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FROM BIOWASTE TO BLUE FOOD: INSECT-DRIVEN AQUACULTURE

Tolga ŞAHİN*

* *Department of Aquaculture, Marine Sciences and Technology Faculty, Çanakkale Onsekiz Mart University, 17020-Çanakkale, Türkiye*

Tolga Şahin: tolgasahin@comu.edu.tr, https://orcid.org/0000-0001-8232-3126

* *Corresponding author: Tolga ŞAHİN, tolgasahin@comu.edu.tr, +90-286-2180018 / 16005*

Abstract

Aquaculture has gained significant momentum in recent years in meeting global protein demand. As one of the principal factors, the latest technological innovations, have also brought about significant challenges. These problems, including high costs, supply constraints and environmental risks arising from continued dependence on traditional feed ingredients such as fish meal and soybean meal have accelerated the search for sustainable and innovative protein sources. Correspondingly, insects, historically part of both human and animal diets, have re-emerged as viable feed resources. Although insect meals are quite rich in terms of high protein, essential amino acids, fatty acids, minerals and bioactive components, which are among the most important advantages of fish feeds in aquatic diets, they also bring about difficulties such as digestibility and variability in micronutrient composition due to their high fat and chitin content. However, technological innovations such as defatting, enzymatic hydrolysis, fermentation and modification of rearing substrates used to combat these difficulties increase the digestibility and productivity of insects and further increase their use in aquaculture feeds. In addition, safety of feeds, better waste-management, regulative changes and public acceptance can be considered as other factors shaping the future of insect feeds in the sector. As a result, increasing insect production capacity and making innovations in processing technologies will significantly improve nutritional content functional properties of insect-based feeds. This process will enable the conversion of low-value biological waste into high-value blue food products, making circular bioeconomy principles practically applicable and will put aquaculture as a resilient and sustainable food production system with a low environmental footprint in the future.

Keywords: Aquafeed innovation, bio-waste conversion, chitin, circular bioeconomy, insect meal, sustainable protein sources

Introduction

Aquaculture has a critical role in increased global demand for animal protein in a more sustainable production activity compared to land-based livestock. However, the sector is facing increasing hurdles due to the limited availability and rising cost of traditional feed ingredients such as fishmeal and soybean meal. Supply fluctuations, ecological constraints and geopolitical factors have further deepened that pressure on feed systems (Şahin, 2025). These issues have necessitated a search for alternative and more sustainable protein sources. Insects, which have been a kind of food for people for thousands of years in different regions of the world, have emerged as promising alternative protein sources due to their rich nutrients and their ability to convert organic wastes into beneficial biomass (Lisboa et al., 2024). Although insects took place in animal nutrition as ingredients since as early as 1969 (Brahmacharimayum et al., 2025; Calvert et al., 1969), investigations on their use have accelerated more after 2010. The regulatory changes introduced in the European Union, particularly in 2017, further marked a milestone by legalizing the use of some insect species in aquaculture feeds and making insects significant for circular bioeconomy models (Madau et al., 2020). Replacing fishmeal with insect meals in aquaculture diets reduces pressure on wild fisheries, which is unsustainable, and helps valorize biological waste into high-value nutrients (Magee et al., 2021; Mertenat et al., 2019), which eventually contributes to the diversification of existing protein sources and enhances feed safety (Yadav et al., 2025).

This review aims to provide an overview of the current use of insects in aquaculture and the main challenges that have been faced during their usage in order to evaluate their potential in shaping the future of fish nutrition. The review also discusses ways of improving farming practices through innovative solutions, increasing their digestibility properties, and their role in environmental sustainability.

Nutritional Potential and Processing Strategies for Insect Meals

Insects are nutrient-dense organisms that can provide significant amounts of protein for aquaculture feeds (Table 1). The most commonly used species (e.g., black soldier fly larvae, mealworms, crickets) have crude protein levels which are comparable to those of high-quality fishmeal (Yadav et al., 2025; Zulkifli et al., 2022). They usually contain all of the essential amino acids that are required by fish, even though some minor deficiencies (for example in methionine or lysine) can be observed depending on the diet and species of the insect (Barroso et al., 2014). Although insect meals have some nutritional limitations which will be discussed later, they also offer important nutritional advantages, particularly because of their higher contents of micronutrients such as iron, zinc and B vitamins (Finke, 2002). Many studies have shown that insect meals can successfully replace 20–50% of fishmeal in diets without negatively affecting growth performance or feed conversion efficiency, despite those available nutrient-limitations (Auzins et al., 2024). This situation clearly shows their potential as alternative feed ingredients, especially when these nutritional deficiencies are overcome by using advanced processing techniques and properly formulated diets (Mastoraki et al., 2024; Sudwischer et al., 2025).

In addition to protein, insect meals also contribute lipids to the diets of reared organisms. Black soldier fly (BSF) larvae, for instance, are rich in medium-chain fatty acids like lauric acid, and mealworms are high in oleic acid (Jayanegara et al., 2020; Suryati et al., 2023). However, the lipid profile of insect meals differs significantly from the naturally high levels of long-chain n-3 polyunsaturated fatty acids found in fish oil. This difference suggests that additional fish oil supplementation or alternative formulation arrangements may be needed to meet the essential fatty acid requirements of some cultured fish species in insect meal-based diets. A major nutritional challenge, namely high fat ratio, occur during the production of practical aquatic diets; for instance, the high fat ratio reported in the previous studies for full-fat black soldier fly larvae as 30-35% has been shown to mitigate dietary energy balance and alter the fatty acid composition of diet (Carpentier et al., 2024). To overcome this issue, the method defatting aimed at partially or fully removing the fat fraction of insect meal has been developed, which concentrates the insect protein and enhances the digestibility of organism fed, thereby resulting in a more efficient meal comparable to the nutritional profile of fishmeal, as it has been reported in the literature as having protein digestibility rates of 75–85%, significantly higher than their full-fat counterparts (Gasco et al., 2022; Renna et al., 2023).

Table 1. Nutrient composition of selected insect species and fish meal for aquafeed applications

Parameter	***A. diaperinus* (larvae)**	***H. illucens* (larvae)**	***T. molitor* (larvae)**	***A. domesticus* (adult/nymph)**	***Z. morio* (larvae)**	**Fish meal**
Crude protein	57.3-70.7	39.4-56.9	45.1-82.6	41.8-76.5	39.4-52.5	70.6-75.0
Crude lipid	13.4-29.2	11.8-57.8	10.0-43.1	7.5-35.0	29.0-46.6	8.2-9.9
Ash	3.5-4.3	2.7-28.4	1.9-5.5	3.0-13.4	0.7-8.2	14.5
Gross energy	19.5-26.4	18.4-22.1	16.0-27.3	17.5-23.0	20.0-25.0	21.0-23.8
Calcium	0.05-0.13	2.1-7.6	0.03-0.27	0.07-1.01	0.02-0.06	4.34
Phosphorus	0.11-0.90	0.6-0.9	0.54-0.79	0.03-0.91	0.42-0.47	2.79

Note: Data represents ranges reported in the literature, accounting for variations in developmental stages (larvae for all insects unless otherwise stated; adults/nymphs for A. domesticus), rearing substrates (e.g., organic waste, grains), and processing methods (e.g., full-fat, defatted, blanching, freezing). Sources include: Adámková et al. (2017); Alfiko et al. (2022); Andrade et al. (2021); da Silva et al. (2024); EFSA NDA Panel (2022); Habte-Tsion et al. (2024); Kim et al. (2023); Kulma et al. (2020); Kuntandi et al. (2018); Kurečka et al. (2021); Lock et al. (2016); Mlček et al. (2019); Park et al. (2013); Rumbos et al. (2019); Soares Araújo et al. (2019); Suryati et al. (2023); Tran et al. (2024); Udomsil et al. (2019); Ververis et al. (2022); Zulkifli et al. (2022). All values are reported on a dry matter (DM) basis. Gross energy is expressed as MJ/kg DM.

Basic processing methods such as defatting and fine/super-fine grinding are often applied to improve the overall quality of different types of insect meals (Gasco et al., 2023). When excess fat is removed, the lipid content decreases and in turn, protein levels increase in terms of quantity per unit of insect meal (Lock et al., 2018). On the other hand, grinding process breaks down the chitin-rich exoskeleton and decreases particle size, which provides better nutrient availability and relieves some of the digestive problems and growth performance issues commonly due to high fat and chitin levels of insect meals (Belghit et al., 2019; Henry et al., 2015). As reported by Nunes et al., 2014, methods in terms of physical processing, such as drying and grinding, can change available protein levels and profiles of amino acids of insect meals, which influence how easily they are digested. Finely/super-finely ground meals have been specifically associated with more effective use of feed and faster passage through the digestive tracts of animals (Dhiman & Prabhakar, 2021), and when combined, these techniques provide solutions to problems like excess chitin overload or lipid imbalances, positioning insect meals as a more viable part of regular aquaculture feed formulations (Lock et al., 2018).

Another important challenge is the presence of chitin, which is a fibrous polysaccharide present in insect exoskeletons (Islam & Yang, 2017). Chitin levels can vary in a wide range, between 4% and 43%, depending on the insect species and the developmental stage of the insect, and the highest concentrations are generally observed in adult insects and in the exoskeletons of larvae (Finke, 2002; Sudwischer et al., 2025). It has been shown that chitin reduces protein digestibility in fish because it prevents access to the amino acids that are trapped in the cuticle or bound to the hardened parts of the body, and as a result the apparent digestibility of protein becomes lower compared to traditional fishmeal (Gasco et al., 2022; Lock et al., 2018). However, most monogastric animals including fish are not able to fully digest chitin, and moreover it can bind some nutrients in the digestive system, which in turn decreases the overall digestibility (Rodríguez-Rodríguez et al., 2024). On the other hand, low chitin content in aquaculture feeds should not always be regarded as a completely negative characteristic because studies in the literature indicate that chitin particles can contribute to intestinal health by acting as a dietary fiber and they can also play an effective role in the regulation of immune response and in maintaining the balance of gut microbiota (Fantatto et al., 2024; Hasan et al., 2023b). Furthermore, derivatives of chitin such as chitosan and chito-oligosaccharides not only help digestion but also have functional properties that can modulate the immune system and protect gut health (Mohan et al., 2023). In this context, the dual role of chitin both as an antinutritional factor that inhibits nutrient absorption and as a functional ingredient providing physiological benefits has a significant potential for future studies.

Therefore, improving the processing methods of insect meals by using techniques such as defatting, enzymatic hydrolysis or fermentation increases their digestibility and the availability of nutrients in a significant way. As a result of this, the inclusion of insect meals in aquafeed formulations becomes much easier and more efficient from the nutritional point of view, which in turn supports the general transition towards the use of sustainable protein sources in the aquaculture sector.

Complementary Strategies for Nutritional Improvement

Due to the unique composition of insect meals, several strategies have been developed to improve their digestibility and nutrient absorption in fish (Figure 1). This section, unlike the previous one which stated on the inherent nutrient composition, focuses on complementary biotechnological and functional strategies that aim to expand and improve the use of insect meals in aquafeed formulations.

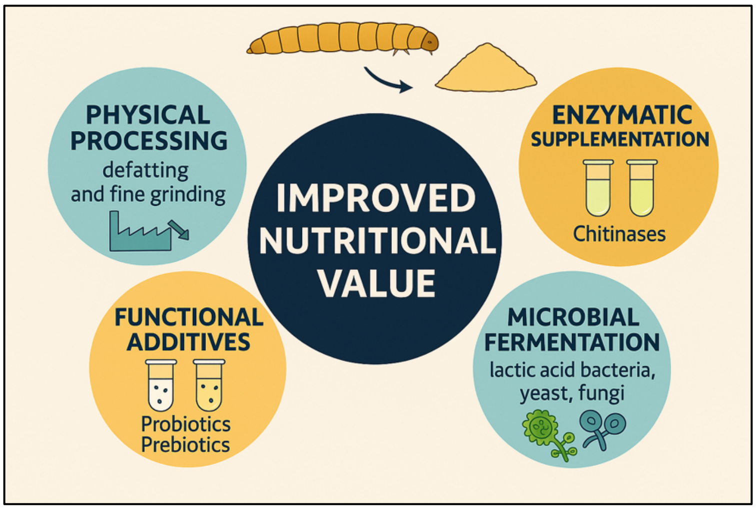

Figure 1. Emerging strategies to enhance the nutritional efficiency of insect-based meals in aquaculture feeds.

The main focus of research in this area is directed to overcoming the chitin barrier that limits the nutritional effectiveness of insect meal (Fantatto et al., 2024). Since most fish species either devoid of endogenous chitinase enzyme activity or express it only in minimal amounts, chitin present in insect meal resists digestion or even remains undigested (Kroeckel et al., 2012). As a result, the use of external chitin-degrading agents, such as selected microbial strains or purified enzymes, has emerged as a promising biotechnological approach to improve chitin breakdown and convert it into absorbable carbohydrate forms (Eggink et al., 2022). Researchers have investigated various enzyme-based and microbial tools including exogenous chitinases, specifically those from fungi and bacteria since those chitinases has been found to be highly effective in breaking down both α- and β-chitin forms (Thakur et al., 2023), that may enhance the effectiveness in terms of nutritive function and digestibility in diets comprising insect meals for fish (Mohan et al., 2023). These exogenous chitinases are of great interest because they break down chitin and help release nutritive compounds that are usually trapped in the insect meal (Hasan et al., 2023b). Supplementing chitinases directly into aquatic diets or pre-treating insect meals using them has been shown to improve protein digestibility and to sustain better growth in fish (Agbohessou et al., 2024). Moreover, using chitinases with other enzymes such as proteases, either by mixing them into the feed or applying them prior to feeding, have been another effective solution, as it makes digestion easier, improves feed conversion ratio, and allows higher inclusion of insect meals in fish feed formulations (Fines & Holt, 2010).

Fermentation, a biotechnological process where microorganisms enhance the characteristics of a product (Campenhout, 2021), extends the shelf life and improves the microbial security of insect meals, by preventing the growth of pathogenic microorganisms (Kewuyemi et al., 2020; Klunder et al., 2012). As well as its role in microbiological security, it also enhances the functionality and nutritional value of insect meals through the use of beneficial bacteria and yeast. These microorganisms are reported to break down complex biopolymers, reduce anti-nutritional compounds, and enrich the final product with probiotics and digestive enzymes (Meng et al., 2023). Considering their abovementioned functions, fermented insect meals have been shown to promote a healthier intestinal structure, refined feed palatability and greater levels of bioactive compounds in fish fed (Yang et al., 2023). There is also evidence suggesting that fermentation increases protein solubility and enhances antioxidant activity through the release of bioactive peptides, offering additional functional and health-promoting properties in insect-based feeds (Kang et al., 2025).

The supplementation of functional compounds (such as probiotics) to insect meals along with microbial and enzymatic approaches, have been shown to potentially improve the gut microbiota, feed efficiency, and welfare parameters of both insects and target animals in some studies (Foysal et al., 2021; Hasan et al., 2023a; Phaengphairee et al., 2023; Santos-Silva et al., 2025). Literature reports that the growth and general health indicators of fish have been demonstrated to be maintained or even improved by replacing 50% of fishmeal with probiotic-enriched mealworm or black soldier fly meals (Alfiko et al., 2022; Naveed et al., 2023). Insect-based diets comprising probiotic compounds may also encourage the growth of beneficial Firmicutes and Actinobacteria in the gut, which have been shown to promote the immune system and maintaining intestinal balance (Foysal & Gupta, 2022). Confirmatory findings have been reported for European sea bass and Nile tilapia, where those findings were linked to better digestion, higher digestive enzyme activities, and a healthier gut structure (Eggink et al., 2022; Fantatto et al., 2024; Rangel et al., 2022).

Saturated lipids such as lauric acid and molecules such as antimicrobial peptides are among the many bioactive materials present in insect meals that exert plenty of beneficial biological impacts on immune function and gut health through their antimicrobial and prebiotic features (Foysal & Gupta, 2022). Together with probiotics, those bioactive compounds can also promote absorption of nutrients as well as immune responses, thereby supporting the growth performance and general fish health (Huyben et al., 2019). The palatability and digestibility of insect proteins, together with their solubility, can be increased by hydrolyzing them enzymatically, which scientific studies validate (Liceaga, 2019), and functional lipids may further reinforce these effects by increasing the nutritional value of insect-based feeds (Suryati et al., 2023).

When all these techniques are gathered, the efficiency of insect meals in aquaculture diets can be elevated by using more comprehensive strategies that employ enzymatic hydrolysis, fermentation and functional additive usage (e.g. probiotics), when integrated with primary physical processing methods described previously. These applications help aquaculture obtain more related to sustainability and resource efficiency, enabling higher inclusion levels of insect meal in commercial fish diets.

Influence of Rearing Substrate on Insect Meal Quality

During the production of insect meals there are many fundamental factors which primarily depend on the rearing substrate's ability to modify the final product's nutritional characteristics and diversify its nutrient profile, functional traits (e.g., antioxidant capacity, antimicrobial properties, or digestibility-enhancing features), and safety aspects that are often ignored in practice (Surendra et al., 2016; Pinotti & Ottoboni, 2021). Many farmed insect species can effectively convert low-value organic materials such as agricultural residues, agro-industrial by-products, post-harvest food wastes after harvest into high-value biomass, and in this way they support nutrient recovery and the reduction of waste within circular bioeconomy systems. However, in order to realize this potential in a real sense, there is a need for a coherent and well-planned strategy. This strategy should combine careful selection of substrates together with proper rearing practices and appropriate processing methods (Fowles & Nansen, 2020).

The type and composition of the substrate are major factors which determine the larval growth, nutrient conversion efficiency, and the nutritional quality of produced insect meal (Kim et al., 2019; Ravi et al., 2020; Carpentier et al., 2024). For example, the crude protein content of insects can vary between 35 and 60% on dry basis depending on the protein content, carbon-to-nitrogen ratio, and harvesting stage of them. Similarly, lipid content and fatty acid compositions are very sensitive to energy and fat content of the substrate. Substrates that are rich in carbohydrates are potential promoters of total fat and lauric acid levels, while omega-3-rich sources such as fish offal and microalgae on the other hand increase long-chain polyunsaturated fatty acids (Ravi et al., 2020; Carpentier et al., 2024). For instance, according to Ameixa et al. (2023), larvae reared on substrates with olive-oil pomace have grown faster and developed a lipid profile with elevated oleic acid and reduced saturated fat. Such flexible feature enables producers to manipulate insect meals to the specific nutritional requirements of different farmed fish species. Figure 2 shows how different substrate manipulation strategies, such as blending various organic sources or the supplementation of nutrients, can change the nutritional composition and functional traits of insect meals which, in the end, improve feed performance in aquaculture systems.

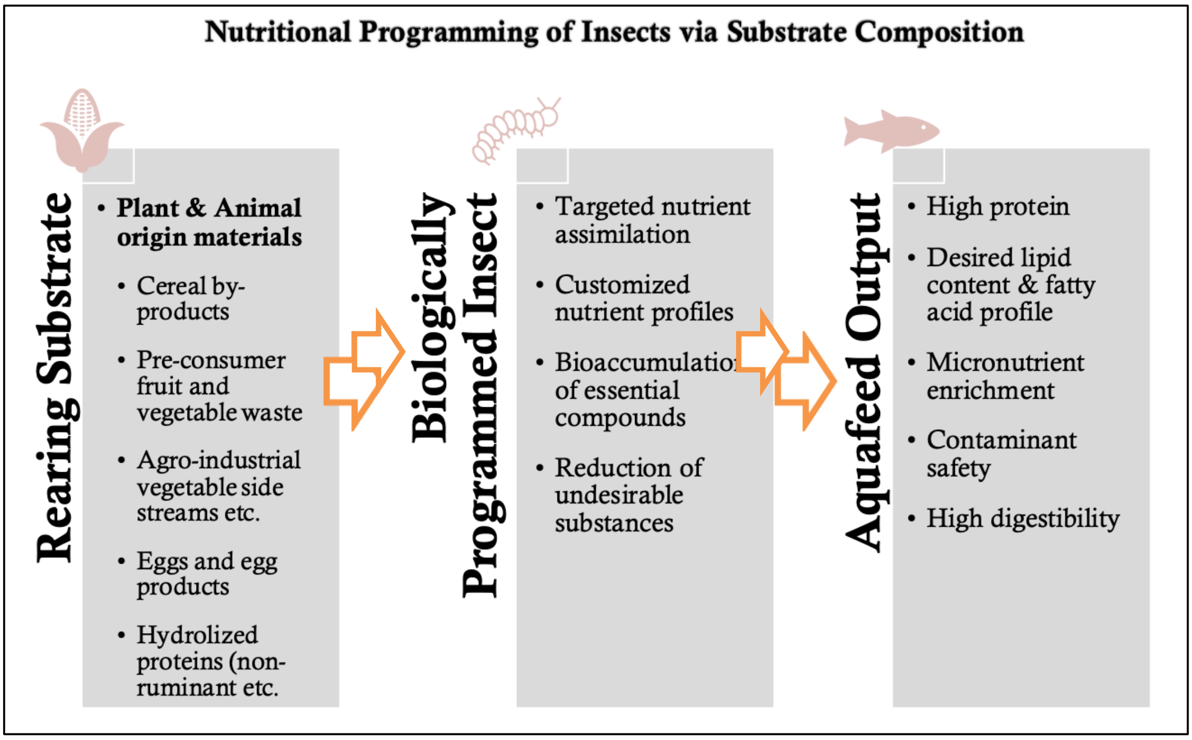

Figure 2. Substrate management strategies used in insect farming for aquafeed production. Adapted from Meijer et al. (2025).

Recent research also emphasizes that substrate choice affects growth rate, feed conversion (commonly measured as feed conversion ratio; Boyd & McNevin, 2022), and the efficiency of biomass transformation, often expressed as protein efficiency ratio or lipid retention (Rumpold et al., 2017). Insect larvae raised on mixed diets or those that contain some animal-origin constituents have been shown to grow swiftly; for instance, black soldier fly prepupae reared on cow manure supplemented with 10-50% fish offal reached 0.14-0.16 g per individual compared with 0.10 g on manure alone (about 40–60% higher mass and 43% more lipid) (St-Hilaire et al., 2007). They also build nutrient profiles that closely mirror those of commercially fed insects. In contrast, larvae that are exclusively fed plant-based diets might develop much more slowly and have reduced nutritional value (Belperio et al., 2024). This indicates that rearing substrates are not only things insects grow on but also kind of tools that play an active role in the adjustment of meals' nutritional quality, functional properties, and safety. Accordingly, defining the right substrate, supplementing it when it is necessary, and its careful management are all critical to meet safety standards of feed and ensure consistent meal quality for aquaculture (Kee et al., 2023).

In addition to protein and fat content, substrate selection determines the transfer of micronutrients, trace elements, and bioactive compounds into insect meals (Siddiqui et al., 2024). The larvae of insects can absorb, accumulate, and transport vitamin-rich residues or mineral compounds obtained from rearing substrates, which is highly beneficial for fish with high requirements for these micronutrients (Ravi et al., 2020).

However, this nutritional flexibility can also cause several undesirable outcomes. For instance, because meals frequently differ in protein, fat, or micronutrient content due to variation in the composition of different waste stream, feed formulators who depend on rigid specifications for insect farming, encounter unexpected challenges. In order to control and manage the variability which is caused by different substrates, feed producers are increasing their quality control measures, they are mixing several substrate batches together in order to reduce inconsistencies, and they are adding specific supplements when necessary (Gasco et al., 2020). On the research side, studies are concentrated on making the substrates more functional; this includes reducing the levels of antinutrients, balancing the essential nutrients and incorporating particular additives. All these efforts together contribute to improving both the safety and the nutritional quality of the final feed product (Suryati et al., 2023).

Safety remains a parallel concern because larvae can also concentrate undesirable substances if the feedstock is contaminated (Lock et al., 2018). Heavy metals, pesticide residues, or mycotoxins have all been detected when poorly managed wastes are used (Rummel et al., 2021). By contrast, trials that relied on clean, well-screened organics reported cadmium and lead at levels comfortably below regulatory limits (Addeo et al., 2024; Amorim et al., 2024). Because novel urban or industrial side-streams can carry a heavier chemical burden than typical farm residues, continuous monitoring is essential. This includes checks of both substrate and biomass, along with safety checks at each processing step. Such measures are particularly important when non-standard feedstocks enter the production chain (Rummel et al., 2021).

Insect diet has an impact on growth, but substrate type is highly important for how easily fish can digest the resulting food. It may be more difficult for fish to receive the full nutritional benefit of the feed if the substrate contains a lot of chitin or other fibrous materials (Belperio et al., 2024; Fantatto et al., 2024). The techniques that were mentioned earlier in the section titled "Influence of Rearing Substrate on Insect Meal Quality" have all been shown to increase the accessibility of nutrients in a significant way. They also have a very critical role in terms of feed safety, and this is the reason why they are strictly regulated within the framework of food safety regulations. In the European Union, for example, only specific types of feed materials are permitted to be used in insect rearing. These permitted materials include pre-consumer vegetable wastes and some approved animal-origin by-products. On the other hand, the use of materials such as post-consumer food leftovers or untreated animal manure is not allowed under any circumstances (Rumpold & Schlüter, 2013). Although these strict regulations are extremely necessary in order to protect the safety of the food chain, they can limit the possibility of utilizing valuable organic waste streams that could otherwise be valorized through insect farming. In order to achieve truly sustainable and efficient insect-based aquafeeds, it is of great importance to take into consideration the functioning of the entire supply chain, especially with regard to the sourcing of feed materials and their transfer between different stages.

Insect Meal and the Circular Bioeconomy

The commercial production of insects and their incorporation into aquaculture feeds are gaining much more importance because they contribute significantly to the circular bioeconomy by encouraging the utilization of waste materials, increasing resource efficiency and supporting sustainable nutrient cycling. Well-known insect species such as *H. illucens* and *T. molitor* possess a remarkable ability to convert low-value organic streams, for example agricultural residues, food-processing by-products and pre-consumer food wastes, into high-value protein sources for animal feed and into biofertilizers, which is completely different from conventional protein sources (Rajendran et al., 2018). This bioconversion process not only enables the production of insect meals that have protein contents comparable to those of fishmeal but also helps to close nutrient loops within agri-food systems and at the same time reduces the environmental burden that is associated with traditional feed manufacturing (Kee et al., 2023). In addition, insect rearing contributes to nutrient recovery, particularly when the leftover material known as frass is utilized as an organic fertilizer (Rummel et al., 2021). However, the nutritional composition of frass can show considerable variation depending on the substrate on which the insects have been reared, which means that its final composition can be adjusted and controlled by making changes in the feeding substrate (Scala et al., 2020). Viewed broadly, bio-converting organic waste into protein with the help of insects and valorizing it prevents waste from accumulating in landfill sites, reduces greenhouse gas emissions, and alleviates pressure on both marine and terrestrial protein sources such as fish meal and soy (van Huis & Oonincx, 2017). Life-cycle analyses further show that black soldier fly larvae reared on waste streams can cut land demand by up to 50 % and reduce water use by about 30–40 % compared with soy-based feed formulations (Carpentier et al., 2024). In addition to offering a well-balanced amino-acid profile, insects supply bioactive compounds, including chitin and various antimicrobial peptides, that have been linked to faster fish growth, improved health, and richer gut microbiota (Gasco et al., 2024). Among these compounds, chitin-derived chito-oligosaccharides stand out for their ability to support immune function and intestinal health, with certain studies showing up to a 15% enhancement in feed conversion efficiency in tilapia fed fermented insect meal (Rangel et al., 2022).

While insect meals show strong environmental potential, their large-scale production still encounters major techno-economic obstacles. Currently, the cost of producing insect-based protein remains considerably higher than that of traditional sources, and many cost-efficiency studies continue to report negative returns under existing production capacities and technological limitations (Tavares et al., 2022). Although estimates suggest that 50% scale-up and automation could achieve cost parity, for example, a techno-economic assessment on black soldier fly (BSF) production suggests that BSF production costs are in the range of €2,000–3,000 per tonne, when fishmeal costs are around €1,200–1,500 per tonne (Auzins et al., 2024). Data obtained from small-scale pilot studies as well as economic modelling studies indicate that improvements in reproductive performance, scaling-up of production capacities and automation of processes have the potential to reduce production costs in a significant way and increase the economic feasibility of insect-based protein sources in the near future (Abro et al., 2022; Auzins et al., 2024). These developments can also contribute to achieving better product consistency because more stable nutritional profiles can be obtained by optimizing substrate mixtures and processing methods (Belperio et al., 2024). The combined application of processing techniques such as defatting, enzymatic hydrolysis and substrate optimization can help to overcome both the nutritional and economic limitations of these feeds and in this way expand their usage areas in aquaculture sector (Fowles & Nansen, 2020).

At the same time, the role of insects within circular bioeconomy strategies is strongly affected by the current regulatory frameworks. In order to ensure feed and food safety, regulatory authorities in the European Union and other regions impose very strict restrictions on the substrates that are allowed to be used. However, by banning materials such as post-consumer food waste and untreated animal manure, these regulations often limit the full waste valorization potential of insect farming (Gasco et al., 2020; Moon & Lee, 2015; Tavares et al., 2022). Although the present legislation restricts the utilization of some waste streams that have high potential, ongoing scientific research on pathogen inactivation suggests that the circularity of the system can be increased by enlarging the range of permitted substrates in the future (Siddiqui et al., 2024). Possible future policy changes that would allow wider substrate use could be supported by scientific evidence regarding safety and pathogen control, and this would encourage a more inclusive circular economy approach (Auzins et al., 2024). In fact, if appropriate safety precautions are taken, the controlled use of pretreated manure has the potential to increase overall waste recovery rates by 20–30% (Fowles & Nansen, 2020).

On the other hand, the development of the insect sector also depends on social factors such as consumer acceptance. Results of surveys show that fish or poultry fed with insects (i.e., indirect consumption of insects) are accepted at increasing levels when the environmental benefits are clearly explained to consumers (Abro et al., 2022; Hamam et al., 2024; Moon & Lee, 2015). These findings support the assessments that were made in the first section of the review and reveal that effective communication of sustainability messages has a positive influence on consumer perception (Hamam et al., 2024).

Insects can serve as a very good example of circular bioeconomy principles in terms of reducing environmental impacts and creating socioeconomic advantages, thanks to their unique ability to transform organic waste streams into high-value animal protein and soil-enhancing by-products. Building upon the environmental, techno-economic, regulatory and social dimensions that have been discussed above, future studies should focus on the design and testing of integrated systems that connect insect farming with aquaculture and agricultural production, ensuring that these systems can be scaled up in a safe and efficient manner (Fowles & Nansen, 2020). Successfully overcoming these challenges has great potential to notably contribute to the development of more resilient, eco-friendly, and globally sustainable aquaculture and livestock systems. In summary, insect-based feeds set an example as a promising and sustainable bridge within the circular bioeconomy framework, effectively converting low-value organic waste into high-quality animal protein while delivering significant environmental, economic, and socio-economic benefits.

Conclusion and Future Outlook

The lasting and long-term success of insect-based feeds in aquaculture industry cannot be reduced only to technical innovations or cost reductions, since it also requires the existence of transparent, harmonized regulatory frameworks and a well-informed public perception. Initially considered a marginal idea, this approach has now reached the level of a reliable alternative to traditional feed-grade protein sources. This transformation is fueled by industry's growing desire for feed and diet formulations that are both sustainable and high in nutritional value. Growing evidence shows that, when used in the proper ratios, insect meals can replace fish meal; it can reduce the environmental footprint of feed production without negatively affecting fish growth performance, health status, or feed utilization efficiency. To fully leverage this potential, complementary measures are required, such as enhancing digestibility through fermentation or targeted enzyme addition, prioritizing nutrient-rich rearing environments, and integrating insect farming with more comprehensive organic waste streams. Within the circular bioeconomy approach, integrated production models linking insects, fish, and plants are expected to become increasingly widespread. In these systems, rearing practices that enhance the nutritional value of insects and insect flours are made more compatible with existing feed production lines. Even so, wider adoption will depend on achieving economies of scale and lowering unit costs. Looking ahead, future work may focus on breeding insect lines that grow faster, contain less chitin, or carry more desirable fatty acid profiles, thereby enhancing feed efficiency. It should also encompass the development of nutrient profiles using omics technologies to better align insect meals with species- and life-stage-specific requirements, and the design of automation-based production systems (e.g. sensor-based monitoring and robotics) that stabilize product quality and reduce labor needs. Additional priorities will involve establishing standardized life-cycle assessment frameworks for different insect species, conducting long-term health and welfare trials in key farmed fish, and implementing harmonized risk-assessment protocols for contaminants and pathogens. Nevertheless, none of this progress will be meaningful unless safety and ethical standards remain transparent and robust, and well-regulated practices together with open communication will be essential to maintain consumer confidence and prevent new risks from entering the food chain.

In short, insect-based feeds represent a promising shift in sustainable aquaculture because they convert organic waste into high-value nutrients while drawing on fewer natural resources. If supported by sound policy and sustained research investment, these feeds are likely to move beyond the pilot phase and become a routine component of aquaculture diets across many regions, making the industry more resilient, environmentally friendly, and fully aligned with circular-economy goals. Over the coming decade, insect-based aquafeeds are poised to occupy a central position in driving the sustainable transformation of aquaculture.

Ethical approval
No ethical approval is needed for this study.

Informed consent
Not applicable

Data availability statement
All data presented in the article are derived from previously published sources, which are appropriately cited. No new datasets were generated or analyzed.

Conflicts of interest
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The author solely conducted all aspects of the study, including conceptualization, literature collection, critical analysis, interpretation, writing, and final revision of the manuscript.

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