minerals. However, the exact nutrient composition varies depending on their diet and developmental stage. Insects exhibit considerable crude protein levels, ranging from 42.1% to 60.7%. While this crude protein level is lower than that found in fishmeal, it is comparable to soybean meal (Henry *et al*., 2015; Allegretti *et al*., 2018). The amino acid composition varies among insect species; for instance, yellow mealworm contains lower lysine levels than fishmeal, whereas

Diptera species, such as black soldier fly and housefly, have higher lysine concentrations. Sulfur-containing amino acids in insects are generally lower than in fishmeal (Henry *et al*., 2015). Tryptophan levels are also lower in most insect species, except for housefly maggot meal, suggesting the need for synthetic amino acid supplementation depending on the specific dietary requirements of fish. Diptera species, with their superior essential amino acid profiles, are considered promising alternatives for replacing fishmeal in aquafeeds (Ordoñez-Araque *et al*., 2022). Fat content varies significantly across insect species and even within the same species, influenced by factors such as developmental stage and diet (Barroso *et al*., 2014). Compared to fish oil, insect meals generally contain lower levels of omega-3 fatty acids but are rich in saturated fatty acids (Makkar *et al*., 2014). Yellow mealworm, and house fly maggot meals have higher concentrations of unsaturated fatty acids, whereas black soldier fly meals exhibit lower unsaturated fatty acid content (Hawkey *et al*., 2021). The lipid composition and fatty acid profiles of insect meals are highly dependent on dietary intake. Altering the nutrient composition of insect diets can modify their fatty acid profiles, making it a crucial factor in optimizing aquafeeds (Makkar *et al*., 2014). Additionally, factors such as culturing conditions and the developmental stage at harvest also influence fatty acid composition (Kolobe *et al*., 2023). Insects provide a wide array of micronutrients, including B vitamins and essential minerals such as calcium, phosphorus, and zinc. These nutrients play critical roles in bone development, immune function, and overall vitality in fish, making insects an indispensable component of sustainable aquaculture practices (Kolobe *et al*., 2023). Chitin is the second most abundant polysaccharide on Earth after cellulose. It is composed of N-acetyl-D-glucosamine units linked by covalent β-1,4 bonds. Chitin and its derivative, chitosan, are naturally occurring biopolymers with diverse applications in food, biomedicine, and industrial sectors due to their high biological activity (Rimoldi *et al*., 2023). Chitin comprises up to 25% of the exoskeleton in *H. illucens*, making it a key component in large-scale insect farming operations for industrial extraction (Wang *et al*., 2020). The growing demand for chitin and its derivatives has prompted the search for more sustainable and widely available sources. Insects have emerged as promising alternatives to traditional chitin sources. Various by-products, including larvae, pupae, and deceased adults, are generated during insect rearing and processing, providing additional opportunities for chitin extraction (Rehman *et al*., 2023). Although chitin is not easily digestible, it has demonstrated potential prebiotic benefits, promoting gut health and enhancing immune function in fish. However, its presence can also hinder digestibility, prompting ongoing research into optimizing its inclusion in aquafeeds. Strategies such as enzymatic chitinase treatment are being explored to improve feed digestibility, enhance disease resistance, and promote environmental sustainability in aquaculture (Hasan *et al*., 2023). The significant nutritional and functional benefits of insects, particularly chitin, position them as a sustainable and effective alternative feed source in aquaculture. This approach addresses environmental concerns while ensuring high-quality fish feeds. The global market for chitin and chitosan derivatives was valued at $3.8 billion in 2020 and is projected to reach $12.3 billion by 2027, with an annual growth rate of 18.4% (FAO, 2022). Recent studies highlight the broad applications of chitin and chitosan in biomaterials, food and nutrition, biomedicine, cosmetics, water purification, biodegradable packaging, and antimicrobial agents (Muneer *et al*., 2021; Rehman *et al*., 2023).

The nutritional composition of insects varies substantially among species, and can differ markedly from that of fishmeal and soybean meal (Makkar, 2018, Table 2).

Factors affecting the nutritional value of insects

Several factors influence the nutritional composition of insects, including species, developmental stage, diet, and processing methods. The nutritional profile of insects varies significantly by species, particularly when compared to fishmeal and soybean meal (Makkar, 2018). Most insect species contain protein levels comparable to soybean meal but generally lower than fishmeal (Hawkey *et al*., 2021; Li *et al*., 2022). Orthoptera (e.g., locusts and crickets) have crude protein levels of 50–55 g per 100 g (Lokeshkumar *et al*., 2022), whereas

Table 2. Main chemical constituents in insect meals versus fishmeal meal and soybean meal.

Constituents % in DM	Black soldier fly larvae	Housefly maggot meal	Meal worm	Locust meal	House cricket	Mormon cricket	Silkworm pupae meal	Silkworm pupae meal (defatted)	Fish meal	Soybean meal
Crude protein	42.1 (56.9)	50.4 (62.1)	52.8 (82.6)	57.3 (62.6)	63.3 (76.5)	59.8 (69.0)	60.7 (81.7)	75.6	70.6	51.8
Lipid	26.0	18.9	36.1	8.5	17.3	13.3	25.7	4.7	9.9	2.0
Calcium	7.56	0.47	0.27	0.13	1.01	0.20	0.38	0.40	4.34	0.39
Phosphorus	0.90	1.60	0.78	0.11	0.79	1.04	0.60	0.87	2.79	0.69
Ca:P ratio	8.4	0.29	0.35	1.18	1.28	0.19	0.63	0.46	1.56	0.57

Note: Values in parentheses are calculated values of the defatted meals (Makkar, 2018); DM = Dry matter.

Diptera often exhibit an amino acid profile similar to fishmeal (Barroso *et al*., 2014), and Coleoptera may provide a superior amino acid composition compared with soybean meal but not fishmeal (Kurečka *et al*., 2021). The amino acid composition varies among insect orders. Generally, insect meals contain lower histidine and threonine than fishmeal but higher tyrosine, lysine, and methionine than soybean meal. Diptera species closely match fishmeal in histidine, lysine, and threonine, while phenylalanine levels surpass those of both fishmeal and soybean meal (Ogunji *et al*., 2008; 2009).

The nutritional composition of insects changes as they mature (Ademolu *et al*., 2010). Typically, protein content increases while lipid content declines. For instance: Diptera larvae contain 40–50% crude protein, increasing to 50–62% in pupae, black soldier fly larvae reach ~61% crude protein at five days old but decline with maturity, and Orthoptera adults tend to have higher protein levels than nymphs. Conversely, adults yellow mealworn tends to be rich in protein and chitin, while larvae contain higher lipid levels.

Insect diets significantly affect their nutrient profile, especially lipids, amino acids, and minerals. For example, wild Orthoptera have ~8.2% lipid content, but this increases under controlled rearing conditions. Modifying black soldier fly larval diets can triple omega-3 levels and improve the omega-6 ratio (Heckmann *et al*., 2018; Van Huis, 2020) and mealworms raised on tailored diets show better feed efficiency, protein content, and survival. However, excessive black soldier fly inclusion (75–100%) in fish diets negatively affects health parameters (Chemello *et al*., 2022).

Processing methods impact nutrient bioavailability and digestibility (Madibela *et al*., 2007). For instance, defatting through mechanical pressing or solvent extraction increases protein content. In addition, drying, fermentation, enzymatic hydrolysis, and thermal processing can enhance digestibility and palatability. Enzymatic and solvent-based extractions may also optimize protein yields and bioactive properties (Lu *et al*., 2011).

Insects are naturally seasonal, making controlled farming essential for year-round availability (Cadinu *et al*., 2020; Van Huis *et al*., 2021). Efficient egg production and optimized rearing conditions (temperature, humidity, and feed quality) are key for large-scale insect farming (Pastor *et al*., 2015).

INSECT SPECIES USED IN AQUAFEEDS

Insects represent the most diverse group of animals on Earth and have long served as a natural food source for fish, particularly for carnivorous and omnivorous species that require relatively high levels of protein in their diets (Van Huis, 2020). While humans have consumed insects for more than 2,000 years in many cultures, their application in aquafeeds is a more recent development, beginning less than four decades ago. Since then, substantial

progress has been made in areas such as species selection, rearing techniques, yield optimization, nutritional profiling, and field performance evaluations (Daniel, 2018). Large-scale commercial insect farming both for human consumption and as animal feed is still relatively new, with the first industrial facility opening in 2015 (Delgado *et al*., 2023). The industry has since expanded rapidly, particularly in China, Europe, North America, Australia, and Southeast Asia (Lourenço *et al*., 2022). At least 16 insect species have been tested as potential protein sources in aquaculture (Nogales-Mérida *et al*., 2019), although commercial interest largely centers on a few species that can be farmed efficiently at scale. Most research has focused on larvae meals from black soldier fly, house fly, and yellow mealworm (Fantatto *et al*., 2024). The insect protein sector is projected to continue growing as investment and interest increase. The International Platform of Insects for Food and Feed (IPIFF) estimates that European production will surpass one million metric tonnes by 2030, compared to just 5,000 tonnes in 2019. Most of this output is expected to go toward pet food and livestock feeds, including aquaculture, rather than direct human consumption. The environmental drawbacks of fishmeal in aquafeeds such as overfishing, biodiversity loss, and pollution have been widely documented (Almond *et al*., 2020). With global population growth driving demand for sustainable protein, insect-based meals have been promoted as a viable alternative within a bioeconomy framework (Phung *et al*., 2023).

According to Sogari *et al*. (2023), insects are promising sustainable protein sources for aquaculture. Research mainly targets carnivorous species (trout, salmon, seabass, tilapia, and largemouth bass) using black soldier fly, yellow mealworm, and sometimes housefly meals. Growth performance depends on insect species, life stage, meal type (whole vs. defatted), and processing. Most studies use iso-lipidic and iso-proteic diets, except one tilapia trial using only iso-proteic diets. For example, trout and seabass fed 18% yellow mealworm showed better body weight, SGR, and FCR than those fed black soldier fly, likely due to higher protein content and digestibility (Reyes *et al*., 2020; Melenchón *et al*., 2022). Largemouth bass showed reduced growth at 12% black soldier fly inclusion (Fischer *et al*., 2022). In rainbow trout, full-fat black soldier fly pre-pupa meal at 15% (25% fishmeal replacement) did not affect growth, but 30% (50% fishmeal replacement) decreased performance, possibly due to chitin and altered fatty acids (St-Hilaire *et al*., 2007). Partial defatting improved outcomes, with up to 40% inclusion (50% fishmeal replacement) showing no growth reduction (Renna *et al*., 2017). Diet quality also depends on rearing substrate; trout fed black soldier fly larvae grown on fish offal performed better than those without enrichment (Sealey *et al*., 2011). Full-fat yellow mealworm meal up to 50% fishmeal replacement showed no performance decline, though feed intake decreased (Belforti *et al*., 2015). Superworm meal improved trout performance at 25% fishmeal replacement but worsened at higher levels (Doğankaya, 2017). In marine species, turbot and seabream showed reduced performance at high black soldier fly inclusion due to low palatability and chitin (Kroeckel *et al*., 2012; Saowakoon and Saowakoon, 2007 and Araki *et al*., 2008). Sea bass responded differently to yellow mealworm inclusion, with 25% improving performance but 50% reducing it (Piccolo *et al*., 2017; Gasco *et al*., 2018). Processing matters: two black soldier fly meals tested in salmon showed that one method (IMA) maintained performance even at 100% fishmeal replacement, while the other (IMB) reduced performance at 25% (Lock *et al*., 2018). Higher inclusion of full-fat black soldier fly meal improved body weight in salmon and tilapia without affecting FCR (Wachira *et al*., 2021; Weththasinghe *et al*., 2021a). Housefly meal in seabass showed similar body weight but worse FCR than yellow mealworm (Tran *et al*., 2022). Defatted black soldier fly generally performs better than whole black soldier fly in trout and seabass (Caimi *et al*., 2021; Tran *et al*., 2022). Prepupa and pupa meals show mixed results due to chitin content, with trout showing reduced growth at 30% pre-pupa but no effect at 45% pupa (Hoc *et al*., 2021; Cardinaletti *et al*., 2022), while bass showed negative effects at 10% prepupa (Fischer *et al*., 2022). Overall, yellow mealworm shows consistent positive effects, while black soldier fly results vary by species and processing; standardization is needed to reduce variability (Sogari *et al*., 2023). In Egyptian

Table 3. Insect inclusion trials and growth outcomes in aquaculture fish species.

Fish species	Insect meal used	Inclusion rate	Main result	Notes
Rainbow trout and seabass	BSF and YM	18%	YM diets produced higher final BW, SGR, and better FCR than BSF	Likely due to higher protein and better digestibility (Reyes *et al*., 2020; Melenchón *et al*., 2022)
Largemouth bass	BSF	12%	Growth decreased compared to control	Chitin may reduce digestibility (Fischer *et al*., 2022)
Rainbow trout	Full-fat BSF pre-pupa meal	15% and 30%	No performance change at 15%; decreased at 30%	Chitin and altered fatty acids reduced nutrient availability (St-Hilaire*et al*., 2007)
Rainbow trout	Defatted BSF larvae	Up to 40%	No negative effects	50% fishmeal substitution possible (Renna *et al*., 2017)
Rainbow trout	BSF larvae (fish-offal enriched)	50% fishmeal replacement	Same performance as control	Diet substrate affects meal quality (Sealey *et al*., 2011)
Rainbow trout	Full-fat TM larvae	Up to 50%	No change in performance; reduced feed intake	Intake decreased with higher TM (Belforti *et al*., 2015)
Rainbow trout	Superworm (*Zophobas morio*)	0–100%	25% fishmeal replacement improved performance; 100%worsened	High levels reduced growth (Doğankaya, 2017)
Turbot	Defatted BSF prepupae	>33%	Performance worsened	Palatability and chitin reduced intake (Kroeckel *et al*., 2012)
European sea bass	Full-fat TM larvae	50%	Lower BW, SGR, PER, FCR	Negative effect at high inclusion (Gasco *et al*., 2018)
Sea bass	TM larvae	25%	Improved performance	Optimal inclusion (Piccolo *et al*., 2017)
Atlantic salmon	Different BSF processing (IMA vs IMB)	25–100%	IMA showed no negative effects; IMB reduced performance	Processing method critical (Lock *et al*., 2018)
Atlantic salmon and Nile tilapia	Full-fat BSF larvae	17–20%	Increased BW; similar FCR	Positive results at moderate levels (Wachira *et al*., 2021; Weththasinghe *et al*., 2021)
Seabass	Housefly meal	20%	Similar BW, but worse FCR than YM	Housefly meal less efficient (Tran *et al*., 2022)
Rainbow trout	Defatted BSF vs whole BSF	15–20%	Defatted performed better	Consistent across trials (Caimi *et al*., 2021; Tran *et al*., 2022)
Rainbow trout	BSF pre-pupa vs pupa meal	30% pre-pupa, 45% pupa	Pre-pupa decreased BW; pupa no effect	High chitin content may reduce (Hoc *et al*., 2021; Cardinaletti *et al*., 2022)

aquaculture, tilapia has been widely studied. Black soldier fly meal at 33% replacement increased weight gain by 14.4% and showed similar economic returns to fishmeal (Wachira *et al*., 2021). African catfish showed better growth and profitability with 25% black soldier fly replacement (Mundida *et al*., 2023). In rainbow trout, combining poultry by-product and black soldier fly meal improved nutrient retention, gut function, growth, and welfare (Cardinaletti *et al*., 2022). Silkworm (*Bombyx mori*) meal can fully replace fishmeal in carp with comparable growth and better digestibility than plant meals (Nandeesha *et al*., 1990; Rahman *et al*., 1996; Swamy and Devaraj, 1994). In shrimp, black soldier fly meal and frass (up to 30%) maintained growth and improved disease resistance (Yildirim-Aksoy *et al*., 2022; Röthig *et al*., 2023). Black soldier fly frass also supported similar growth in prawns with improved economics (Tiu, 2012). Recent research shows that wax mpth (*Galleria mellonella*) larvae powder can replace 15% of soybean meal without reducing growth or FCR (Abozaid *et al*., 2024). Table 3 summarizes recent studies on insect-based aquafeeds, highlighting the most commonly used insect species (black soldier fly, yellow mealworm, and housefly), inclusion levels tested, and observed effects on growth performance. The results show that moderate inclusion levels (typically up to ~20–30%) are generally safe for most species, while higher levels often reduce growth due to chitin content, palatability issues, and nutrient imbalance.

SOLUTIONS AND FUTURE DIRECTIONS FOR INSECT-BASED AQUAFEEDS

Nutritional limitations

Insect meals can be limited by chitin content, amino acid imbalance, and low omega-3 levels. Chitin may reduce digestibility and growth, but this can be mitigated by adding chitinase enzymes or chitinolytic bacteria, which also enhance immune responses. Amino acid imbalances can be addressed through dietary supplementation or by blending insect meals with complementary protein sources. Research is ongoing to enhance omega-3 fatty acid levels in insects through dietary manipulation of rearing substrates or genetic selection, especially for black soldier fly larvae.

Processing and feed technology

Processing methods can significantly improve the nutritional quality and digestibility of insect meals. Defatting increases protein concentration and amino acid content but may be energy-intensive; therefore, blending defatted insect meal with other ingredients may be more practical. Extrusion technology has been shown to improve feed digestibility and nutrient availability. Fermentation and other bioprocessing methods are also being explored to enhance palatability and reduce anti-nutritional factors.

Safety assurance

Safety concerns remain a major barrier to widespread adoption. Insect meals may accumulate heavy metals, harbor pathogenic microbes, or trigger allergic reactions. Ensuring safety requires strict control of rearing substrates, standardized processing protocols, and robust testing for contaminants. Novel decontamination techniques are also being developed to reduce chemical residues and microbial risks.

Scale-up and cost

Large-scale production is needed to improve the economic feasibility of insect meals. This requires automation of rearing and processing, efficient waste management, and optimization of FCR. Using locally available agricultural by-products as substrates can reduce production costs and improve sustainability. Improved facility design and energy-efficient systems will also reduce the environmental footprint of insect farming.

Regulations and consumer acceptance

A clear and enforceable legal framework is essential to support the insect feed industry. Current regulations are inconsistent across regions, which limits market access and investment. Increasing public awareness through reliable education and transparent communication can improve consumer acceptance and reduce misconceptions about insect-based feeds.

Collaboration and standardization

Successful implementation depends on collaboration among academia, industry, and government. Standardized production protocols are needed to reduce variability in nutrient composition across insect species, developmental stages, and substrates. This includes standardized guidelines for substrate selection, rearing conditions, processing methods, and quality control.

Research gaps and future research needs

Despite the progress made, several research gaps remain:

1. Nutrient variability in black soldier fly and yellow mealworm due to substrate, developmental stage, and processing.

2. Limited long-term feeding trials, especially regarding immune function, gut health, reproduction, and whole life-cycle performance.

3. Insufficient species-specific guidelines, particularly for marine carnivores and shrimp.

4. Incomplete safety data, including heavy metals, allergens, and pathogen transfer.

5. Economic feasibility and large-scale production require further evaluation, including integration into circular-economy system.

6. Environmental impact assessments and consumer acceptance studies are still limited.

RECOMMENDATIONS

- Comprehensive evaluation of insect species: Conduct thorough studies on various insect species, such as black soldier fly larvae, mealworms, and crickets, to assess their nutritional profiles, growth potential, and adaptability for aquaculture feed. This includes evaluating their impact on fish health and overall aquaculture productivity.

- Utilization of organic waste in insect farming: Promotes the use of organic waste streams as feed substrates for insect cultivation. This approach can mitigate environmental impacts, reduce waste, and lower the carbon footprint associated with insect production.

- Environmental footprint assessment: Perform life cycle assessments to compare the environmental footprints of insect-based feeds with traditional sources like fishmeal and soybean meal. This ensures that the adoption of insect meals contributes to sustainable aquaculture practices.

- Resource-efficient production systems: Innovate farming systems that minimize the use of water, land, and energy while enabling large-scale insect production for aquafeeds. Emphasis should be placed on optimizing resource utilization to enhance sustainability.

- Regulatory standardization: Develop clear, standardized regulations and guidelines for incorporating insects into aquaculture feeds. This includes setting standards for feed quality, processing methods, and safety protocols to prevent contamination by pathogens, heavy metals, and other contaminants.

- Biosecurity and monitoring: Ensure robust biosecurity practices to minimize the risk of disease transmission from insects to farmed fish and the surrounding environment. Regular testing for pathogens and contaminants should be integral to standard operating procedures.

- Safety feeding trials: Develop feeding trials for monitoring the safety of insect meals in aquaculture diets, including tests for toxins, heavy metals, and pesticides, to ensure the health and safety of both fish and consumers.

- Economic feasibility: Assess the cost-effectiveness of using insect-based feeds compared to traditional protein sources like fishmeal and soybean meal. This includes analyzing production costs, market prices, and potential economic benefits to determine the viability of large-scale adoption.

CONCLUSION

Overall, available evidence indicates that insect meals represent a promising alternative protein source for aquaculture, with the potential to improve sustainability by reducing reliance on conventional feed ingredients such as fishmeal and soybean meal. Insects provide high-quality protein, beneficial lipids, and the ability to convert organic waste into biomass, supporting circular economy models and potentially reducing environmental impacts associated with traditional feed production.

However, several barriers must be addressed before insect-based feeds can be widely adopted. Key limitations include regulatory constraints, variable nutrient composition and digestibility across insect species and processing methods, and high production costs due to limited automation and scale. Safety outcomes also appear to be context-dependent, as risks related to microbial contamination, allergens, and chemical residues vary with insect species, rearing substrates, and processing conditions. Consumer acceptance and market readiness further influence the feasibility of large-scale implementation.

Future research should prioritize standardization of production and processing methods, long-term feeding trials across diverse aquaculture species, and comprehensive safety assessments under real-world farming conditions. In addition, economic analyses and supportive policy frameworks are needed to support scale-up, improve cost-effectiveness, and facilitate regulatory harmonization. Addressing these priorities could accelerate the integration of insect meals into mainstream aquafeed production and support more sustainable aquaculture practices in commercial aquafeeds.

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