

Review

Feed Sources for Sustainable Aquaculture: Black Soldier Fly Larvae (BSFL)

Lenuța Dîrvari^{1,2}, Cristian-Alin Barbacariu^{1,*} , Marian Burducea^{1,*}  and Daniel Simeanu² 

¹ Research and Development Station for Aquaculture and Acvatic Ecology, “Alexandru Ioan Cuza” University of Iasi, 11, Carol I Blvd., 700506 Iasi, Romania; lenuta.dirvari@uaic.ro

² Faculty of Food and Animal Sciences, “Ion Ionescu de la Brad” University of Life Sciences, 700489 Iasi, Romania; daniel.simeanu@iuls.ro

* Correspondence: alin.barbacariu@uaic.ro (C.-A.B.); marian.burducea@uaic.ro (M.B.); Tel.: +40-765491341 (C.-A.B.)

Abstract

As global aquaculture is on the rise, the demand for sustainable and high-quality feed ingredients is intensifying. Black soldier fly larvae (BSFL) meal has emerged as a promising alternative to traditional fishmeal due to its favorable nutritional profile, waste recycling potential, and low environmental impact. This review explores the novel role of BSF meal in aquafeeds, highlighting its effects on fish growth performance, feed efficiency, and fillet quality. Furthermore, the antimicrobial and immune-boosting properties of lauric acid and chitin are discussed. However, despite its promise, several challenges still hinder the large-scale adoption of BSFL meal in aquaculture. These include regulatory restrictions on substrates, concerns over fish meat quality and safety, consumer acceptance, and the economic and logistical hurdles of industrial-scale BSFL farming. This paper synthesizes current scientific findings and regulatory frameworks, identifies key gaps in knowledge, and discusses the potential of BSFL meal as a sustainable alternative in aquafeeds while addressing its challenges.

Keywords: BSFL; aquafeed; alternative protein; fish nutrition; growth performance



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Key Contribution: This manuscript presents a comprehensive review of the use of black soldier fly (*Hermetia illucens*) meal in aquafeeds, with a special focus on novel dimensions not sufficiently addressed in the previous literature. Unlike previous reviews that focus predominantly on nutritional performance and growth outcomes, our article takes a broader, multidisciplinary approach.

1. Introduction

Aquaculture makes a major contribution to global food security, especially in areas where animal protein sources are rather limited (e.g., countries in Africa and Asia). Sea food is a renowned source of quality protein, providing about 16% of the animal protein consumed worldwide [1]. It has exceptional sensory qualities and high nutritional value, due to its rich content of polyunsaturated fatty acids (ω -3 fatty acids, EPA, and DHA), minerals (P, Se, I, Fe, Mg, and Ca), and vitamins (A, D, B12, B3, and B2) [2]. According to the Food and Agriculture Organization of the United Nations (FAO)’s latest report on the State of World Fisheries and Aquaculture, fish production from aquaculture surpassed capture fisheries in 2022, reaching 94.4 million tons, which accounted for 51% of the total [3]. Statistics indicate that the global population is expected to increase to 9.7 billion

by 2050 [4]; this is putting pressure on natural resources, including seafood production systems, leading to negative impacts on the environment and generating more greenhouse gas emissions [5,6].

Fishmeal and fish oil are indispensable components in the structure of feed for fish farming and mostly come from wild-caught fish [7]. Fishmeal is an excellent source of protein, with very good digestibility and palatability, containing all the essential amino acids necessary for the development of organisms, vitamins (A, D, E, and B12), minerals (Ca and P), and omega-3 fatty acids [8]. The production of fishmeal and fish oil has remained stable, but demand for these ingredients has increased due to the rapid development of aquaculture as well as the livestock sector, in particular pig and poultry farming. According to Mailuf et al. [9], in 2021, 87% of fishmeal was used in aquaculture, 7% in pig farming, 4% in pet food, and about 1% in poultry farming. Statistics show that the excessive use of fishmeal in recent decades has put pressure on the dynamics of wild fish stocks, with no possibility of rapid recovery [10]. It was observed that the fishmeal supply in 2023 was 23% lower than in 2022 [11]. According to Naylor et al. [12], about 10% of the fish from capture fisheries is used to formulate feed for aquaculture. Therefore, with the decreasing availability of wild fish and crustaceans, the only remaining way to meet the increased demand for animal protein is aquaculture [13]. The high costs of key feed ingredients such as fishmeal and fish oil are a major challenge for the sector, and in this context, the identification and integration of alternative sources of protein in fish diets is a topical issue. It should be emphasized that carnivorous fish that require protein- and oil-rich diets, such as Atlantic salmon (*Salmo salar*) and rainbow trout (*Oncorhynchus mykiss*), rely heavily on protein and fish oil from wild-caught fish in their diets [14,15].

Protein is the most expensive ingredient in a feed formulation, hence the need to find affordable alternative sources for fish feed. Other causes that have led to the identification of alternative protein sources in addition to the growing global population are climate change, resource limitations, and the cost and availability of conventional protein sources (soy, fishmeal, and fish oil). The need for new sources of protein also stems from changes in people's eating behaviors, who are becoming more attentive to their diets and are shifting towards quality foods [16].

In recent decades, numerous alternative sources of plant and animal protein have been investigated and used in fish feed to reduce the dependence on fishmeal, an increasingly expensive and limited resource [17]. These include soybean meal, pea, rapeseed, corn gluten meal, rapeseed meal, as well as animal by-products such as meat and bone meal, feather meal, or blood meal [18–22]. In this context, a number of new protein sources, such as insect meal, food industry by-products (pomaces and dried distillers grains with solubles (DDGS)) [23,24], macroalgae, and unicellular organisms, are being evaluated as possible alternatives in fish feed. Each of these sources offers a number of advantages: plant proteins are more accessible and relatively inexpensive, insects are rich in protein, and microorganisms can be cultivated sustainably and have a very good nutritional profile. Single-Cell Protein (SCP) is a promising category of alternative protein sources derived from single-celled organisms such as bacteria (e.g., *Methylococcus*), yeasts (*Saccharomyces*), algae (*Arthrospira* and *Chlorella*), and filamentous fungi. The use of unicellular proteins in fish feed has also been shown to be beneficial in terms of feed conversion efficiency, improving the growth rates and welfare of fish while reducing the environmental impact and competition for conventional feed resources [25]. Alternative sources of protein can partially or fully replace fishmeal and soybean meal in feed diets, but the effects on fish growth, nutrient utilization, and health vary. A number of factors, such as the presence of anti-nutritional factors, digestibility, and levels of essential amino acids, need to be considered [26].

Researchers' interest in the use of insect meal as a substitute for fishmeal in fish feed has increased in recent years. Insects with potential as an alternative protein source include the black soldier fly larvae (BSFL) [27], silkworms (*Bombyx mori*) [28], yellow worms (*Tenebrio molitor*) [29], grasshoppers (*Locusta migratoria* and *Schistocerca gregaria*) [30], crickets (*Acheta domesticus* and *Gryllus assimilis*) [31], and house flies (*Musca domestica*) [32]. Insects are known to be found in the natural diet of freshwater and marine fish, especially in the early stages of their development [33], because they are rich in amino acids, fats, vitamins, and minerals [34]. Africa is ahead of other regions of the world in adopting the use of the black soldier fly (and other insect species) as a source of animal feed [35]. Local legislation allows different types of waste to be used to feed the larvae, and then the larvae and their by-products are used to produce feed for farm animals or pets.

Native to many regions of Africa, BSFL could contribute to waste recycling, and its growth could be favored by the warm climate. In African countries, livestock production accounts for approximately 30% of the gross value of agricultural production, and therefore, the cost of feed limits the development of the sector. For example, in Kenya, the price of feed accounts for about 70%, and large-scale insect farming can be an alternative protein solution, as insects can feed on various types of organic waste [36]. Some freshwater fish species such as tilapia (*Oreochromis niloticus*) and African catfish (*Clarias gariepinus*) could be raised with BSFL-based feed, contributing to the development of African aquaculture [37,38]. The contribution of aquaculture to the development of African countries is significant because it provides proteins of animal origin.

As the global insect-based feed industry is expected to grow from USD 128 million in 2019 to an estimated USD 3.4 billion by 2030, the use of BSF meal in aquaculture is gaining considerable interest [39].

However, despite promising research results on growth performance, immune modulation, and waste valorization, several challenges remain. These include regulatory constraints regarding substrates used for rearing BSFL; questions about fish product quality and consumer acceptance; inconsistencies in nutrient composition based on rearing substrates; and difficulties scaling up BSFL production at industrial levels.

This review aims to explore the current status of BSFL use in aquafeeds, synthesize recent findings, highlight the opportunities and risks of large-scale adoption, and discuss how BSFL meal can contribute to the future of sustainable aquaculture.

2. Materials and Methods

This review was conducted through a structured literature search to compile and synthesize scientific findings related to the use of *Hermetia illucens* (black soldier fly larvae—BSFL) meal as an alternative ingredient in aquaculture feeds. The relevant literature was identified using the following electronic databases: Web of Science, Scopus, PubMed, and Google Scholar. The search spanned from 2002 to 2025 and included 200 peer-reviewed journal articles, regulatory reports, and review papers.

The keywords and Boolean operators used included combinations of the following terms: “Black Soldier Fly” OR “BSFL” OR “*Hermetia illucens*” AND “aquaculture”, “fish feed”, “sustainability”, “growth performance”, “fillet quality”, “chitin”, “lauric acid”, “consumer acceptance”, “regulatory”, “microbial safety”, and “antimicrobial activity”.

Inclusion criteria included the following: articles published in English; studies focused on the application of BSFL meal in fish diets; research addressing nutritional composition, growth performance, feed conversion ratio, fillet characteristics, or bioactive effects (e.g., antimicrobial effects and immune modulation); and literature discussing regulatory aspects or consumer perceptions relevant to BSFL-fed aquaculture.

Exclusion criteria consisted of the following: studies on terrestrial animals or unrelated insect species and publications lacking specific data on BSF applications in aquafeeds.

3. *Hermetia illucens*: Biology and Nutrient Composition

3.1. Biology of Species

Hermetia illucens, also known as the black soldier fly, is a common species in the family Stratiomyidae, order Diptera. Since the late twentieth century, *H. illucens* has attracted attention due to its usefulness in recycling organic waste and generating animal feed [40]. Black soldier flies are at their nutritional peak during the pupal stage when they can be fed to animals such as poultry, fish, pigs, lizards, turtles, and even dogs. This insect is one of the few insect species approved for use as aquaculture feed in the EU. They can be kept at room temperature for several weeks and have the longest shelf life between 10 and 16 °C [41]. BSFLs are characterized by a rapid reproductive cycle and high concentrations of proteins, lipids, vitamins, and minerals [14,42]. The insects can develop in fairly small spaces and generally larvae and pupae are reared together on a feeding substrate in small trays made of various materials such as wood, fiberglass, polyethylene [43].

The life cycle of the BSF comprises four developmental stages—egg, larva, pupa, and adult—and is influenced by a number of factors such as temperature, humidity, light intensity, and type of food [44] (Figure 1). A female lays between 206 and 639 eggs. They hatch in 3–4 days. The newly hatched larvae are 1 mm long and weigh 0.1 g. They grow for 18–36 days depending on the substrate on which they develop. The prepupal stage lasts up to 7 days and the pupal stage 1–2 weeks [45]. BSFL adults are considered non-pathogenic as they do not feed [46].

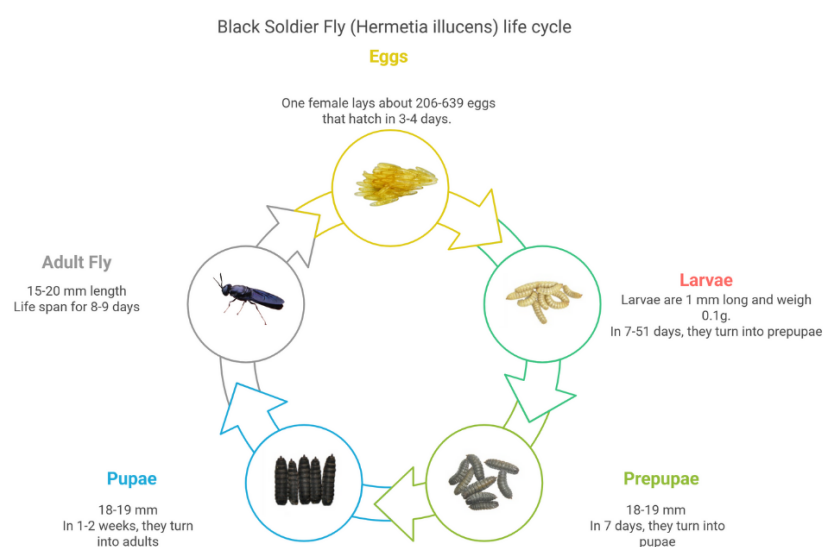


Figure 1. Life cycle of the black soldier fly (*Hermetia illucens*). The cycle includes five stages: eggs, larvae, prepupae, pupae, and adult flies.

Since adults do not consume food, this behavior helps the larvae accumulate larger amounts of lipids that increase their chances of survival when they enter the adult stage. The increased fat requirement of larvae increases their ability to consume food waste [47]. Studies have shown that BSF larvae can prevent the spread of house flies and reduce harmful bacteria, such as *Escherichia coli* and *Salmonella enterica*, by secreting bactericidal compounds. Therefore, industrial rearing of BSFL does not favor disease transmission [48].

3.2. Nutrient Composition of Insect Meal

BSF meal has a nutritional composition rich in proteins (up to 52%) and lipids (up to 38%), as well as minerals, which makes it a suitable ingredient for fish diets (Table 1). Some authors suggest that BSFL meal may contain 35–57% crude protein, 32.6% fat, 6.7% crude fiber, and 8.6% ash content [49,50]. Schiavone et al. [51] and Halloran et al. [52] show that BSF larvae contain between 37 and 63% protein and 20 and 40% fat.

Table 1. Chemical composition of FM and BSFL.

Parameter	Fishmeal			BSFL		
Dry matter (%)	92.10	91.70	94.10	-	-	93.19
Protein content (%)	65.20	37.70	48.60	42.10	39.38–48.20	52.46
Fat content (%)	9.20	32.60	32.00	26.00	25.69–38.36	9.29
Ash content (%)	16.80	10.70	58.50	-	7.26–8.27	7.80
NDF (%)	5.30	16	181.10	-	-	-
ADF (%)	0.50	8.40	92.50	-	-	22.10
Gross energy (kcal/kg)	4.510	5.660	-	-	-	-
Gross energy (MJ/kg)	18.90	23.70	26.60	-	-	22.76
Calcium (g/kg)	41.30	30.30	6.80	7.56	13.00–21.17	3.64
Iron (mg/kg)	352	375	1600	-	-	-
Sodium (g/kg)	10.57	0.91	1.20	-	3.38–5.02	-
Zinc (mg/kg)	99	93	154.0	-	300–1200	-
Phosphorus (g/kg)	26.40	6.60	9.30	9	6.00–9.10	10.1
Magnesium (g/kg)	2.20	2.90	3.30	-	2.50–3.31	-
References	[53]	[54]	[55]	[56]	[57]	[58]

The composition of insect meal is directly influenced by the substrate on which the insects are grown, as this determines their nutritional profile [59]. Table 2 presents several types of substrates used in the rearing of *Hermetia illucens* larvae.

Table 2. Types of substrates used in the rearing of *Hermetia illucens* larvae.

Types of Substrates	References
Degassed sludge and chicken feed	[60]
Pineapple waste, jackfruit waste, rumen content, fish offal, and mixed substrates	[61]
Market waste: fruits, vegetables, meat, and fish in decomposition; hotel waste: cooked foods and vegetable and non-vegetable wastes	[62]
Animal waste (slaughterhouse remains, fish, mussels, butcher waste, etc.), fodder waste (wheat bran, soy flour, cornmeal, dog food, old bread, alfalfa, etc.), fermentation products (by-products from winemaking, beer waste, and tofu yeast), food waste (waste from markets, canteens, hotels, municipal organic waste, brown algae, etc.), fruits, garden waste, vegetables, and mixed waste	[63]
Soybeans	[64]
Spent mushroom substrate	[65]
Rice bran, fruit waste (papaya and bananas), vegetable waste (mustard leaves and watercress), tofu by-products, liquid palm sugar, and sago (Putak flour)	[66]
Aquaculture solid waste	[67]
Fresh soybean curd residue and coconut endosperm	[68]
<i>Sesbania grandiflora</i> and <i>Moringa oleifera</i> leaves and agro-industrial by-products, including soybean waste, wheat pollard, rice bran, and milk-extracted coconut meat	[69]

For example, insects fed on protein- and carbohydrate-rich substrates, such as wheat bran, will produce a meal with higher protein and lipid contents. In contrast, a substrate based on vegetable waste, such as fruit and vegetable scraps, may result in a flour with a higher carbohydrate content. The type of substrate also influences the content of fatty acids, minerals, and vitamins, thus affecting the nutritional value of insect meal used in fish feed.

In the case of carbohydrate-rich substrates, a greater amount of lipids accumulates in the larvae, while protein-based substrates will increase the protein content [70]. Also, the fatty acid profile can be manipulated by adding plant sources to the growth substrate [71].

The study of larval fatty acid (FA) profiles indicated that feeding them with fermented substrates leads to an improved larval FA profile, which is a plus considering their use as aquatic animal feed [72].

Boafo et al. [73] conducted a study in Ghana that investigated the use of six types of substrates selected as suitable for egg laying by female *Hermetia illucens* and subsequent larval development. The substrate types selected were pig manure, bird manure, fruit waste, millet porridge puree, waste from local sorghum beverage producers, and waste from roots and tubers. All substrates were attractive for larval development, but pig manure was the most productive one. The type of substrate used influenced the total prepupal weight. The yield on pig manure was significantly higher compared to the other substrates, and chicken manure and fruit waste had similar prepupal yields. The substrate millet porridge had a higher yield in prepupal development compared to chicken manure, fruit waste, and roots and tubers. Regarding the contents of crude protein, fat, crude ash, crude fiber, and moisture in the prepupae grown on these substrates, they were 36.2–43.4%, 25.6–41.3%, 7.7–19.8%, 9.9–12.3%, and 57.5–61.8%.

In a study by Jucker et al. [74], larvae fed three diets varied in protein and fat contents. Thus, diet 1 was fruit based (oranges, apples, and pears), diet 2 vegetable based (cabbage, lettuce, and green beans) and diet 3 mixed (fruits and vegetables). The mixed diet group had the highest protein content of 17.6 g/100 g compared to the other two groups. Larvae reared on the fruit-based diet had a higher fat content, especially saturated fatty acids. The calcium content was high in all experimental variants, ranging between 1421.3 mg/g and 2703.7 mg/g.

Another study by Ahmad et al. [75] aimed to determine the growth rate of BSFL and to study the effectiveness of composting fruit (apples, pineapple, papaya, and bananas) and vegetable (tomato, cabbage, cucumber, and lettuce) wastes from local markets and canteens by these larvae.

The waste was divided into three categories that included fruits, raw vegetables, and cooked vegetables. These wastes were administered into two categories of larvae of 2 and 4 g. The data obtained showed that larvae reared on fruit substrate had the best growth, of 1700%, compared to the initial weight of 2 g, and of 1200% starting from a 4 g initial weight, respectively. Fruit residues had the highest percentage of reduction, by 57% using larvae, indicating that they could be more suitable as a substrate for larval development. Furthermore, the study shows that waste reduction with different amounts of larvae did not show significant differences. This study shows the ability of larvae to transform organic substrates into biomass.

3.2.1. Amino Acid Composition of BSFLM

Table 3 presents the amino acid composition in BSFL. BSFLM is a rich source of amino acids including lysine, methionine, cysteine, arginine, and tryptophan [76]. In their study, Lu et al. [77] examined the amino acid profile of black soldier fly larvae and found that the most abundant essential amino acids in black soldier fly larvae were leucine (average 44.6 g/kg), lysine (average 38.8 g/kg), and valine (average 40.1 g/kg), which are higher

than those found in soybean meal, with valine also exceeding the content found in fishmeal. The least abundant essential amino acids were methionine (average 9.3 g/kg, ranging from 6.3 g/kg to 13.4 g/kg) and tryptophan (average 3.6 g/kg, ranging from 2.3 g/kg to 5.3 g/kg), which were comparable to soybean meal levels but much lower than those in fishmeal. In BSFL, the lysine content is significantly lower compared to fishmeal, ranging between 21.80 g/kg and 27.70 g/kg [54,55].

Table 3. Amino acid composition of FM and BSFL.

Parameter	Fishmeal			BSFL		
Arginine (%)	5.70	18.70	19.90	22.00	1.94	1.80–2.55
Histidine (%)	2.41	11.70	13.80	13.40	1.32	2.08–2.77
Isoleucine (%)	4.74	15.8	19.10	19.30	1.57	1.76–2.40
Leucine (%)	7.74	26.30	30.60	30.00	2.59	2.67–3.62
Lysine (%)	7.91	21.80	23.00	27.70	2.22	2.44–3.60
Methionine (%)	3.02	6.80	7.10	7.60	0.58	0.61–1.07
Cysteine (%)	0.94	2.40	2.20	3.30	0.28	0.12–0.16
Phenylalanine (%)	4.12	15.30	16.40	17.10	1.51	1.35–2.11
Tyrosine (%)	3.33	21.40	-	26.50	2.30	1.71–3.09
Threonine (%)	4.37	14.50	16.20	18.40	1.42	1.42–1.94
Tryptophan (%)	1.18	5.40	5.40	-	0.53	-
Valine (%)	5.43	22.6	28.20	29.40	2.25	2.29–3.09
References	[53]	[54]	[42]	[55]	[78]	[57]

3.2.2. Methionine and Lysine

Although BSFL represent a sustainable protein resource, with a protein level similar to that of fishmeal, their amino acid profile shows some deficiencies, especially regarding the levels of methionine and lysine, amino acids essential for optimal growth of fish, especially carnivorous ones. A comparative analysis of the amino acid content of black soldier fly larvae meal against the nutritional requirements of different fish species indicates both the advantages and disadvantages of this protein source. In the case of using BSFL meal, these limitations can be overcome by supplementing the diet with synthetic amino acids, by combining BSFL with other complementary protein sources, or by adjusting the feeding substrate of the larvae to improve the amino acid level.

Methionine and lysine are two essential amino acids with an important role in fish nutrition. Methionine is the primary methyl donor in organisms and is vital for protein synthesis, the synthesis of important metabolites like phosphatidylcholine and creatine, and the antioxidant system through cysteine and glutathione production [79]. It also regulates immunity, energy metabolism, and reproduction [80]. The methionine requirement of fish varies according to species, age, and cysteine and taurine levels and is between 0.49% and 2.5% of the diet. Methionine should be added to the diet when fishmeal in fish feed is substituted by other vegetable protein sources [81]. According to some authors, the methionine concentration ranges between 6.80 g/kg and 7.60 g/kg, significantly lower compared to fishmeal [54,55].

For example, the methionine requirement for African catfish (*Clarias gariepinus*) is between 18.7 and 21.4 g/kg [82]; for carp (*Cyprinus carpio*), the methionine requirement would be 0.855 g/100 g DM according to Schwarz et al. [83]; and for juvenile rainbow trout (*Oncorhynchus mykiss*), it is 0.52–1.49% of the diet, respectively, of dietary protein [84].

Lysine, on the other hand, is critical for growth, nitrogen balance, and preventing fat accumulation. It helps maintain osmotic pressure and acid–base balance in body fluids while also promoting muscle growth through hyperplasia and hypertrophy of muscle fibers. Research on different fish species fed lysine-supplemented diets have shown better growth

rates, increased immunity, and improved fecundity compared to fish fed lysine-deficient diets. In addition, lysine-supplemented diets are more economically efficient [85].

In the case of lysine, the optimal level for grass carp was recommended between 2.13 and 2.39% of the diet [86]; for rainbow trout fingerlings (*Oncorhynchus mykiss*), it is 1.30% of the diet [87]; for white sturgeons (*Acipenser transmontanus*), it is 15.8% [88]; and for Nile tilapia juveniles (*Oreochromis niloticus*), the requirement was estimated at 5.12% of the diet [89].

Addressing the amino acid imbalances of BSFL meal, particularly methionine and lysine deficiencies, can be approached from multiple angles. At the fish nutrition level, supplementation with crystalline or coated amino acids has proven effective. In gibel carp (*Carassius auratus gibelio*), diets low in protein but supplemented with crystalline or coated methionine and lysine significantly improved antioxidant capacity, intestinal health, and muscle quality, with coated forms showing superior effects on enzyme activity and fat deposition [90]. From an insect production perspective, new advances in BSFL nutritional enhancement may help reduce the need for supplementation. For example, suppression of nutrient amino acid transporters in BSFL excretion systems increased the larval content of several essential amino acids (e.g., histidine ↑257% and valine ↑198%), although this came at the cost of reduced larval biomass [91]. However, supplementation of BSFL substrates with lysine has shown limited benefits: crystalline lysine addition above 0.3% reduced larval growth, survival, and prepupal rates, suggesting that larvae themselves do not benefit from lysine fortification beyond a minimal threshold [92].

3.2.3. Fatty Acids Composition of BSFL

An important disadvantage of *Hermetia illucens* larvae meal is given by the low level of long-chain polyunsaturated fatty acids (PUFAs), especially eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), necessary for the healthy development of fish, especially marine species. Replacing fishmeal and fish oil in the feed of farmed salmon with sustainable ingredients, but which have low levels of the essential fatty acids EPA and DHA, may decrease the nutritional value of the fish and also the growth performance and health [93].

Research over the past decades on essential fatty acids in fish has led to the establishment of minimum requirements necessary to prevent nutrition-related pathologies, to find optimal levels for their growth and development, and to identify innovative sources of PUFAs to maintain the nutritional quality of farmed fish in a context of limited marine resources [94].

To overcome this deficiency, the diets of fish consuming BSFLM feed can be supplemented with rich sources of PUFAs, such as alternative lipid sources (vegetable oils and animal fats) or genetically modified microalgae and oilseed crops [95,96].

Although BSFLM is a sustainable protein source, its use in fish feed requires nutritional improvements to ensure an optimal level of essential fatty acids.

The black soldier fly grows and reproduces readily and can be reared on biowaste. Insects often accumulate fat, especially in their immature stages. The lipid content of un-degraded black soldier fly larvae is high (26–35%) [97]. The lipid extracts from *Hermetia illucens* larvae are characterized by a high concentration of fatty acids, especially lauric acid, which ranges from 37% to 62%, depending on the extraction methods employed [98]. Other significant fatty acids include palmitic acid (C16:0), oleic acid (C18:1n-9), and linoleic acid (C18:2), with linoleic acid being a notable omega-6 polyunsaturated fatty acid (PUFA) [98]. Additionally, *Hermetia illucens* larvae contain small amounts of omega-3 fatty acids, such as α-linolenic acid (C18:3) [98]. In contrast, other species like *Tenebrio molitor* (mealworm) have significantly lower levels of lauric acid, typically containing less than 0.5% [99]. Table 4 present comparative fatty acids composition between fishmeal and BSFL.

Table 4. Fatty acid composition of FM and BSFL.

Parameter	Fishmeal			BSFL		
C8:0 caprylic acid (%)	-	-	0.003	-	-	-
C10:0 capric acid (%)	-	-	0.201	0.70	0.86	0.44–0.85
C11:0 undecanoic acid (%)	-	-	0.004	-	-	-
C12:0 lauric acid (%)	0.09	122	8.567	14.10	45.97	17.89–37.18
C13:0 tridecanoic acid (%)	-	-	0.009	-	-	-
C14:0 myristic acid (%)	4.10	18.10	2.488	1.90	8.70	5.21–11.77
C14:1 myristoleic acid (%)	-	-	0.042	-	-	-
C15:0 pentadecanoic acid (%)	-	-	0.048	-	0.15	-
C15:1 pentadecenoic acid (%)	-	-	0.009	-	-	-
C16:0 palmitic acid (%)	12	32.80	8.870	5.30	12.21	20.65–24.59
C16:1 palmitoleic acid (%)	4.80	11.80	0.924	1.10	1.91	1.75–2.67
C17:0 heptadecanoic acid (%)	-	-	0.053	-	0.20	-
C17:1 heptadecanoic acid (%)	-	-	0.032	-	0.20	-
C18:0 stearic acid (%)	2.40	6	1.194	0.90	2.53	2.95–4.42
C18:1 oleic acid (%)	8.20	32.30	8.869	7.30	11.24	9.28–15.35
C18:2 linoleic acid (%)	1.40	19.70	3.815	2.70	14.07	4.71–24.08
C18:3 linolenic acid (%)	1.20	2.80	0.400	0.20	1.65	0.32–1.99
C18:4 stearidonic acid (%)	1	0.80	-	-	-	-
C20:0 arachidic acid (%)	0.20	0	0.041	0.0	0.10	-
C20:1 eicosenoic acid (%)	4.50	0	0.034	-	0.06	ND–0.46
C20:3 eicosatrienoic acid (%)	-	-	0.008	-	-	ND–0.38
C20:4 arachidonic acid (%)	1.60	0	0.118	-	0.14	-
C20:5 eicosapentaenoic acid (%)	6	1.30	0.079	0.30	-	-
C22:0 behenic acid (%)	0.20	0	-	-	-	ND–0.26
C22:1 erucic acid (%)	5.20	0	-	-	-	-
C22:2 docosadienoic acid (%)	-	0.20	0.081	-	-	-
C22:5 docosapentaenoic acid (%)	1.80	-	-	-	-	-
C22:6 docosahexaenoic acid (%)	4.40	0.60	-	-	-	-
C24:0 lignoceric acid (%)	0	0	-	-	-	-
References	[53]	[54]	[47]	[78]	[100]	[57]

ND = not detected.

3.2.4. Lauric Acid in BSFL

Lauric acid (C12:0) is a medium-chain saturated fatty acid found in various natural sources, including coconut oil, palm kernel oil, and certain insect species. Among insects, *Hermetia illucens* larvae are particularly notable for their high content of lauric acid, making them a promising candidate for use in aquaculture as a feed additive [99].

Lauric acid derived from *Hermetia illucens* larvae exhibits significant bioactivities, including antibacterial, antiviral, antifungal, and anticancer properties [101]. For instance, lauric acid has shown potent antibacterial activity against Gram-positive bacteria, such as *Staphylococcus aureus*, with a minimum inhibitory concentration (MIC) of 500 µg/mL [102]. It also demonstrates antiviral efficacy, particularly against the herpes simplex virus type 1, where it inactivates the virus at a concentration of 2 mg/mL [103]. Lauric acid has antifungal properties as well, being effective against *Candida albicans* at an effective concentration of 10 mg/mL [104]. Furthermore, lauric acid has been found to induce antiproliferative and pro-apoptotic responses in breast and endometrial cancer cells, highlighting its potential as an anticancer agent [105].

In aquaculture, lauric acid has shown positive effects on fish health. A study by Belghit et al. [106] found that insect-based diets high in lauric acid significantly reduced liver lipids in freshwater Atlantic salmon (*Salmo salar*). Despite the high content of saturated fatty acids in these diets, the apparent digestibility coefficients of all fatty acids were high. Lauric acid, being a medium-chain fatty acid, was rapidly oxidized and had low deposition in

the liver, leading to a decrease in liver triacylglycerols compared to the control diet. This suggests that lauric acid is efficiently utilized for energy rather than stored as fat, potentially improving the metabolic health of the fish.

In another study, Fontinha et al. [107] evaluated the effects of introducing lauric acid into the diets of juvenile European sea bass on growth performance, oxidative stress enzymes, immunological parameters, and plasma metabolites. This study indicated that supplementation with up to 2% lauric acid in the diet stimulated growth performance in juvenile European sea bass, and 1% lauric acid improved oxidative status and gut microbiota and downregulated anti-inflammatory genes.

3.2.5. Chitin and Chitosan in BSFL

Chitin is a natural biopolymer with the chemical formula $C_8H_{13}O_5N$, structurally similar to cellulose. It is primarily extracted from crustacean shells, mollusks, insects, fungi, and certain plants [108]. Chitosan, a cationic polysaccharide derived from chitin through a deacetylation process, is composed of glucosamine and N-acetyl-glucosamine monomer residues linked by β (1→4) linkages [109]. Both chitin and chitosan are widely recognized for their excellent biodegradable properties, non-toxic nature, and eco-friendly characteristics. These biopolymers have applications in various industries, including food, medicine, cosmetics, agriculture, and textiles, due to their ability to enhance growth rates, improve immunological functions, and reduce gut microbial pathogens in both terrestrial and aquatic animals [110].

Chitin and chitosan can be successfully derived from various stages of insects, particularly those used in the insect-based food industry. For example, chitin and chitosan have been extracted from *Tenebrio molitor* (mealworm), including its larval, molt, and adult stages [111]. These extracts have been shown to have distinct properties, such as antibacterial activities, which make them suitable for applications in packaging and biomedicine. Additionally, *Hermetia illucens* has also been studied as a potential source of chitin and chitosan, with pupal exuviae being identified as the most suitable biomass for production due to their high chitin content [112]. Adult stages of *Hermetia illucens* contain up to 5% chitin [113].

Both chitin and chitosan possess significant biological properties, such as antimicrobial, antioxidant, and wound-healing abilities, which make them suitable for various applications in food, biomedical, and industrial fields [110]. These compounds have been shown to have immunomodulatory effects, helping to improve disease resistance and immune responses in aquaculture species [114,115]. In aquaculture, chitin and chitosan have been used as feed additives to improve the growth, immunity, and disease resistance of aquatic animals. For instance, chitin supplementation in the diet of common carp (*Cyprinus carpio*) has resulted in enhanced immune resistance and improved growth performance [114]. Similarly, mrigal carp (*Cirrhinus mrigala*) fed chitin-enriched diets exhibited improved immune response and disease resistance to *Aphanomyces invadans* [115]. Moreover, studies on Nile tilapia (*Oreochromis niloticus*) have shown that chitin supplementation enhances growth performance and the feed conversion ratio (FCR), along with an improved immune response [116]. The potential of chitosan, particularly from *Epinephelus bruneus*, has also been demonstrated in improving growth and immune responses, providing a viable option for aquaculture feed additives [117].

A major challenge in utilizing insect-based chitin in aquaculture is its digestibility. Chitin, being a complex polymer, can interfere with the digestion of other nutrients. Chitinase, an enzyme responsible for breaking down chitin, is necessary for enhancing the digestibility of insect meal in aquatic animals. Studies have shown that carnivorous and omnivorous fish possess the required chitinolytic enzymes like chitinase, chitobiase, and

lysozyme, which aid in the digestion of chitin [118]. These enzymes are important for the breakdown of chitin in the digestive system, facilitating better nutrient absorption and reducing the negative impact on growth performance. Despite the promising applications of chitin and chitosan in aquaculture, further research is needed to optimize their use, particularly in the development of chitinase supplementation strategies.

In a study conducted by Renna et al. [119], which aimed to introduce partially defatted BSFL meal into the diet of rainbow trout, it was observed that a percentage of 40% corresponding to 2 g of chitin/100 g of dry matter did not produce negative effects on growth, although digestibility decreased.

Including chitin in the diet of rainbow trout at a rate of up to 3% did not influence growth performance, blood biochemistry, nutrient digestibility, or intestinal activity [120].

Eggink et al. [121] investigated the effect of chitin on nutrient digestibility and chitinase activity in fish. BSFL meal with different chitin concentrations (18, 27, and 154 g chitin/kg DM) was tested in the diet of Nile tilapia (*Oreochromis niloticus*) and rainbow trout (*Oncorhynchus mykiss*). The fish were able to digest chitin, but its digestibility decreased at higher levels of chitin in the diet.

Chitin effects are species specific and dose dependent. At low levels, it may stimulate immunity and gut health, while at higher levels, it tends to reduce digestibility of protein and lipids, impairing growth. According to a recent review, the role of chitin in aquafeeds is highly variable and depends on both the inclusion level and the species considered [122]. In turbot, diets containing 1.47% chitin from 16.5% BSFL prepupae meal significantly reduced growth performance [122,123]. In Atlantic salmon, chitin inclusions above 1 g/100 g diet impaired body weight, the condition factor, and protein digestibility [122,124]. By contrast, results in rainbow trout have been inconsistent: while 26.4% BSFL meal (0.73% chitin) reduced weight gain and lipid digestibility [122,125], other studies using up to 12% BSFL meal (1% chitin) reported no adverse effects on growth performance [122,126]. These contrasting findings highlight that chitin can be beneficial in moderation but may become detrimental when dietary levels exceed species-specific tolerance thresholds. Optimizing chitin inclusion requires understanding the nutritional physiology of each species and carefully balancing its potential immunostimulant benefits against the risk of reduced nutrient utilization [122].

Future studies should also focus on improving the digestibility of insect-based chitin and its integration into sustainable aquaculture practices. Additionally, understanding the interaction between chitin, gut microbiota, and the overall health of aquatic species will be important in maximizing the benefits of these biopolymers in aquaculture systems.

4. Impact of BSFL Meal in Aquaculture

Numerous studies have been carried out in aquaculture where fishmeal has been replaced with black soldier fly larvae meal (BSFL) in different proportions in fish such as carp (*Cyprinus carpio*, var. Jian), Nile tilapia (*Oreochromis niloticus*), lemon fin barb (*Hypsibarbus wetmorei*), meagre (*Argyrosomus regius*), catfish (*Clarias gariepinus*), rainbow trout (*Oncorhynchus mykiss*), and gilthead seabream (*Sparus aurata*), and positive results have been observed (Table 5).

The aim of a study by Kroeckel et al. [123] was to determine the nutritional value of Hermetia meal for juvenile turbot (*Scophthalmus maximus*) by determining growth performance, feed intake, and nutrient retention efficiency. Diets had 0%, 17%, 33%, 49%, 64%, and 76% insect meal. No negative effects on feed intake and the feed conversion ratio were observed by including 33% HM. SGR was lower in all diets containing BSFL, while FCR was significantly higher in diets with inclusion levels above 33%. Chitinase activity or chitinolytic active bacteria were not detected in the midgut of turbot. Chitin

in the BSFL could have influenced feed intake and nutrient digestibility and, therefore, growth performance.

Li et al. [97] conducted a study in *Cyprinus carpio* var. Jian by replacing soybean oil with insect meal oil at 0, 25, 50, 50, 75, and 100%. The aim of this study was to estimate how insect meal oil influences BSFLO (black soldier fly larvae oil), growth performance, feed conversion, fatty acid profiles, biochemical parameters, and lipid metabolism. The results showed that growth, nutrient utilization, and serum biochemical parameters of fish from five groups were not different ($p > 0.05$). The fatty acid compositions of intraperitoneal adipose tissue, muscle, and hepatopancreas were closely correlated with the studied diets. The results suggested that the growth of Jian carp was not adversely affected by black fly larvae oil.

Experiments were carried out on juvenile *Lates calcarifer* (barramundi or Asian perch) in order to analyze the efficacy of replacing FM with BSFLM in proportions of 0, 25, 50, 75, and 100. The experiment demonstrated that an appropriate level for optimal growth could be higher than 28.4% but less than 50%, without negative effects on amino acid composition [127].

Magalhães et al. [128] found that up to 19.5% BSF, corresponding to 22.5% total protein, can replace FM in diets for juvenile *Dicentrarchus labrax* (European sea bass), with no negative effects on growth parameters and nutritional indices.

Another experiment conducted in *Cyprinus carpio*, var. Jian to estimate the effects of replacing fishmeal with defatted meal of black soldier fly larvae followed the effects on growth performance, antioxidant enzyme activities, digestive enzyme activities, and hepatopancreas and intestinal morphology. The proposed diets contained 0%, 25%, 50%, 50%, 75%, 75%, and 100% BSFL. The results showed that the growth performance and nutrient utilization of fish from five groups were not different. Hepatopancreas lipid content and serum cholesterol of the treated groups were significantly lower than that of control group. Histologic examination of the intestine showed that at a level of 75% or more FM protein replaced, pathologic changes were observed. The study demonstrates that it is appropriate to replace up to 50% of dietary FM protein with BSFL [129].

Also, in a study conducted on *Cyprinus carpio*, var. Jian, the researchers replaced FM with BSFLM in order to evaluate the growth and body composition of Jian carp. FM in Jian carp diet was replaced with 0, 35, 70, and 105 g/kg BSFLM. Thus, it was observed that the growth parameters, biochemical parameters, and amino acid composition were not affected by the replacement with BSFLM. In conclusion, replacing 100% FM with insect meal in Jian carp diets does not produce negative effects on growth while decreasing the amount of n-3 unsaturated fatty acids (HUFAs) in the fish body. This indicates that BSFLM could be used after nutrient supplementation with n-3 HUFAs to increase fish quality [130].

Another study comprised three experimental variants containing 33, 66, and 100% insect meal to test growth potential, nutrient utilization, liver health, and sensory fillet parameters in Atlantic salmon (*Salmo salar*). Feed intake, daily growth gain, and the feed conversion ratio were not affected by the inclusion of insect meal in the diets. The protein, lipid, and amino acid compositions of the whole body were not affected by replacing fishmeal with insect meal, while the fatty acid composition of the whole body reflected the composition of the diets. Sensory testing of the fillet revealed only small changes in its sensory quality. Overall, this study showed that a total replacement of fishmeal with black fly larvae meal in Atlantic salmon diets is possible without negative effects on growth performance, feed utilization, nutrient digestibility, liver characteristics, or sensory qualities of the fillet [106].

A relevant example is that of Japanese perch (*Lateolabrax japonicus*), where Wang et al. [131] investigated the partial replacement of fishmeal with defatted insect larval meal.

The study included five isoprotein (39%) and isolipid (11%) diets with substitution levels of 0%, 16%, 32%, 48%, and 64% BSFL. The results showed that with up to 64% substitution, no negative effects on growth performance or liver and intestinal histomorphology were observed, suggesting good tolerance of this species to the tested ingredient.

Comparable results were also obtained in Siberian sturgeon (*Acipenser baerii*), a valuable species in freshwater aquaculture. In this case, BSFL meal was tested at levels of 5%, 10%, 15%, 20%, 25%, and 30%, and the evaluations focused on feed quality, growth performance, acceptability, and digestibility. Despite some physical changes to the feed (reduction in density, sink rate, and stability), biological performances, such as weight gain and protein conversion efficiency, were significantly improved without affecting nutrient digestibility [132].

Among salmonids, rainbow trout (*Oncorhynchus mykiss*) was the subject of a large study by Kumar et al. [133], in which the addition of BSFL (8% and 16%) to soybean meal (SBM) diets reduced the occurrence of intestinal enteritis. Furthermore, complete substitution of fish oil or soybean oil with BSFLO (black soldier fly larvae oil) did not adversely affect the histological structure of the liver or intestine but led to decreased inflammation and improved immunity, suggesting that defatting insect meal could be optional for this species.

On the other hand, in gilthead sea bream (*Sparus aurata*), the use of BSFL meal at proportions of 25%, 35%, and 50% in isoenergetic and isoprotein diets generated significant increases in the content of essential amino acids such as lysine, methionine, isoleucine, leucine, threonine, and valine. However, levels of minerals such as phosphorus, calcium, and sodium progressively decreased as the percentage of BSFL increased in the diet ($p < 0.01$) [27].

This trend towards improved biological performance is also observed in goldfish (*Carassius auratus*), where the inclusion of BSFL in the diet led to improved growth, feed utilization, and blood biochemical profile. However, negative effects on skin color, carotenoid content, and liver histological integrity were reported, suggesting that some aesthetic and physiological aspects may be negatively affected at high concentrations [134].

Equally promising were the results obtained in studies on tench (*Tinca tinca*), a species in which substitution levels of 0%, 15%, 30%, 45%, 65%, and 70% with partially defatted BSFL meal were tested. Survival was high (95.8–100%) in all groups, and the best growth performance was observed at the 45% BSFL level. Although essential amino acid content decreased, there were no negative effects on growth, indicating possible sufficiency of the remaining levels. At the same time, a linear decrease in body lipid content was observed [135].

Ornamental species such as *Betta splendens* (Siamese fighting fish) have also benefited from BSFL supplementation. A 2023 study showed that the inclusion of 13% BSFL in the diet resulted in significant improvements in growth, hematological profile, and liver and intestinal morphology, highlighting the potential of this ingredient also in niche aquaculture [136].

In koi carp (*Cyprinus carpio* var. koi), the use of insect meal at rates of 50, 100, 150, and 200 g/kg resulted in significant increases in their weight and specific growth rate, especially at the 200 g/kg level. An improvement in the immune response was also observed, indicating a dual value—nutritional and functional—of insect meal in this species [137].

Another significant example comes from Nile tilapia (*Oreochromis niloticus*) aquaculture, where BSFL was tested as a replacement for fishmeal at proportions of 0%, 25%, 50%, and 75% in a 21-week experiment. The 50% BSFL diet achieved the best results in terms of final weight, daily growth, specific growth rate, FCR, and survival. Furthermore,

economic analysis showed that the 75% BSFL diet had the lowest feed cost (USD 0.79), which supports the economic feasibility of using BSFL on an industrial scale [138].

Table 5. Some studies evaluating the effects of BSFL in aquaculture.

Species	Period	BSFL Level (%)	Results Obtained	References
<i>Cyprinus carpio</i> (carp)—fingerlings	-	0, 12.5, 25, and 37.5% (fermented BSFL)	The 37.5% BSFL diet had the best results in terms of feed utilization efficiency, protein efficiency ratio, specific growth rate, survival, and linolenic acid levels.	[139]
<i>Ctenopharyngodon idellus</i> (grass carp)—juveniles	8 weeks	0, 25, 50, 75, and 100% (defatted BSFL)	There were no significant differences related to growth, feed efficiency, and proximal muscle composition. Malondialdehyde ↓. Gut microbiota analysis did not reveal significant changes. <i>Aeromonas</i> and <i>Shewanella</i> decreased significantly. BSFL 100% did not affect growth performance and carcass composition.	[140]
<i>Oreochromis niloticus</i> (Nile tilapia)—juveniles	12 weeks	0, 10, 20, 40, 60, 80, and 100%	Somatic indices, feed utilization efficiency, survival rate, and hematological parameters did not show significant changes. Lysozyme and peroxidase activities in skin mucus increased.	[141]
<i>Hypsibarbus wetmorei</i> (lemon fin barb)—fingerlings	8 weeks	0, 25, 50, 75, and 100%	Growth performance improved with 75% BSFL and above this percentage decreased. Protein retention ↓ and lipid retention ↑. No significant differences in FCR. No pathological changes. Up to 75% showed no negative effects on fish growth and health.	[142]
<i>Argyrosomus regius</i> (meagre)—juveniles	9 weeks	0, 10, 20, and 30%	No significant histomorphologic changes were observed between treatments. No significant differences in gut bacterial profiles. No significant differences in protease, peroxidase, lysozyme activities, nitric oxide production, and total immunoglobulin levels. A level of 10% BSF is recommended to avoid pathologic changes in the intestine.	[143]
<i>Clarias gariepinus</i> (catfish)—fingerlings	16 weeks	25, 50, and 75%	The 50% BSFL diet achieved a better FCR. Growth performance and survival demonstrated that BSFL has the potential to replace FM by up to 75%. Fish productivity and feed cost can be reduced.	[144]

Table 5. Cont.

Species	Period	BSFL Level (%)	Results Obtained	References
<i>Oncorhynchus mykiss</i> (rainbow trout)—juveniles	90 days	Dried BSFL prepupae (1, 2, or 3 times/day)	Reduced growth and feed intake, and chitin accumulation in the intestine led to constipation (2–3 meals of dry BSFL/day) and anus necrosis. Inclusion of one meal of dry BSF resulted in increased PUFA-3, PUFA-6, and DPA acids in fish.	[145]
<i>Oncorhynchus mykiss</i> (rainbow trout) and <i>Clarias gariepinus</i> (catfish)—fry	4 weeks	0, 33, 66, and 100%	BSFL could replace up to 66% of the diet of catfish and rainbow trout fry without negatively affecting growth performance.	[146]
<i>Channa striata</i> (snakehead)—juveniles	9 weeks	0, 25, 50, 75, and 100%	In over 50%, growth was negatively affected. SOD, catalase, and GPx activity was improved. Blood biochemistry and plasma metabolites were not altered. Reduced appetite on the 100 HM diet.	[147]
<i>Oncorhynchus mykiss</i> (rainbow trout)—juveniles	-	30:70 diet, BSFL and standard feed	The diets tested had a good digestibility between 82.6 and 100%.	[148]
<i>Sparus aurata</i> (gilthead seabream)—juveniles	67 days	0, 15, 30, and 45% (defatted BSFL)	Growth-related gene expression and plasma metabolite profiles were not significantly affected. ALT and GDH ↑. Increased digestive enzyme activity in the hindgut of fish fed BSFL 15% diet. Enrichment of the gut microbiota	[149]
<i>Oreochromis niloticus</i> (Nile tilapia)—larvae	4 weeks	0, 40, 50, and 60% BSFLM	Good survival, specific growth rate varied significantly, and FCR decreased to 1.08 (60%). PER varied from 0.81 (40%) to 2.34 (imported feed). Better survival on experimental diets than on control. For economic profitability, 50 and 60% of BSFL mass is recommended.	[64]
<i>Clarias gariepinus</i> (catfish)—fingerlings	8 weeks	0, 33, 66, and 100% BSFL	Showed 100% survival. Using 100% replacement results in good growth rate. Protein and lipids ↑. Higher profit at 100% BSFL replacement.	[150]
<i>Salmo salar</i> (Atlantic salmon)—juveniles	60 days	0, 5, 10, and 20% full-fat BSFL	Up to 20% can improve the intestinal microbiota due to lauric acid, chitin, and peptides in BSFL.	[151]
<i>Oncorhynchus mykiss</i> (rainbow trout)—adults	8 weeks	0, 15, 30, 45, 60, and 75% BSFLM defatted using butane extraction	Using 45% BSF stimulated autophagy and gut health. Replacing over 60% of FM with BSF would reduce the growth rate.	[152]
<i>Oreochromis niloticus</i> (Nile tilapia)—juveniles	5 weeks	0, 20, and 40% defatted BSF larvae meal	Improved FCR, SGR, and PER. BSF did not affect gene expression of proinflammatory cytokines. Improved intestinal health in juvenile Nile tilapia.	[153]

The arrows ↑ and ↓ indicate increased and decreased, respectively.

Feeds based on *Hermetia illucens* are being tested for use in feeding other aquatic organisms due to the protein and lipid profile that is of interest to aquaculture farmers. Thus, there are some studies targeting shrimp, crayfish, crabs, mussels, etc.

In the case of Pacific white shrimp, *Litopenaeus vannamei*, it has become the most productive shrimp species in the world because it has a fast growth rate and satisfactory economic results. Therefore, the studies carried out on this species seem to support the idea of using BSFL meal as a protein source.

Chen et al. [154], in their study on shrimp that lasted 7 weeks, formulated four different diets: the control diet with 25% fishmeal and three experimental variants with 10%, 20%, and 30% BSFL, respectively. The results obtained showed no differences in survival but pointed out that the 20% BSFL diet stimulated fat synthesis. The 30% inclusion rate negatively affected β -oxidation and glycolysis, which decreased growth performance and body composition. As a conclusion, the use of defatted *Hermetia illucens* larval meal instead of whole meal may prevent changes in the fatty acid profile of the feed, thus allowing greater inclusion in shrimp diets.

The research conducted by Zheng et al. [155], who evaluated the effect of replacing fishmeal (FM) with defatted black soldier fly meal in an experiment that had several diets containing 0%, 20%, 40%, 60%, 80%, and 100% *Hermetia illucens* meal, provided information related to the growth rate, meat quality, and transcriptome of Pacific white shrimp (*Litopenaeus vannamei*). The study shows that BSF was able to replace 20% of FM with positive results, and a higher fat replacement of more than 40% resulted in decreased growth performance and meat qualities of Pacific white shrimp (fat, collagen, and amino acids) and increased cooking and thawing losses.

Nunes et al. [156], in their study, investigated the growth but also the economic performance of feed for *Penaeus vannamei* postlarvae using the replacement of fishmeal with BSFLM at 0, 25, 50, 75, and 100%. The results showed that replacing FM with BSFLM was a good idea, but it should be noted that economic profitability was maintained only when the maximum price of BSFLM did not exceed USD 3.04/kg. This level corresponds to a 75% replacement of FM. The authors suggest that further research may be needed to provide an opinion on economically efficient levels of inclusion.

In the case of freshwater crayfish, the research carried out by Albanou et al. [157] showed that the use of black soldier fly meal in the feed of *Pontastacus leptodactylus* juveniles can be a source of nutrients. Thus, the experiment was carried out for 98 days and followed how the diet with 0, 50, and 100% BSFL influences growth performance, fatty acid profile, and body composition. Juveniles fed *Hermetia illucens* diets were observed to have a better survival rate, but those on the control diet showed better FCR and SGR. By studying the fatty acid profile, the authors indicated that PUFAs, SFAs, and ω 6 fatty acids decreased when BSFL meal was introduced into the diet.

A 60-day study on the juvenile crayfish *Pontastacus leptodactylus* showed that diets exclusively based on fresh larvae of *Hermetia illucens* or *Tenebrio molitor* resulted in complete mortality by the 30th day of the experiment. Mixed diets containing 50% commercial feed and 50% BSFL or TM showed growth and survival comparable to commercial feed, and a moderate survival rate was obtained in the BSF group. Therefore, the use of fresh insects is not recommended, but replacing 50% FM with BSFL can be an alternative in feeding juvenile crayfish.

Subchan et al. [158] investigated the effect of BSFL pellets on the growth of *Cherax quadricarinatus*. The experimental diets included a control with fishmeal pellets, variant 1 with BSFL pellets, and variant 2 with BSFL and fishmeal pellets. The results of the study showed that the three treatments did not produce significant changes in the growth of the crayfish. The parameters monitored were carapace length, wet biomass, dry biomass,

feed use efficiency, and feed conversion ratio. BSFL meal pellets did not produce negative changes in the growth of the crayfish, and the authors suggested that they can be a substitute for fishmeal in aquaculture feeds.

Yao et al. [159] investigated the impact of replacing fishmeal with defatted black soldier fly larval meal (0, 25, 50, 75, and 100%) in the diet of juvenile Chinese crab (*Eriocheir sinensis*) on growth performance, oxidative stress, non-specific immune response, and gut microbiota. The final weight, FCR, and survival rate of the 25 and 50% BSFL meal variants were observed to perform comparable to the control. Adverse effects on growth, gut morphology, and microbiota were observed when replacing 75% of dietary fishmeal, and at 100% replacement, non-specific immunity and survival rate decreased. The study comes with evidence that BSFL meal can be a sustainable alternative with benefits on microbiota and immunity in crustaceans.

In the case of Chinese soft-shelled turtles (*Pelodiscus sinensis*) raised in Asia for meat that is delicious and has medicinal properties, research by Li et al. [160], where five experimental groups were fed diets with 0.5%, 10%, 15%, and 20% BSFLM, respectively, indicated that the inclusion of 10% and 15% resulted in good antioxidant capacity and nutritional value. The authors followed growth performance, blood biochemistry, antioxidant capacity, and amino acid profile. The results suggest that replacing 10% FM with BSFLM is feasible for Chinese softshell turtles. The analyzed studies on the introduction of meal from *Hermetia illucens* larvae into the feed of aquatic species indicate, however, that the degree of tolerance and nutritional efficiency vary significantly depending on the species and the replacement percentages. While some organisms, such as shrimp and clams, have responded positively to high levels of fishmeal replacement, others, such as crabs or turtles, require lower percentages to avoid negative effects on growth and survival. The obtained results emphasize the need to adapt diets according to the specific requirements of each species, age, as well as the importance of more thorough research on the use of BSFL in aquaculture.

Moreover, nowadays, black soldier fly larvae are already used in poultry diets as a sustainable, nutrient-rich substitute for conventional protein sources such as soybean meal and fishmeal. They provide high levels of protein (42–59%) and essential amino acids, as well as valuable lipids (9–30% ether extract) and energy (5035–5861 kcal/kg), depending on the processing method applied [161]. In addition, BSFL contain bioactive compounds such as chitin and medium-chain fatty acids (e.g., lauric acid), which have been reported to enhance gut health, modulate immune responses, and reduce pathogen load in poultry [162]. Moreover, feeding trials in broilers demonstrated that including full-fat BSFL in diets (up to 20%) improved the feed conversion ratio by about 10% ($p < 0.05$). Interestingly, BSFL inclusion also led to a significant reduction in lymphocytes (−47.7%) and white blood cell counts (−35.9%), with a notable decrease in CD3+ and CD3+CD8+ T lymphocytes at the highest inclusion level [163]. These findings suggest that BSFL not only enhance growth performance but may also influence immune function by reducing energy costs associated with immune responses. Furthermore, post-harvest processing methods play a crucial role in determining the nutritional profile and physical properties of BSFL products. A recent study showed that both the type of larvae (defatted vs. non-defatted) and drying methods (parabola dome, hot-air oven, and microwave) significantly ($p < 0.001$) influenced parameters such as color, bulk density, particle size, crude protein (42–59%), crude fiber (7–14%), ether extract (9–30%), and energy content (5035–5861 kcal/kg). Among these, microwave and hot-air oven drying were found to be the most suitable methods, as they retained higher nutrient levels and improved feed quality compared to traditional drying [161].

Replacing fishmeal with black soldier fly meal may represent a promising strategy for developing sustainable aquaculture, but its effectiveness varies with species, age (juvenile stages may be sensitive to diet changes), inclusion level, and type of insect meal (defatted or non-defatted). The results indicate that omnivorous fish can tolerate higher levels of replacement, while carnivorous species may require lower percentage replacements of fishmeal to avoid affecting growth rate, digestibility, and meat quality.

Therefore, further research is needed to establish what optimal level of BSF flour inclusion is required by species and age but also to improve the nutritional profile and digestibility of this alternative protein source.

5. Impact of BSFL Meal on Fish Meat Quality and Sensory Attributes

Beyond perception, the quality of fish raised on insect-based diets is a key consideration. Stadtlander et al. [164] demonstrated that replacing 50% of fishmeal with *Hermetia illucens* meal (HIM) in rainbow trout diets maintained feed conversion efficiency and growth performance, with minor variations in protein utilization. HIM-fed fish exhibited a slightly darker coloration but retained similar taste and texture compared to those fed traditional fishmeal-based diets. Sealey et al. [165] investigated black soldier fly prepupae as a fishmeal replacement in rainbow trout diets. Their study revealed differences in moisture and lipid content between fish fed BSFL and conventional fishmeal diets. Despite these compositional changes, sensory evaluations conducted with untrained panelists found no significant taste differences. This suggests that while lipid and fatty acid composition influence volatile compounds responsible for aroma and flavor, the inclusion of insect meal does not significantly alter the consumer-perceived sensory quality of fish fillets [166].

The study conducted by Radhakrishnan et al. [167] that BSFL meal can be included at up to 10% in Atlantic salmon diets without negatively affecting fillet quality, validating its potential as a sustainable food ingredient. EPA + DHA levels in salmon fillet were stable. Sensory evaluation by members of the untrained group showed no significant differences in overall liking between the diet groups. The study also found that the color of salmon fillets fed BSFL meal did not differ significantly from those fed the control diet. However, the 10% BSFL group was associated with attributes such as rancid taste and sour odor.

The inclusion of black soldier fly larvae meal in aquafeeds has also been shown to positively impact the quality of fish products. For instance, in rainbow trout (*Oncorhynchus mykiss*), dietary supplementation of BSFL meal did not impair the fillet quality, guaranteeing its nutritional value [168]. Additionally, BSFL meal inclusion in the diet of Atlantic salmon (*Salmo salar*) did not compromise the physico-chemical quality of the fillets, maintaining the nutritional profile and sensory attributes [169]. In European sea bass (*Dicentrarchus labrax*), BSFL meal supplementation improved the fillet quality traits during shelf life, including color and fatty acid profile [170].

In a study, Herve et al. [171] analyzed the influence of food-grade larvae on the meat quality of *Clarias gariepinus* by replacing fishmeal with diets containing 0, 50, 75, and 100% BSFLM. Consumers who participated in the study rated the taste of the fish as good in all diets, except for the 75% BSFLM diet, where 49% of the participants indicated a pleasant taste. Among the tasters, 37.5% rated the fish fed with commercial feed as bad. The catfish meat was generally rated as very juicy by most tasters, except for the control diet (which contained local feed containing 100% fishmeal), which was rated as unpalatable. Overall, acceptability was high, with all group members unanimously rating the fish in the diet at 75% BSFLM for its overall quality.

A company in Denmark conducted a study in collaboration with the Norwegian University of Life Sciences and Austevoll Melaks AS, a Norwegian salmon producer, in which they compared a conventional diet with a diet in which soybean meal was replaced

with 4% insect meal. In addition to the growth performance obtained, the studies showed that the BSFL-enriched diet positively affected the texture and quality of the salmon fillet. Following sensory tests, it was found that 67% of consumers preferred the taste of salmon fed with 4% BSFL [172].

6. Consumer Attitudes and Acceptance

Consumer perception plays an essential role in the adoption of insect meal as an alternative protein source in aquaculture, Roccatello et al. [173] conducted a study involving 303 participants to assess consumer attitudes toward fish products derived from insect-fed fish. The study found that sustainability awareness and knowledge of insect-based feed benefits significantly influenced acceptance levels. Participants who demonstrated higher awareness and understanding of the environmental advantages of insect-based feeds were more likely to accept these products. Conversely, factors such as age, dietary habits, and food neophobia were identified as barriers to acceptance. The study further revealed that providing consumers with clear, science-based information improved their willingness to accept fish raised on insect meal-based diets. A key finding was that respondents who answered positively to general knowledge questions about aquaculture and sustainability showed greater agreement with statements like “The use of insect-based feed makes the aquaculture sector more sustainable.” Additionally, these consumers placed higher importance on feed quality and food safety when evaluating fish products. Despite these positive attitudes, the use of insect meal in fish feed remains unconventional in the minds of many consumers, particularly in European markets, where limited studies have explored public perceptions [174–176].

7. Advantages and Disadvantage of Using Insect Meal

7.1. Advantages

Table 6 presents the main advantages of using insect meal in animal nutrition, highlighting both environmental and nutritional benefits. This alternative protein source is part of the global trend of transition towards more sustainable and efficient agri-food practices.

However, it is important to emphasize that the effectiveness of these advantages depends on different factors such as the type of *Hermetia illucens* meal (defatted or non-defatted), the growth substrate, the level of inclusion in the diet, age, and target species. For example, the positive effects of chitin can be reversed at high concentrations, affecting digestibility. Also, production costs, the legal framework, and acceptability by beneficiaries remain key variables in the large-scale adoption of these ingredients.

Economic and environmental assessments of black soldier fly larvae meal highlight both opportunities and challenges for its broader application in aquaculture. At the farm level, inclusion of BSFL meal has been shown to improve growth performance, feed efficiency, and profitability in multiple species. For instance, in Siberian sturgeon, diets containing 10–15% BSFL were the most lucrative, improving feed utilization and reducing the fish-in–fish-out ratio by up to 75%, despite the higher ingredient cost [177]. Similarly, studies on Nile tilapia fry demonstrated that replacing 75% of fishmeal with BSFL lowered feed costs by nearly 32% and increased the profit index by 3.97%, with optimal growth predicted at 81–84% BSFL inclusion [178]. In Kenya, socio-economic analysis revealed that a 50% replacement level achieved an 8.94% reduction in feed cost per kilogram of fish produced, though awareness and adoption among farmers remain limited, with attitudes and perceived usefulness being the strongest predictors of uptake [179]. At a broader scale, the socio-economic balance of insect meal production remains negative under current conditions due to high processing and investment costs, but is expected to improve with industrial upscaling, technological advances, and shifting nutrient market

values [180]. Cost estimates for BSFL meal are currently around EUR 3.5 per kg, but projections suggest that large-scale automation could reduce this below EUR 2 per kg, improving competitiveness while also valorizing biowaste and generating co-products such as frass [181]. Life-Cycle Assessment (LCA) studies further show that while BSFL protein may have a higher climate footprint per kilogram of protein than fishmeal or soybean meal, it requires substantially less land and delivers significant benefits in food waste management, achieving net negative emissions of -24.8 kg CO₂ eq per ton of waste treated [182]. In conclusion, the advantages of insect meal are real, but for practical applicability, a thorough analysis is required that takes into account both the environmental impact and economic profitability.

Table 6. Advantages.

Benefits	References
Using insects as a source of protein can help protect marine resources and reduce overfishing.	[183]
BSFL has high nutritional value, as insects are rich in protein, essential amino acids, and other nutrients necessary for optimal fish growth.	[184]
Insect meal, in particular from the larvae of <i>Hermetia illucens</i> , contains high amounts of lauric acid, which is why it is increasingly used in fish feed, stimulating both growth and the immune system. It is a quick source of energy that is easily metabolized, which can help convert feed more efficiently. It also has antimicrobial properties, contributing to the intestinal health of the fish and reducing the risk of infection, which is a plus in aquaculture, where high stocking densities are practiced and disease prevention is essential.	[185,186]
Studies show that it has high digestibility, over 92%.	[187]
BSFL ensures efficient feed conversion, with insects efficiently converting consumed feed into biomass, thus contributing to environmental protection.	[188]
BSF larvae consume organic waste from the food industry as well as from agriculture, thus reducing its volume by up to 80%. This can be an effective solution for reducing organic waste, especially in countries with lower living standards.	[189]
Insects can be grown on various organic wastes, turning them into valuable resources, reducing the need for land, water, and energy.	[183,188]
Insect production has a lower carbon footprint compared to traditional livestock farming.	[190]
Insect meal can be cheaper due to their short life cycle and their ability to utilize accessible and inexpensive resources.	[191]
The nutritional composition of insect meal can be adjusted by changing the insect diet during a growing cycle. Also, chitin is a constituent of the exoskeleton of insects, and studies show that it can stimulate the immune system in animals consuming feed containing insect meal. Chitin increases the body's resistance to the attack of pathogens and can increase immunity.	[192–194]

7.2. Disadvantage

Despite the many advantages, the use of insect meal can also have some negative aspects. Insect meals contain a lot of chitin, which can negatively influence digestion and the absorption of nutrients [123].

Additionally, non-defatted BSF maggot meal has been linked to liver steatosis in some studies [195,196]. Therefore, some research recommends defatted BSFL to replace FM in animal feed.

Its amino acid composition is not completely balanced, with deficiencies in essential amino acids such as methionine, lysine, or tryptophan. These compounds are necessary for healthy growth and maintenance of an adequate state of health. For this reason, the introduction of *Hermetia illucens* meal into feed requires supplementation with essential amino acids to prevent nutritional imbalances and to ensure performance comparable to that obtained from conventional proteins.

There are global concerns regarding food safety, processing hygiene, and possible contamination during production chains. To encourage the use of insects as a food source, researchers propose standardization of growing and processing processes as well as effective promotion strategies to increase food safety [197].

Another inconvenience could be related to the degree of consumer acceptance of the consumption of fish meat fed with diets containing different concentrations of BSFL, but this shortcoming could be removed by in-depth studies that highlight the safety of consumption and the positive impact on fish growth.

8. Regulation

In the European Union, proteins derived from insects were allowed as ingredients for pet food (dogs, cats, birds, or reptiles) and for fur animals (mink). In 2017, authorization was also issued for the use of insects as food for fish, according to Regulation no. 2001/999 (annex IV), amended by Regulation 2017/893 (annex X) (Regulation-2017/893-EN-EUR-Lex, 2025). It allows for the use of proteins from seven insect species—black soldier fly (*Hermetia illucens*), common housefly (*Musca domestica*), yellow mealworm (*Tenebrio molitor*), and crickets (*Acheta domesticus*, *Gryllus assimilis*, and *Gryllodes sigillatus*)—in the feed of aquaculture animals, birds, and pigs.

In November 2021, as part of EU legislation on animal by-products (Regulation (EU) 2021/1925), the use of processed animal protein (PAP) of silkworms (*Bombyx mori*) in aquaculture, poultry, and pig feed was authorized, expanding the list from seven to eight authorized species.

Regarding the nature of the substrates allowed for larvae grow, in the European Union (EU), insect farmers are subjected to strict regulations that classify insects as farm animals. These regulations prohibit the use of animal by-products as a substrate for the growth of insects, limiting them to waste from the agri-food industry. This limitation derives from the concerns of the authorities regarding the possible occurrence of problems of a microbiological nature. In conclusion, insect farmers cannot use post-consumer waste streams such as catering waste or household food waste, which are more environmentally sustainable and could provide sufficient food sources for large-scale insect production [198].

In the USA, black soldier fly meal is allowed since 2018 for use according to the Association of American Feed Control Officials (AAFCO). It has agreed with Enterra Feed Corporation to use BSFL meal from larvae reared on food scraps in the salmonid feed.

Regarding the African continent, there is not necessarily a legislative framework, with the authorities preferring to rely on international legislation (FAO and WHO), but nevertheless, there are studies and attempts to promote the use of BSFL in animal feed. For

example, a Cape Town company, Agriprotein, produces BSF maggots for fish, chicken, and pig feed [199].

9. Conclusions

Insects are a quality protein source because they have a well-balanced nutritional profile, provide essential amino acid requirements for animal organisms, and are rich in polyunsaturated fatty acids, vitamins, and minerals. Insect meal may have a more stable cost due to the controlled production method and availability of raw materials compared to fishmeal, which has fluctuating prices due to reduced availability.

Even though BSF meal has some characteristics that make it a good ingredient for fish feed, it does not match the nutritional value of fishmeal, but it can be a good competitor (especially when supplemented with certain amino acids that BSF meal has that are present in limited quantities compared to FM), particularly in underdeveloped countries without access to the sea, where fishmeal is expensive.

More research and data are needed on carbon emissions, energy, and water consumption involved in insect farming technologies. In order to produce insects on an industrial scale, it is necessary to improve the farming facilities for automated and economically efficient production processes.

It is also absolutely necessary to develop a plan of hygiene measures and sanitary standards to prevent diseases and contamination with pathogens during the growing process. It is necessary to develop reliable methods of preparation and preservation to ensure the safety of feed, including the inactivation of intestinal microbiota.

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References

1. Tidwell, J.H.; Allan, G.L. Fish as Food: Aquaculture's Contribution. *EMBO Rep.* **2001**, *2*, 958–963. [CrossRef] [PubMed]
2. Simeanu, C.; Simeanu, D.; Popa, A.; Usturoi, A.; Bodescu, D.; Dolis, M.G. Research Regarding Content in Amino-Acids and Biological Value of Proteins from Polyodon Spathula Sturgeon Meat. *Rev. Chim.* **2017**, *68*, 1063–1069. [CrossRef]
3. FAO Report: Global Fisheries and Aquaculture Production Reaches a New Record High. Available online: <https://www.fao.org/newsroom/detail/fao-report-global-fisheries-and-aquaculture-production-reaches-a-new-record-high/en> (accessed on 5 June 2025).
4. Kumar, L.; Chhogyel, N.; Gopalakrishnan, T.; Hasan, M.K.; Jayasinghe, S.L.; Kariyawasam, C.S.; Kogo, B.K.; Ratnayake, S. Chapter 4—Climate Change and Future of Agri-Food Production. In *Future Foods*; Bhat, R., Ed.; Academic Press: San Diego, CA, USA, 2022; pp. 49–79, ISBN 978-0-323-91001-9.
5. Gil, M.; Rudy, M.; Duma-Kocan, P.; Stanisławczyk, R.; Krajewska, A.; Dziki, D.; Hassoon, W.H. Sustainability of Alternatives to Animal Protein Sources, a Comprehensive Review. *Sustainability* **2024**, *16*, 7701. [CrossRef]
6. Henchion, M.; Hayes, M.; Mullen, A.M.; Fenelon, M.; Tiwari, B. Future Protein Supply and Demand: Strategies and Factors Influencing a Sustainable Equilibrium. *Foods* **2017**, *6*, 53. [CrossRef]
7. Péron, G.; Mittaine, J.F.; Gallic, B.L. Where Do Fishmeal and Fish Oil Products Come from? An Analysis of the Conversion Ratios in the Global Fishmeal Industry. *Mar. Policy* **2010**, *34*, 815–820. [CrossRef]

8. Hussain, S.M.; Bano, A.A.; Ali, S.; Rizwan, M.; Adrees, M.; Zahoor, A.F.; Sarker, P.K.; Hussain, M.; Arsalan, M.Z.-H.; Yong, J.W.H.; et al. Substitution of Fishmeal: Highlights of Potential Plant Protein Sources for Aquaculture Sustainability. *Heliyon* **2024**, *10*, e26573. [CrossRef]
9. Majluf, P.; Matthews, K.; Pauly, D.; Skerrett, D.J.; Palomares, M.L.D. A Review of the Global Use of Fishmeal and Fish Oil and the Fish In: Fish Out Metric. *Sci. Adv.* **2024**, *10*, eadn5650. [CrossRef]
10. Pauly, D.; Zeller, D. Catch Reconstructions Reveal That Global Marine Fisheries Catches Are Higher than Reported and Declining. *Nat. Commun.* **2016**, *7*, 10244. [CrossRef]
11. IFFO 2024. Available online: www.iffco.com/iffos-estimates-2023-fishmeal-and-fish-oil-production-and-insights-2024 (accessed on 4 June 2025).
12. Naylor, R.L.; Hardy, R.W.; Bureau, D.P.; Chiu, A.; Elliott, M.; Farrell, A.P.; Forster, I.; Gatlin, D.M.; Goldberg, R.J.; Hua, K.; et al. Feeding Aquaculture in an Era of Finite Resources. *Proc. Natl. Acad. Sci. USA* **2009**, *106*, 15103–15110. [CrossRef]
13. Daniel, N. A Review on Replacing Fish Meal in Aqua Feeds Using Plant Protein Sources. *Int. J. Fish. Aquat. Stud.* **2018**, *6*, 164–179.
14. Abd El-Hack, M.E.; Shafi, M.E.; Alghamdi, W.Y.; Abdelnour, S.A.; Shehata, A.M.; Noreldin, A.E.; Ashour, E.A.; Swelum, A.A.; Al-Sagan, A.A.; Alkhateeb, M.; et al. Black Soldier Fly (*Hermetia illucens*) Meal as a Promising Feed Ingredient for Poultry: A Comprehensive Review. *Agriculture* **2020**, *10*, 339. [CrossRef]
15. Tacon, A.G.J.; Metian, M. Feed Matters: Satisfying the Feed Demand of Aquaculture. *Rev. Fish. Sci. Aquac.* **2015**, *23*, 1–10. [CrossRef]
16. Kenny, T.A.; Woodside, J.V.; Perry, I.J.; Harrington, J.M. Consumer Attitudes and Behaviors toward More Sustainable Diets: A Scoping Review. *Nutr. Rev.* **2023**, *81*, 1665–1679. [CrossRef] [PubMed]
17. Serra, V.; Pastorelli, G.; Tedesco, D.E.A.; Turin, L.; Guerrini, A. Alternative Protein Sources in Aquafeed: Current Scenario and Future Perspectives. *Vet. Anim. Sci.* **2024**, *25*, 100381. [CrossRef] [PubMed]
18. Desouky, A.; Hwihi, H.; Shaban, W.; Azab, A. Evaluating of Pea Peels Meal as a Fishmeal Alternative in Formulated Diet Ingredients of *Oreochromis Niloticus*. *Egypt. J. Aquat. Biol. Fish.* **2023**, *27*, 725–737. [CrossRef]
19. Hernández, C.; Lizárraga-Velázquez, C.E.; Contreras-Rojas, D.; Sánchez-Gutiérrez, E.Y.; Martínez-Montaña, E.; Ibarra-Castro, L.; Peña-Marín, E.S. Fish Meal Replacement by Corn Gluten in Feeds for Juvenile Spotted Rose Snapper (*Lutjanus guttatus*): Effect on Growth Performance, Feed Efficiency, Hematological Parameters, Protease Activity, Body Composition, and Nutrient Digestibility. *Aquaculture* **2021**, *531*, 735896. [CrossRef]
20. Howlader, S.; Sumi, K.R.; Sarkar, S.; Billah, S.M.; Ali, M.L.; Howlader, J.; Shahjahan, M. Effects of Dietary Replacement of Fish Meal by Soybean Meal on Growth, Feed Utilization, and Health Condition of Stinging Catfish, *Heteropneustes Fossilis*. *Saudi J. Biol. Sci.* **2023**, *30*, 103601. [CrossRef]
21. Kaiser, F.; Harbach, H.; Schulz, C. Rapeseed Proteins as Fishmeal Alternatives: A Review. *Rev. Aquac.* **2022**, *14*, 1887–1911. [CrossRef]
22. Tan, B.; Mai, K.; Zheng, S.; Zhou, Q.; Liu, L.; Yu, Y. Replacement of Fish Meal by Meat and Bone Meal in Practical Diets for the White Shrimp *Litopenaeus vannamei* (Boone). *Aquac. Res.* **2005**, *36*, 439–444. [CrossRef]
23. Barbacariu, C.-A.; Dîrvari, L.; Șerban, D.A.; Rîmbu, C.M.; Horhoge, C.E.; Dumitru, G.; Todirașcu-Ciornea, E.; Lungoci, C.; Burducea, M. Evaluating the Use of Grape Pomace in *Cyprinus carpio* Nutrition: Effects on Growth, Biochemistry, Meat Quality, Microbiota, and Oxidative Status. *Fishes* **2024**, *9*, 219. [CrossRef]
24. Barbacariu, C.-A.; Rîmbu, C.M.; Dîrvari, L.; Burducea, M.; Boiangiu, R.S.; Todirașcu-Ciornea, E.; Dumitru, G. Evaluation of DDGS as a Low-Cost Feed Ingredient for Common Carp (*Cyprinus Carpio* Linneus) Cultivated in a Semi-Intensive System. *Life* **2022**, *12*, 1609. [CrossRef]
25. Glencross, B.; Huyben, D.; Schrama, J. The Application of Single-Cell Ingredients in Aquaculture Feeds—A Review. *Fishes* **2020**, *5*, 22. [CrossRef]
26. Kumar, V.; Lee, S.; Cleveland, B.M.; Romano, N.; Lalgudi, R.S.; Benito, M.R.; McGraw, B.; Hardy, R.W. Comparative Evaluation of Processed Soybean Meal (EnzoMeal™) vs. Regular Soybean Meal as a Fishmeal Replacement in Diets of Rainbow Trout (*Oncorhynchus Mykiss*): Effects on Growth Performance and Growth-Related Genes. *Aquaculture* **2020**, *516*, 734652. [CrossRef]
27. Oteri, M.; Di Rosa, A.R.; Lo Presti, V.; Giarratana, F.; Toscano, G.; Chiofalo, B. Black Soldier Fly Larvae Meal as Alternative to Fish Meal for Aquaculture Feed. *Sustainability* **2021**, *13*, 5447. [CrossRef]
28. Rahimnejad, S.; Hu, S.; Song, K.; Wang, L.; Lu, K.; Wu, R.; Zhang, C. Replacement of Fish Meal with Defatted Silkworm (*Bombyx Mori* L.) Pupae Meal in Diets for Pacific White Shrimp (*Litopenaeus Vannamei*). *Aquaculture* **2019**, *510*, 150–159. [CrossRef]
29. Gu, J.; Liang, H.; Ge, X.; Xia, D.; Pan, L.; Mi, H.; Ren, M. A Study of the Potential Effect of Yellow Mealworm (*Tenebrio Molitor*) Substitution for Fish Meal on Growth, Immune and Antioxidant Capacity in Juvenile Largemouth Bass (*Micropterus Salmoides*). *Fish Shellfish Immunol.* **2022**, *120*, 214–221. [CrossRef] [PubMed]
30. Okoye, F.C.; Nnaji, J. Effects of Substituting Fish Meal with Grasshopper Meal on Growth and Food Utilization of the Nile Tilapia, *Oreochromis Niloticus* Fingerlings. 2005. Available online: <https://www.researchgate.net/publication/277161891> (accessed on 1 August 2025).

31. Perera, G.S.C.; Bhujel, R.C. Replacement of Fishmeal by House Cricket (*Acheta Domesticus*) and Field Cricket (*Gryllus Bimaculatus*) Meals: Effect for Growth, Pigmentation, and Breeding Performances of Guppy (*Poecilia Reticulata*). *Aquac. Rep.* **2022**, *25*, 101260. [CrossRef]
32. Saleh, H. Review on Using of Housefly Maggots (*Musca Domestica*) in Fish Diets. *J. Zool. Res.* **2020**, *2*, 39–46. [CrossRef]
33. Arru, B.; Furesi, R.; Gasco, L.; Madau, F.A.; Pulina, P. The Introduction of Insect Meal into Fish Diet: The First Economic Analysis on European Sea Bass Farming. *Sustainability* **2019**, *11*, 1697. [CrossRef]
34. Huis, A. Potential of Insects as Food and Feed in Assuring Food Security. *Annu. Rev. Entomol.* **2012**, *58*, 563–583. [CrossRef]
35. Chia, S.Y. Black Soldier Fly Larvae as a Sustainable Animal Feed Ingredient in Kenya. Ph.D. Thesis, Wageningen University and Research, Wageningen, The Netherlands, 2021.
36. Shumo, M.; Khamis, F.; Subramanian, S.; Ekesi, S.; Fiaboe, K.; Borgemeister, C.; Huis, A.; Osuga, I. The Nutritive Value of Black Soldier Fly Larvae Reared on Common Organic Waste Streams in Kenya. *Sci. Rep.* **2019**, *9*, 10110. [CrossRef]
37. Hamid, N.; Zakaria, N.; Ali, N. Study on Utilization of Black Soldier Fly Larvae (*Hermetia illucens*) as Protein Substitute in the Pellet Diet of Clarias Gariepinus Fingerling. *Adv. Agric. Food Res. J.* **2021**, *3*, 1–6. [CrossRef]
38. Fahmi, M.; Nurjanah, N.; Sudadi, A.; Adanitri, G.; Melisza, N. The Nutrient Content of Nile Tilapia Fed with Black Soldier Fly (BSF) Larvae. *Aquac. Aquar. Conserv. Legis.* **2021**, *14*, 2718–2727.
39. Lin, F.Y.; Li, A. A Primer on the Black Soldier Fly Market in Asia. 2021. Available online: <https://www.manaimpact.com/post/a-primer-on-the-black-soldier-fly-market-in-asia> (accessed on 2 June 2025).
40. Tomberlin, J.K.; Van Huis, A. Black Soldier Fly from Pest to ‘Crown Jewel’ of the Insects as Feed Industry: An Historical Perspective. *J. Insects Food Feed.* **2020**, *6*, 1–4. [CrossRef]
41. Raghuvanan, N.; Varghese, T.; Jana, P.; Angela Brightly, R.J.; Sethupathy, A.M.; Sudarshan, S.; Alrashdi, Y.B.A.; Ibrahim, A.E.; El Deeb, S. Current Status and Global Research Trend Patterns of Insect Meal in Aquaculture from Scientometric Perspective: (2013–2022). *Aquac. Nutr.* **2024**, *2024*, 5466604. [CrossRef] [PubMed]
42. Sprangers, T.; Ottoboni, M.; Klootwijk, C.; Olyn, A.; Deboosere, S.; Meulenaer, B.; Michiels, J.; Eeckhout, M.; De Clercq, P.; De Smet, S. Nutritional Composition of Black Soldier Fly (*Hermetia illucens*) Prepupae Reared on Different Organic Waste Substrates. *J. Sci. Food Agric.* **2017**, *97*, 2594–2600. [CrossRef]
43. Moyo, S.; Moyo, B. Potential Utilization of Insect Meal as Livestock Feed. In *Animal Feed Science and Nutrition: Production, Health and Environment*; IntechOpen: London, UK, 2022; ISBN 978-1-83969-860-6.
44. Caruso, D.; Devic, E.; Subamia, I.; Talamond, P.; Baras, E. *Technical Handbook of Domestication and Production of Diptera Black Soldier Fly (BSF) Hermetia illucens, Stratiomyidae*; IPB Press: Bogor, Indonesia, 2013; ISBN 978-979-493-610-8.
45. Jeyaprakashabari, S.; Aanand, S. Black Soldier Fly Larvae Meal in Fish Culture. *AgriCos E-Newsl.* **2022**, *2*, 52–56. [CrossRef]
46. Diener, S.; Zurbrugg, C.; Tockner, K. Conversion of Organic Material by Black Soldier Fly Larvae: Establishing Optimal Feeding Rates. *Waste Manag. Res. J. Int. Solid Wastes Public Clean. Assoc. ISWA* **2009**, *27*, 603–610. [CrossRef]
47. Loho, L.; Lo, D. Proximate and Fatty Acid Analysis of Black Soldier Fly Larvae (*Hermetia illucens*). *IOP Conf. Ser. Earth Environ. Sci.* **2023**, *1169*, 012082. [CrossRef]
48. Lalander, C.; Fidjeland, J.; Diener, S.; Eriksson, S.; Vinnerås, B. High Waste-to-Biomass Conversion and Efficient *Salmonella* Spp. Reduction Using Black Soldier Fly for Waste Recycling. *Agron. Sustain. Dev.* **2014**, *35*, 261–271. [CrossRef]
49. Veldkamp, T.; Van Duinkerken, G.; Van Huis, A.; Lakemond, C.M.M.; Ottevanger, E.; Bosch, G.; Van Boekel, T. *Insects as a Sustainable Feed Ingredient in Pig and Poultry Diets: A Feasibility Study = Insecten Als Duurzame Diervoergrondstof in Varkens-En Pluimveevoeders: Een Haalbaarheidsstudie*; Report 638; Wageningen UR Livestock Research, Part of Stichting Dienst Landbouwkundig Onderzoek (DLO Foundation): Wageningen, The Netherlands, 2012; ISSN 1570–8616.
50. Williams, J.P.; Williams, J.R.; Kirabo, A.; Chester, D.; Peterson, M. Nutrient Content and Health Benefits of Insects. In *Insects as Sustainable Food Ingredients*; Academic Press: San Diego, CA, USA, 2016; pp. 61–84, ISBN 978-0-12-802856-8.
51. Schiavone, A.; Marco, M.; Martinez, S.; Dabbou, S.; Renna, M.; Madrid, J.; Hernandez, F.; Rotolo, L.; Costa, P.; Gai, F.; et al. Nutritional Value of a Partially Defatted and a Highly Defatted Black Soldier Fly Larvae (*Hermetia illucens* L.) Meal for Broiler Chickens: Apparent Nutrient Digestibility, Apparent Metabolizable Energy and Apparent Ileal Amino Acid Digestibility. *J. Anim. Sci. Biotechnol.* **2017**, *8*, 51. [CrossRef]
52. Halloran, A.; Flore, R.; Vantomme, P.; Roos, N. *Edible Insects in Sustainable Food Systems*; Springer: Berlin/Heidelberg, Germany, 2018. [CrossRef]
53. Fish Meal, Protein 65% | Tables of Composition and Nutritional Values of Feed Materials INRA CIRAD AFZ. Available online: <https://www.feedtables.com/content/fish-meal-protein-65> (accessed on 4 June 2025).
54. Black Soldier Fly Larvae, Fat > 20%, Dried | Tables of Composition and Nutritional Values of Feed Materials INRA CIRAD AFZ. Available online: <https://www.feedtables.com/content/black-soldier-fly-larvae-fat-20-dried-0> (accessed on 4 June 2025).
55. Mahmoud, A.E.; Morel, P.C.H.; Potter, M.A.; Ravindran, V. The Apparent Metabolizable Energy and Ileal Amino Digestibility of Black Soldier Fly (*Hermetia illucens*) Larvae Meal for Broiler Chickens. *Br. Poult. Sci.* **2023**, *64*, 377–383. [CrossRef]

56. Alfiko, Y.; Xie, D.; Astuti, R.T.; Wong, J.; Wang, L. Insects as a Feed Ingredient for Fish Culture: Status and Trends. *Aquac. Fish.* **2022**, *7*, 166–178. [\[CrossRef\]](#)
57. Zulkifli, N.F.N.M.; Seok-Kian, A.Y.; Seng, L.L.; Mustafa, S.; Kim, Y.-S.; Shapawi, R. Nutritional Value of Black Soldier Fly (*Hermetia illucens*) Larvae Processed by Different Methods. *PLoS ONE* **2022**, *17*, e0263924. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Sándor, Z.J.; Banjac, V.; Vidosavljević, S.; Káldy, J.; Egessa, R.; Lengyel-Kónya, É.; Tömösközi-Farkas, R.; Zalán, Z.; Adányi, N.; Libisch, B.; et al. Apparent Digestibility Coefficients of Black Soldier Fly (*Hermetia illucens*), Yellow Mealworm (*Tenebrio Molitor*), and Blue Bottle Fly (*Calliphora Vicina*) Insects for Juvenile African Catfish Hybrids (*Clarias Gariepinus* × *Heterobranchus Longifilis*). *Aquac. Nutr.* **2022**, *2022*, 4717014. [\[CrossRef\]](#)
59. Riekkinen, K.; Väkeväinen, K.; Korhonen, J. The Effect of Substrate on the Nutrient Content and Fatty Acid Composition of Edible Insects. *Insects* **2022**, *13*, 590. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Laganaro, M.; Bahrndorff, S.; Eriksen, N.T. Growth and Metabolic Performance of Black Soldier Fly Larvae Grown on Low and High-Quality Substrates. *Waste Manag.* **2021**, *121*, 198–205. [\[CrossRef\]](#)
61. Wamboga, M.; Musinguzi, S.P.; Tinzaara, W.; Echaku, S. Effect of Types and Quantities of Substrates on Growth Performance of Black Soldier Fly Larvae (*Hermetia illucens*). *J. Exp. Agric. Int.* **2025**, *47*, 263–270. [\[CrossRef\]](#)
62. Holeh, G.; Opiyo, M.; Brown, C.; Sumbule, E.; Gatagwu, J.; Oje, E.; Munyi, F. Effect of Different Waste Substrates on the Growth, Development and Proximate Composition of Black Soldier Fly (*Hermetia illucens*) Larvae. *Livest. Res. Rural. Dev.* **2022**, *34*, 1–11.
63. Hosseindoust, A.; Ha, S.H.; Mun, J.Y.; Kim, J.S. A Metanalysis to Evaluate the Effects of Substrate Sources on the Nutritional Performance of Black Soldier Fly Larvae: Implications for Sustainable Poultry Feed. *Poult. Sci.* **2024**, *103*, 103299. [\[CrossRef\]](#)
64. Vodounnou, J.V.; Iko, R.; Okou, G.; Kpogue, D.; Montcho, S.A.; Micha, J.-C. Complete Substitution of Fish Meal with Black Soldier Flies *Hermetia illucens* (L. 1758) Larvae Meal at Varying Incorporation Rates for Feeding *Oreochromis Niloticus* Raised in Captivity. *Aquac. Sci. Manag.* **2025**, *2*, 1. [\[CrossRef\]](#)
65. Kanjanarat, K.; Laksanawimol, P.; Lersawhanwaree, J.; Khan, S.; Thancharoen, A. Utilizing Spent Mushroom Substrate for Rearing Black Soldier Fly (*Hermetia illucens*) Larvae: Enhancing Fertilizer Efficiency and Improving Animal Feed Quality for Sustainable Agriculture. *PeerJ* **2025**, *13*, e19590. [\[CrossRef\]](#) [\[PubMed\]](#)
66. Weko, M.; Bao, F.; Ega, M.; Mia, H.; Una, K.; Viana, M.; Wale, L.; Nalle, C.; Burithnaban, Y.; Lema, A.; et al. Nutrient Profile Black Soldier Fly Larvae (*Hermetia Illucens*): Effect of Feeding Substrate and Harvested Time. *Biotropia* **2023**, *30*, 297–307. [\[CrossRef\]](#)
67. Rossi, G.; Ojha, S.; Müller-Belecke, A.; Schlüter, O. Fresh Aquaculture Sludge Management with Black Soldier Fly (*Hermetia illucens* L.) Larvae: Investigation on Bioconversion Performances. *Sci. Rep.* **2023**, *13*, 20982. [\[CrossRef\]](#) [\[PubMed\]](#)
68. Abduh, M.Y.; Perdana, M.P.; Bara, M.A.; Anggraeni, L.W.; Putra, R.E. Effects of Aeration Rate and Feed on Growth, Productivity and Nutrient Composition of Black Soldier Fly (*Hermetia illucens* L.) Larvae. *J. Asia-Pac. Entomol.* **2022**, *25*, 101902. [\[CrossRef\]](#)
69. Somarny, W.W.M.Z.; Kuppusamy, G.; Samat, N.; Azam Ali, S. Performance of Black Soldier Fly Larvae (*Hermetia illucens* L.) on Different Feed Substrates. *J. Insects Food Feed.* **2023**, *10*, 345–358. [\[CrossRef\]](#)
70. Barragán-Fonseca, K.; Dicke, M.; van Loon, J. Nutritional Value of the Black Soldier Fly (*Hermetia illucens* L.) and Its Suitability as Animal Feed. *J. Insects Food Feed* **2017**, *3*, 105–120. [\[CrossRef\]](#)
71. Oonincx, D.; Broekhoven, S.; Huis, A.; van Loon, J. Feed Conversion, Survival and Development, and Composition of Four Insect Species on Diets Composed of Food By-Products. *PLoS ONE* **2015**, *10*, e0144601. [\[CrossRef\]](#)
72. Ijdema, F.; Lievens, S.; Smets, R.; Poma, G.; Borght, M.V.D.; Lievens, B.; Smet, J.D. Modulating the Fatty Acid Composition of Black Soldier Fly Larvae via Substrate Fermentation. *Animal* **2025**, *19*, 101383. [\[CrossRef\]](#)
73. Boafu, H.; Gbemavo, C.; Timpong-Jones, E.; Eziah, V.; Billah, M.; Chia, S.Y.; Aidoo, O.; Clottey, V.; Kenis, M. Substrates Most Preferred for Black Soldier Fly *Hermetia illucens* (Linnaeus, 1758) (Diptera: Stratiomyidae) Oviposition Are Not the Most Suitable for Their Larval Development. *J. Insects Food Feed* **2022**, *9*, 183–192. [\[CrossRef\]](#)
74. Jucker, C.; Erba, D.; Leonardi, M.G.; Lupi, D.; Savoldelli, S. Assessment of Vegetable and Fruit Substrates as Potential Rearing Media for *Hermetia illucens* (Diptera: Stratiomyidae) Larvae. *Environ. Entomol.* **2017**, *46*, 1415–1423. [\[CrossRef\]](#) [\[PubMed\]](#)
75. Ahmad, I.; Mohamed, Z.; Amrul, N.; Quan, C.; Jalil, N.; Basri, N.; Azmi, M.R. Composting Fruit and Vegetable Waste Using Black Soldier Fly Larvae. *J. Kejuruter.* **2021**, *33*, 837–843. [\[CrossRef\]](#)
76. Makkar, H.P.S.; Tran, G.; Heuzé, V.; Ankers, P. State-of-the-Art on Use of Insects as Animal Feed. *Anim. Feed. Sci. Technol.* **2014**, *197*, 1–33. [\[CrossRef\]](#)
77. Lu, S.; Taethaisong, N.; Meethip, W.; Surakhunthod, J.; Sinpru, B.; Sroichak, T.; Archa, P.; Thongpea, S.; Paengkoum, S.; Purba, R.A.P.; et al. Nutritional Composition of Black Soldier Fly Larvae (*Hermetia illucens* L.) and Its Potential Uses as Alternative Protein Sources in Animal Diets: A Review. *Insects* **2022**, *13*, 831. [\[CrossRef\]](#)
78. Kawasaki, K.; Hashimoto, Y.; Hori, A.; Kawasaki, T.; Hirayasu, H.; Iwase, S.; Hashizume, A.; Ido, A.; Miura, C.; Miura, T.; et al. Evaluation of Black Soldier Fly (*Hermetia illucens*) Larvae and Pre-Pupae Raised on Household Organic Waste, as Potential Ingredients for Poultry Feed. *Animals* **2019**, *9*, 98. [\[CrossRef\]](#)
79. Espe, M.; Adam, A.C.; Saito, T.; Skjærven, K.H. Methionine: An Indispensable Amino Acid in Cellular Metabolism and Health of Atlantic Salmon. *Aquac. Nutr.* **2023**, *2023*, 5706177. [\[CrossRef\]](#)

80. Wang, W.; Yang, P.; He, C.; Chi, S.; Li, S.; Mai, K.; Song, F. Effects of Dietary Methionine on Growth Performance and Metabolism through Modulating Nutrient-Related Pathways in Largemouth Bass (*Micropterus Salmoides*). *Aquac. Rep.* **2021**, *20*, 100642. [\[CrossRef\]](#)
81. Wang, L.; Gao, C.; Wang, B.; Wang, C.; Sagada, G.; Yan, Y. Methionine in Fish Health and Nutrition: Potential Mechanisms, Affecting Factors, and Future Perspectives. *Aquaculture* **2023**, *568*, 739310. [\[CrossRef\]](#)
82. Elesho, F.E.; Sutter, D.A.H.; Swinkels, M.A.C.; Verreth, J.A.J.; Kröckel, S.; Schrama, J.W. Quantifying Methionine Requirement of Juvenile African Catfish (*Clarias Gariepinus*). *Aquaculture* **2021**, *532*, 736020. [\[CrossRef\]](#)
83. Schwarz, F.J.; Kirchgessner, M.; Deuringer, U. Studies on the Methionine Requirement of Carp (*Cyprinus carpio* L.). *Aquaculture* **1998**, *161*, 121–129. [\[CrossRef\]](#)
84. Kim, K.-I.; Kayes, T.B.; Amundson, C.H. Requirements for Sulfur Amino Acids and Utilization of D-Methionine by Rainbow Trout (*Oncorhynchus Mykiss*). *Aquaculture* **1992**, *101*, 95–103. [\[CrossRef\]](#)
85. Liaqat, I.; Mukhtar, B.; Malik, M.; Shah, S.H.; Azzam, A.; Slahuddin, S. Lysine Supplementation in Fish Feed. *Int. J. Appl. Biol. Forensics* **2017**, *1*, 26–31.
86. Huang, D.; Liang, H.; Ren, M.; Ge, X.; Ji, K.; Yu, H.; Maulu, S. Effects of Dietary Lysine Levels on Growth Performance, Whole Body Composition and Gene Expression Related to Glycometabolism and Lipid Metabolism in Grass Carp, *Ctenopharyngodon Idellus* Fry. *Aquaculture* **2021**, *530*, 735806. [\[CrossRef\]](#)
87. Kim, K.-I.; Kayes, T.B.; Amundson, C.H. Requirements for Lysine and Arginine by Rainbow Trout (*Oncorhynchus Mykiss*). *Aquaculture* **1992**, *106*, 333–344. [\[CrossRef\]](#)
88. Ng, W.; Hung, S. Estimating the Ideal Dietary Essential Amino Acid Pattern for Growth of White Sturgeon, *Acipenser Transmontanus* (Richardson). *Aquac. Nutr.* **2006**, *1*, 85–94. [\[CrossRef\]](#)
89. Santiago, C.B.; Lovell, R.T. Amino Acid Requirements for Growth of Nile Tilapia. *J. Nutr.* **1988**, *118*, 1540–1546. [\[CrossRef\]](#)
90. Lin, X.; Du, Y.; de Cruz, C.; Zhao, J.; Shao, X.; Xu, Q. Effects of Supplementation with Crystalline or Coated Methionine and Lysine in Low Protein Diet on Growth Performance, Intestinal Health and Muscle Quality of Gibel Carp, *Carassius Auratus* Gibelio. *Aquac. Rep.* **2024**, *36*, 102084. [\[CrossRef\]](#)
91. Liu, C.-M.; Uehara, T.; Shimoda, M. Enhancing the Nutritional Value of Black Soldier Fly Larvae through the Nutrient Amino Acid Transporter Suppression in the Excretion System. *J. Insects Food Feed.* **2024**, *11*, 497–507. [\[CrossRef\]](#)
92. Koethe, M.; Taubert, J.; Vervuert, I. Impact of Lysine Supplementation on Growth and Development of *Hermetia illucens* Larvae. *J. Insects Food Feed.* **2021**, *8*, 35–44. [\[CrossRef\]](#)
93. Sprague, M.; Dick, J.; Tocher, D. Impact of Sustainable Feeds on Omega-3 Long-Chain Fatty Acid Levels in Farmed Atlantic Salmon, 2006–2015. *Sci. Rep.* **2016**, *6*, 21892. [\[CrossRef\]](#)
94. Tocher, D. Omega-3 Long-Chain Polyunsaturated Fatty Acids and Aquaculture in Perspective. *Aquaculture* **2015**, *449*, 94–107. [\[CrossRef\]](#)
95. Turchini, G.; Torstensen, B.; Ng, W.-K. Fish Oil Replacement in Finfish Nutrition. *Rev. Aquac.* **2009**, *1*, 10–57. [\[CrossRef\]](#)
96. Sprague, M.; Betancor, M.; Tocher, D. Microbial and Genetically Engineered Oils as Replacements for Fish Oil in Aquaculture Feeds. *Biotechnol. Lett.* **2017**, *39*, 1599–1609. [\[CrossRef\]](#) [\[PubMed\]](#)
97. Li, S.; Ji, H.; Zhang, B.; Tian, J.; Zhou, J.; Yu, H. Influence of Black Soldier Fly (*Hermetia illucens*) Larvae Oil on Growth Performance, Body Composition, Tissue Fatty Acid Composition and Lipid Deposition in Juvenile Jian Carp (*Cyprinus carpio* Var. Jian). *Aquaculture* **2016**, *465*, 43–52. [\[CrossRef\]](#)
98. Almeida, C.; Murta, D.; Nunes, R.P.; Baby, A.; Fernandes, A.; Barros, L.; Rijo, P.; Rosado, C. Characterization of Lipid Extracts from the *Hermetia illucens* Larvae and Their Bioactivities for Potential Use as Pharmaceutical and Cosmetic Ingredients. *Heliyon* **2022**, *8*, e09455. [\[CrossRef\]](#)
99. Borrelli, L.; Varriale, L.; Dipineto, L.; Pace, A.; Menna, L.; Fioretti, A. Insect Derived Lauric Acid as Promising Alternative Strategy to Antibiotics in the Antimicrobial Resistance Scenario. *Front. Microbiol.* **2021**, *12*, 620798. [\[CrossRef\]](#)
100. Daszkiewicz, T.; Murawska, D.; Kubiak, D.; Han, J. Chemical Composition and Fatty Acid Profile of the Pectoralis Major Muscle in Broiler Chickens Fed Diets with Full-Fat Black Soldier Fly (*Hermetia illucens*) Larvae Meal. *Animals* **2022**, *12*, 464. [\[CrossRef\]](#)
101. Suryati, T.; Julaha, E.; Farabi, K.; Ambarsari, H.; Hidayat, A.T. Lauric Acid from the Black Soldier Fly (*Hermetia illucens*) and Its Potential Applications. *Sustainability* **2023**, *15*, 10383. [\[CrossRef\]](#)
102. Kabara, J.J.; Swieczkowski, D.M.; Conley, A.J.; Truant, J.P. Fatty Acids and Derivatives as Antimicrobial Agents. *Antimicrob. Agents Chemother.* **1972**, *2*, 23–28. [\[CrossRef\]](#)
103. Thormar, H.; Isaacs, C.; Brown, H.R.; Barshatzky, M.R.; Pessolano, T. Inactivation of Enveloped Viruses and Killing of Cells by Fatty Acids and Monoglycerides. *Antimicrob. Agents Chemother.* **1987**, *31*, 27–31. [\[CrossRef\]](#)
104. Akula, S.T.; Nagaraja, A.; Ravikanth, M.; Kumar, N.G.R.; Kalyan, Y.; Divya, D. Antifungal Efficacy of Lauric Acid and Caprylic Acid—Derivatives of Virgin Coconut Oil against *Candida Albicans*. *Biomed. Biotechnol. Res. J. BBRJ* **2021**, *5*, 229. [\[CrossRef\]](#)

105. Lappano, R.; Sebastiani, A.; Cirillo, F.; Rigiracciolo, D.; Galli, G.; Curcio, R.; Malaguarnera, R.; Belfiore, A.; Cappello, A.; Maggiolini, M. The Lauric Acid-Activated Signaling Prompts Apoptosis in Cancer Cells. *Cell Death Discov.* **2017**, *3*, 17063. [\[CrossRef\]](#) [\[PubMed\]](#)
106. Belghit, I.; Liland, N.S.; Gjesdal, P.; Biancarosa, I.; Menchetti, E.; Li, Y.; Waagbø, R.; Krogdahl, Å.; Lock, E.-J. Black Soldier Fly Larvae Meal Can Replace Fish Meal in Diets of Sea-Water Phase Atlantic Salmon (*Salmo Salar*). *Aquaculture* **2019**, *503*, 609–619. [\[CrossRef\]](#)
107. Fontinha, F.; Martins, N.; Magalhães, R.; Peres, H.; Oliva-Teles, A. Dietary Lauric Acid Supplementation Positively Affects Growth Performance, Oxidative and Immune Status of European Seabass Juveniles. *Fishes* **2025**, *10*, 190. [\[CrossRef\]](#)
108. Elieh-Ali-Komi, D.; Sharma, L.; Dela Cruz, C. Chitin and Its Effects on Inflammatory and Immune Responses. *Clin. Rev. Allergy Immunol.* **2018**, *54*, 213. [\[CrossRef\]](#)
109. Aranaz, I.; Alcántara, A.R.; Civera, M.C.; Arias, C.; Elorza, B.; Heras Caballero, A.; Acosta, N. Chitosan: An Overview of Its Properties and Applications. *Polymers* **2021**, *13*, 3256. [\[CrossRef\]](#)
110. Mohan, K.; Ganesan, A.R.; Muralisankar, T.; Jayakumar, R.; Sathishkumar, P.; Uthayakumar, V.; Chandirasekar, R.; Revathi, N. Recent Insights into the Extraction, Characterization, and Bioactivities of Chitin and Chitosan from Insects. *Trends Food Sci. Technol.* **2020**, *105*, 17–42. [\[CrossRef\]](#)
111. Khatami, N.; Guerrero, P.; Martín, P.; Quintela, E.; Ramos, V.; Saa, L.; Cortajarena, A.L.; de la Caba, K.; Camarero-Espinosa, S.; Abarrategi, A. Valorization of Biological Waste from Insect-Based Food Industry: Assessment of Chitin and Chitosan Potential. *Carbohydr. Polym.* **2024**, *324*, 121529. [\[CrossRef\]](#)
112. Triunfo, M.; Tafi, E.; Guarnieri, A.; Salvia, R.; Scieuzo, C.; Hahn, T.; Zibek, S.; Gagliardini, A.; Panariello, L.; Coltelli, M.; et al. Characterization of Chitin and Chitosan Derived from *Hermetia illucens*, a Further Step in a Circular Economy Process. *Sci. Rep.* **2022**, *12*, 6613. [\[CrossRef\]](#)
113. Marino-Perez, R. Edible Orthopteroids: The Mexican Case. *Metaleptea* **2015**, *35*, 7–8.
114. Gopalakannan, A.; Arul, V. Immunomodulatory Effects of Dietary Intake of Chitin, Chitosan and Levamisole on the Immune System of Cyprinus Carpio and Control of Aeromonas Hydrophila Infection in Ponds. *Aquaculture* **2006**, *255*, 179–187. [\[CrossRef\]](#)
115. Mari, L.S.S.; Jagruthi, C.; Anbazahan, S.M.; Yogeshwari, G.; Thirumurugan, R.; Arockiaraj, J.; Mariappan, P.; Balasundaram, C.; Harikrishnan, R. Protective Effect of Chitin and Chitosan Enriched Diets on Immunity and Disease Resistance in Cirrhina Mrigala against Aphanomyces Invadans. *Fish Shellfish Immunol.* **2014**, *39*, 378–385. [\[CrossRef\]](#) [\[PubMed\]](#)
116. Elserafy, S.S.; Abdel-Hameid, N.H.; Abdel-Salam, H.A.; Dakrouni, A.M. Effect of shrimp waste extracted chitin on growth and some biochemical parameters of the Nile tilapia. *Egypt. J. Aquat. Biol. Fish.* **2021**, *25*, 313–329. [\[CrossRef\]](#)
117. Harikrishnan, R.; Kim, J.-U.; Balasundaram, C.; Heo, S.-M. Dietary Supplementation with Chitin and Chitosan on Haematology and Innate Immune Response in Epinephelus Bruneus against Philasterides Dicertrarchi. *Exp. Parasitol.* **2012**, *131*, 116–124. [\[CrossRef\]](#) [\[PubMed\]](#)
118. Hasan, I.; Gai, F.; Cirrincione, S.; Rimoldi, S.; Saroglia, G.; Terova, G. Chitinase and Insect Meal in Aquaculture Nutrition: A Comprehensive Overview of the Latest Achievements. *Fishes* **2023**, *8*, 607. [\[CrossRef\]](#)
119. Renna, M.; Schiavone, A.; Gai, F.; Dabbou, S.; Lussiana, C.; Malfatto, V.; Prearo, M.; Capucchio, M.; Biasato, I.; Biasibetti, E.; et al. Evaluation of the Suitability of a Partially Defatted Black Soldier Fly (*Hermetia illucens* L.) Larvae Meal as Ingredient for Rainbow Trout (*Oncorhynchus Mykiss* Walbaum) Diets. *J. Anim. Sci. Biotechnol.* **2017**, *8*, 57. [\[CrossRef\]](#)
120. Pascon, G.; Cardinaletti, G.; Daniso, E.; Bruni, L.; Messina, M.; Parisi, G.; Tulli, F. Effect of Dietary Chitin on Growth Performance, Nutrient Utilization, and Metabolic Response in Rainbow Trout (*Oncorhynchus Mykiss*). *Aquac. Rep.* **2024**, *37*, 102244. [\[CrossRef\]](#)
121. Eggink, K.; Pedersen, P.; Lund, I.; Dalsgaard, J. Chitin Digestibility and Intestinal Exochitinase Activity in Nile Tilapia and Rainbow Trout Fed Different Black Soldier Fly Larvae Meal Size Fractions. *Aquac. Res.* **2022**, *53*, 5536–5546. [\[CrossRef\]](#)
122. Pascon, G.; Opere Akinyi, R.; Cardinaletti, G.; Daniso, E.; Messina, M. Chitin and Its Effects When Included in Aquafeed. *Aquac. Int.* **2025**, *33*, 202–224. [\[CrossRef\]](#)
123. Kroeckel, S.; Harjes, A.-G.E.; Roth, I.; Katz, H.; Wuertz, S.; Susenbeth, A.; Schulz, C. When a Turbot Catches a Fly: Evaluation of a Pre-Pupae Meal of the Black Soldier Fly (*Hermetia illucens*) as Fish Meal Substitute—Growth Performance and Chitin Degradation in Juvenile Turbot (*Psetta Maxima*). *Aquaculture* **2012**, *364*, 345–352. [\[CrossRef\]](#)
124. Karlsen, Ø.; Amlund, H.; Berg, A.; Olsen, R. The Effect of Dietary Chitin on Growth and Nutrient Digestibility in Farmed Atlantic Cod, Atlantic Salmon and Atlantic Halibut. *Aquac. Res.* **2015**, *48*, 123–133. [\[CrossRef\]](#)
125. Dumas, A.; Raggi, T.; Barkhouse, J.; Lewis, E.; Weltzien, E. The Oil Fraction and Partially Defatted Meal of Black Soldier Fly Larvae (*Hermetia illucens*) Affect Differently Growth Performance, Feed Efficiency, Nutrient Deposition, Blood Glucose and Lipid Digestibility of Rainbow Trout (*Oncorhynchus Mykiss*). *Aquaculture* **2018**, *492*, 24–34. [\[CrossRef\]](#)
126. Ratti, S.; Zarantonello, M.; Chemello, G.; Giammarino, M.; Palermo, F.; Cocci, P.; Mosconi, G.; Tignani, M.; Pascon, G.; Cardinaletti, G.; et al. Spirulina-Enriched Substrate to Rear Black Soldier Fly (*Hermetia illucens*) Prepupae as Alternative Aquafeed Ingredient for Rainbow Trout (*Oncorhynchus Mykiss*) Diets: Possible Effects on Zootechnical Performances, Gut and Liver Health Status, and Fillet Quality. *Animals* **2023**, *13*, 173. [\[CrossRef\]](#)

127. Katya, K.; Borsra, M.Z.S.; Ganesan, D.; Kuppusamy, G.; Herriman, M.; Salter, A.; Ali, S.A. Efficacy of Insect Larval Meal to Replace Fish Meal in Juvenile Barramundi, Lates Calcarifer Reared in Freshwater. *Int. Aquat. Res.* **2017**, *9*, 303–312. [\[CrossRef\]](#)
128. Magalhães, R.; Sánchez-López, A.; Leal, R.S.; Martínez-Llorens, S.; Oliva-Teles, A.; Peres, H. Black Soldier Fly (*Hermetia illucens*) Pre-Pupae Meal as a Fish Meal Replacement in Diets for European Seabass (*Dicentrarchus Labrax*). *Aquaculture* **2017**, *476*, 79–85. [\[CrossRef\]](#)
129. Li, S.; Ji, H.; Zhang, B.; Zhou, J.; Yu, H. Defatted Black Soldier Fly (*Hermetia illucens*) Larvae Meal in Diets for Juvenile Jian Carp (*Cyprinus carpio* Var. Jian): Growth Performance, Antioxidant Enzyme Activities, Digestive Enzyme Activities, Intestine and Hepatopancreas Histological Structure. *Aquaculture* **2017**, *477*, 62–70. [\[CrossRef\]](#)
130. Zhou, J.S.; Liu, S.S.; Ji, H.; Yu, H.B. Effect of Replacing Dietary Fish Meal with Black Soldier Fly Larvae Meal on Growth and Fatty Acid Composition of Jian Carp (*Cyprinus carpio* Var. Jian). *Aquac. Nutr.* **2018**, *24*, 424–433. [\[CrossRef\]](#)
131. Wang, G.; Peng, K.; Hu, J.; Yi, C.; Chen, X.; Wu, H.; Huang, Y. Evaluation of Defatted Black Soldier Fly (*Hermetia illucens* L.) Larvae Meal as an Alternative Protein Ingredient for Juvenile Japanese Seabass (*Lateolabrax Japonicus*) Diets. *Aquaculture* **2019**, *507*, 144–154. [\[CrossRef\]](#)
132. Rawski, M.; Mazurkiewicz, J.; Kierończyk, B.; Józefiak, D. Black Soldier Fly Full-Fat Larvae Meal as an Alternative to Fish Meal and Fish Oil in Siberian Sturgeon Nutrition: The Effects on Physical Properties of the Feed, Animal Growth Performance, and Feed Acceptance and Utilization. *Animals* **2020**, *10*, 2119. [\[CrossRef\]](#)
133. Kumar, V.; Fawole, F.J.; Romano, N.; Hossain, M.S.; Labh, S.N.; Overturf, K.; Small, B.C. Insect (Black Soldier Fly, *Hermetia illucens*) Meal Supplementation Prevents the Soybean Meal-Induced Intestinal Enteritis in Rainbow Trout and Health Benefits of Using Insect Oil. *Fish Shellfish Immunol.* **2021**, *109*, 116–124. [\[CrossRef\]](#)
134. Khieokhajonkhet, A.; Uanlam, P.; Ruttarattanamongkol, K.; Aeksiri, N.; Tatsapong, P.; Kaneko, G. Replacement of Fish Meal by Black Soldier Fly Larvae Meal in Diet for Goldfish *Carassius Auratus*: Growth Performance, Hematology, Histology, Total Carotenoids, and Coloration. *Aquaculture* **2022**, *561*, 738618. [\[CrossRef\]](#)
135. Carral, J.M.; Sáez-Royuela, M. Replacement of Dietary Fishmeal by Black Soldier Fly Larvae (*Hermetia illucens*) Meal in Practical Diets for Juvenile Tench (*Tinca Tinca*). *Fishes* **2022**, *7*, 390. [\[CrossRef\]](#)
136. Kari, Z.A.; Téllez-Isaías, G.; Hamid, N.K.A.; Rusli, N.D.; Mat, K.; Sukri, S.A.M.; Kabir, M.A.; Ishak, A.R.; Dom, N.C.; Abdel-Warith, A.-W.A.; et al. Effect of Fish Meal Substitution with Black Soldier Fly (*Hermetia illucens*) on Growth Performance, Feed Stability, Blood Biochemistry, and Liver and Gut Morphology of Siamese Fighting Fish (*Betta Splendens*). *Aquac. Nutr.* **2023**, *2023*, 6676953. [\[CrossRef\]](#) [\[PubMed\]](#)
137. Linh, N.V.; Wannavijit, S.; Tayyatham, K.; Dinh-Hung, N.; Nititanarapee, T.; Sumon, M.A.A.; Srinual, O.; Permpoonpattana, P.; Doan, H.V.; Brown, C.L. Black Soldier Fly (*Hermetia illucens*) Larvae Meal: A Sustainable Alternative to Fish Meal Proven to Promote Growth and Immunity in Koi Carp (*Cyprinus carpio* Var. Koi). *Fishes* **2024**, *9*, 53. [\[CrossRef\]](#)
138. Ouko, K.O.; Mboya, J.B.; Mukhebi, A.W.; Obiero, K.O.; Ogello, E.O.; Munguti, J.M.; Tanga, C.M. Effect of Replacing Fish Meal with Black Soldier Fly Larvae Meal on Growth Performance and Economic Efficiency of Nile Tilapia. *Fundam. Appl. Agric.* **2024**, *9*, 1–9. [\[CrossRef\]](#)
139. Herawati, V.E.; Pinandoyo; Darmanto, Y.; Hutabarat, J.; Seto; Windarto; Rismaningsih, N.; Radjasa, O.K. Fermented Black Soldier Fly (*Hermetia illucens*) Meal Utilization in Artificial Feed for Carp (*Cyprinus Carpio*). *AAFL Bioflux* **2020**, *13*, 1038–1047. Available online: <http://www.bioflux.com.ro/aafl> (accessed on 4 June 2025).
140. Lu, R.; Chen, Y.; Yu, W.; Lin, M.; Yang, G.; Qin, C.; Meng, X.; Zhang, Y.; Ji, H.; Nie, G. Defatted Black Soldier Fly (*Hermetia illucens*) Larvae Meal Can Replace Soybean Meal in Juvenile Grass Carp (*Ctenopharyngodon Idellus*) Diets. *Aquac. Rep.* **2020**, *18*, 100520. [\[CrossRef\]](#)
141. Tippayadara, N.; Dawood, M.A.O.; Krutmuang, P.; Hoseinifar, S.H.; Doan, H.V.; Paolucci, M. Replacement of Fish Meal by Black Soldier Fly (*Hermetia illucens*) Larvae Meal: Effects on Growth, Haematology, and Skin Mucus Immunity of Nile Tilapia, *Oreochromis Niloticus*. *Animals* **2021**, *11*, 193. [\[CrossRef\]](#)
142. Kamarudin, M.S.; Rosle, S.; Yasin, I.S.M. Performance of Defatted Black Soldier Fly Pre-Pupae Meal as Fishmeal Replacement in the Diet of Lemon Fin Barb Hybrid Fingerlings. *Aquac. Rep.* **2021**, *21*, 100775. [\[CrossRef\]](#)
143. Couto, A.; Serra, C.R.; Guerreiro, I.; Coutinho, F.; Castro, C.; Rangel, F.; Lavrador, A.S.; Monteiro, M.; Santos, R.A.; Peres, H.; et al. Black Soldier Fly Meal Effects on Meagre Health Condition: Gut Morphology, Gut Microbiota and Humoral Immune Response. *J. Insects Food Feed.* **2022**, *8*, 1281–1295. [\[CrossRef\]](#)
144. Maranga, B.; Kagali, R.; Mbogo, K.; Orina, S.; Munguti, J.; Ogello, E. Growth Performance of African Catfish (*Clarias Gariepinus*) Fed on Diets Containing Black Soldier Fly (*Hermetia illucens*) Larvae Under Aquaponic System. *Aquac. Stud.* **2022**, *23*, AQUAST910. [\[CrossRef\]](#)
145. Öztürk, R.Ç.; Yandi, I.; Terzi, Y.; Altinok, I. Growth, Health and Fillet Quality of Rainbow Trout (*Oncorhynchus Mykiss*) Fed Directly with Black Soldier Fly (*Hermetia illucens*) Prepupae. *Turk. J. Fish. Aquat. Sci.* **2023**, *23*, 21683. [\[CrossRef\]](#)

146. Bartucz, T.; Csókás, E.; Nagy, B.; Gyurcsák, M.P.; Bokor, Z.; Bernáth, G.; Molnár, J.; Urbányi, B.; Csorbai, B. Black Soldier Fly (*Hermetia illucens*) Meal as Direct Replacement of Complex Fish Feed for Rainbow Trout (*Oncorhynchus Mykiss*) and African Catfish (*Clarias Gariepinus*). *Life* **2023**, *13*, 1978. [\[CrossRef\]](#) [\[PubMed\]](#)
147. Siddaiah, G.M.; Kumar, R.; Kumari, R.; Chandan, N.K.; Debbarma, J.; Damle, D.K.; Das, A.; Giri, S.S. Dietary Fishmeal Replacement with *Hermetia illucens* (Black Soldier Fly, BSF) Larvae Meal Affected Production Performance, Whole Body Composition, Antioxidant Status, and Health of Snakehead (*Channa striata*) Juveniles. *Anim. Feed. Sci. Technol.* **2023**, *297*, 115597. [\[CrossRef\]](#)
148. Odden, S.B.; Biasato, I.; Caimi, C.; Belghit, I.; Radhakrishnan, G.; Gasco, L. Batch-to Batch Variation in Nutrient Digestibility of Black Soldier Fly Larvae Meals in Rainbow Trout. *J. Insects Food Feed.* **2024**, *11*, 61–72. [\[CrossRef\]](#)
149. Moutinho, S.; Peres, H.; Martins, N.; Serra, C.; Santos, R.A.; Monroig, Ó.; Oliva-Teles, A. Use of Black Soldier Fly (*Hermetia illucens*) Larvae Meal in Diets for Gilthead Seabream Juveniles: Effects on Growth-Related Gene Expression, Intermediary Metabolism, Digestive Enzymes, and Gut Microbiota Modulation. *Aquaculture* **2024**, *580*, 740357. [\[CrossRef\]](#)
150. Gangbazo, D.N.S.K.; Adjahouinou, D.C.; Djissou, A.; Godome, T.; Tossavi, E.; Diegane, N.; Fall, J.; Aboh, A.B. Use of Black Soldier Fly (*Hermetia illucens*) Larvae Meal in the Diet of *Clarias Gariepinus* (Burchell, 1882) Fingerlings Reared in Controlled Environments. *J. Anim. Health Prod.* **2025**, *13*, 632–641. [\[CrossRef\]](#)
151. Rawski, M.; Mazurkiewicz, J.; Mikołajczak, Z.; Kierończyk, B.; Skrzypczak, P.; Szymkowiak, P.; Józefiak, D. Black Soldier Fly Meal as a Gastrointestinal Tract Microbiota Remodelling Factor: A New Natural and Sustainable Source of Prebiotic Substances for Fish? *Aquac. Res.* **2025**, *2025*, 8852384. [\[CrossRef\]](#)
152. Li, X.; Chen, Y.; Liao, Z.; Chen, X.; Gu, X.; Ye, T.; Pu, H.; Li, W.; Zhu, B.; Zhao, W.; et al. Effects of Butane-Defatted Black Soldier Fly Larvae Meal Replace Dietary Fishmeal on Growth, Antioxidant Capacity and Intestine Health of Rainbow Trout (*Oncorhynchus Mykiss*). *Aquaculture* **2025**, *607*, 742640. [\[CrossRef\]](#)
153. Maulu, S.; Eynon, B.; Abarra, S.; Rawling, M.; Merrifield, D.L. Black Soldier Fly, *Hermetia illucens*, Larvae Meal Improves Intestinal Health and Growth Performance of Nile Tilapia, *Oreochromis Niloticus*, Juveniles. *J. World Aquac. Soc.* **2025**, *56*, e70035. [\[CrossRef\]](#)
154. Chen, Y.; Chi, S.; Zhang, S.; Dong, X.; Yang, Q.; Liu, H.; Tan, B.; Xie, S. Effect of Black Soldier Fly (*Hermetia illucens*) Larvae Meal on Lipid and Glucose Metabolism of Pacific White Shrimp *Litopenaeus vannamei*. *Br. J. Nutr.* **2021**, *128*, 1674–1688. [\[CrossRef\]](#) [\[PubMed\]](#)
155. Zheng, J.Y.; Gan, Z.R.; Huang, T.Y.; Xiao, Y.; Xu, W.Y.; Li, X.Q.; Leng, X.J. Replacement of Fish Meal with Defatted Black Soldier Fly (*Hermetia illucens*) in Diet of Pacific White Shrimp (*Litopenaeus vannamei*): Growth, Flesh Quality and Transcriptome. *J. Insects Food Feed.* **2024**, *11*, 873–893. [\[CrossRef\]](#)
156. Nunes, A.J.P.; Yamamoto, H.; Simões, J.P.; Pisa, J.L.; Miyamoto, N.; Leite, J.S. The Black Soldier Fly (*Hermetia illucens*) Larvae Meal Can Cost-Effectively Replace Fish Meal in Practical Nursery Diets for Post-Larval *Penaeus Vannamei* under High-Density Culture. *Fishes* **2023**, *8*, 605. [\[CrossRef\]](#)
157. Alvanou, M.; Kyriakoudi, A.; Makri, V.; Lattos, A.; Feidantsis, K.; Papadopoulos, D.; Georgoulis, I.; Apostolidis, A.; Michaelidis, B.; Mourtzinou, I.; et al. Effects of Dietary Substitution of Fishmeal by Black Soldier Fly (*Hermetia illucens*) Meal on Growth Performance, Whole-Body Chemical Composition, and Fatty Acid Profile of *Pontastacus Leptodactylus* Juveniles. *Front. Physiol.* **2023**, *14*, 1156394. [\[CrossRef\]](#)
158. Subchan, W.; Nawangsari, F.; Prihatin, J. The Effect of Flour-Based Feed Black Soldier Fly Larvae on Crayfish (*Cherax Quadricarinatus* von Martens) Growth. In Proceedings of the 5th International Conference on Life Sciences and Biotechnology (ICOLIB 2023) BIO Web of Conferences, Jember, India, 21 May 2024; Volume 101, p. 01005. [\[CrossRef\]](#)
159. Yao, W.; Zhang, C.; Mao, H.; Hua, G.; Liu, Q.; Zhao, S.; Shuang, H.; Poolsawat, L.; Yuan, S.; Wang, J.; et al. Effects of Dietary Defatted Black Soldier Fly (*Hermetia illucens*) Larvae Meal Substituting Fish Meal on Growth, Antioxidative Capacity, Immunity, Intestinal Histology and Microbiota of Juvenile Chinese Mitten Crab (*Eriocheir sinensis*). *Aquac. Rep.* **2024**, *38*, 102302. [\[CrossRef\]](#)
160. Li, M.; Li, M.; Wang, G.; Liu, C.; Shang, R.; Chen, Y.; Li, L. Defatted Black Soldier Fly (*Hermetia illucens*) Larvae Meal Can Partially Replace Fish Meal in Diets for Adult Chinese Soft-Shelled Turtles. *Aquaculture* **2021**, *541*, 736758. [\[CrossRef\]](#)
161. Pornsuwan, R.; Pootthachaya, P.; Bunchalee, P.; Hanboonsong, Y.; Cherdthong, A.; Tengjaroenkul, B.; Boonkum, W.; Wongtangtintharn, S. Evaluation of the Physical Characteristics and Chemical Properties of Black Soldier Fly (*Hermetia illucens*) Larvae as a Potential Protein Source for Poultry Feed. *Animals* **2023**, *13*, 2244. [\[CrossRef\]](#)
162. Dörper, A.; Veldkamp, T.; Dicke, M. Use of Black Soldier Fly and House Fly in Feed to Promote Sustainable Poultry Production. *J. Insects Food Feed.* **2021**, *7*, 761–780. [\[CrossRef\]](#)
163. de Souza Vilela, J.; Andronicos, N.; Kolakshyapati, M.; Hilliar, M.; Sibanda, T.Z.; Andrew, N.; Swick, R.; Wilkinson, S.; Ruhnke, I. Black Soldier Fly Larvae in Broiler Diets Improve Broiler Performance and Modulate the Immune System. *Anim. Nutr.* **2021**, *7*, 695–706. [\[CrossRef\]](#)
164. Stadlander, T.; Stamer, A.; Buser, A.; Wohlfahrt, J.; Leiber, F.; Sandrock, C. *Hermetia illucens* Meal as Fish Meal Replacement for Rainbow Trout on Farm. *J. Insects Food Feed.* **2017**, *3*, 165–175. [\[CrossRef\]](#)
165. Sealey, W.; Gaylord, G.; Barrows, F.; Tomberlin, J.; McGuire, M.; Ross, C.; St-Hilaire, S. Sensory Analysis of Rainbow Trout, *Oncorhynchus Mykiss*, Fed Enriched Black Soldier Fly Prepupae, *Hermetia illucens*. *J. World Aquac. Soc.* **2011**, *42*, 34–45. [\[CrossRef\]](#)

166. Turchini, G.M.; Mentasti, T.; Caprino, F.; Panseri, S.; Moretti, V.M.; Valfrè, F. Effects of Dietary Lipid Sources on Flavour Volatile Compounds of Brown Trout (*Salmo trutta* L.) Fillet. *J. Appl. Ichthyol.* **2004**, *20*, 71–75. [CrossRef]
167. Radhakrishnan, G.; Philip, A.J.P.; Caimi, C.; Lock, E.-J.; Araujo, P.; Liland, N.S.; Rocha, C.; Cunha, L.M.; Gasco, L.; Belghit, I. Evaluating the Fillet Quality and Sensory Characteristics of Atlantic Salmon (*Salmo Salar*) Fed Black Soldier Fly Larvae Meal for Whole Production Cycle in Sea Cages. *Aquac. Rep.* **2024**, *35*, 101966. [CrossRef]
168. Bruni, L.; Randazzo, B.; Cardinaletti, G.; Zarantonello, M.; Fabio, M.; Secci, G.; Francesca, T.; Olivotto, I.; Parisi, G. Dietary Inclusion of Full-Fat *Hermetia illucens* Prepupae Meal in Practical Diets for Rainbow Trout (*Oncorhynchus Mykiss*): Lipid Metabolism and Fillet Quality Investigations. *Aquaculture* **2020**, *529*, 735678. [CrossRef]
169. Bruni, L.; Belghit, I.; Lock, E.-J.; Secci, G.; Taiti, C.; Parisi, G. Total Replacement of Dietary Fish Meal with Black Soldier Fly (*Hermetia illucens*) Larvae Does Not Impair Physical, Chemical or Volatile Composition of Farmed Atlantic Salmon (*Salmo Salar* L.). *J. Sci. Food Agric.* **2019**, *100*, 1038–1047. [CrossRef]
170. Moutinho, S.; Pedrosa, R.; Magalhães, R.; Oliva-Teles, A.; Parisi, G.; Peres, H. Black Soldier Fly (*Hermetia illucens*) Pre-Pupae Larvae Meal in Diets for European Seabass (*Dicentrarchus Labrax*) Juveniles: Effects on Liver Oxidative Status and Fillet Quality Traits during Shelf-Life. *Aquaculture* **2020**, *533*, 736080. [CrossRef]
171. Hervé, M.K.; Calice, M.D.; Dzepe, D.; Djouaka, R.F.; Chia, S.Y.; Efole, T.; Ndindeng, S.A. Black Soldier Fly (*Hermetia illucens*) Larvae Improve Growth Performance and Flesh Quality of African Catfish (*Clarias Gariepinus*). *Discov. Anim.* **2025**, *2*, 9. [CrossRef]
172. Salmon Business. 2025. Available online: <https://www.salmonbusiness.com/new-study-finds-67-prefer-the-taste-of-salmon-fed-with-insect-based-feed/> (accessed on 6 June 2025).
173. Roccatello, R.; Endrizzi, I.; Aprea, E.; Dabbou, S. Insect-Based Feed in Aquaculture: A Consumer Attitudes Study. *Aquaculture* **2024**, *582*, 740512. [CrossRef]
174. Baldi, L.; Mancuso, T.; Peri, M.; Gasco, L.; Trentinaglia, M.T. Consumer Attitude and Acceptance toward Fish Fed with Insects: A Focus on the New Generations. *J. Insects Food Feed.* **2022**, *8*, 1249–1264. [CrossRef]
175. Bazoche, P.; Poret, S. Acceptability of Insects in Animal Feed: A Survey of French Consumers. *J. Consum. Behav.* **2021**, *20*, 251–270. [CrossRef]
176. Popoff, M.; MacLeod, M.; Leschen, W. Attitudes towards the Use of Insect-Derived Materials in Scottish Salmon Feeds. *J. Insects Food Feed.* **2017**, *3*, 131–138. [CrossRef]
177. Rawski, M.; Mazurkiewicz, J.; Kierończyk, B.; Józefiak, D. Black Soldier Fly Full-Fat Larvae Meal Is More Profitable Than Fish Meal and Fish Oil in Siberian Sturgeon Farming: The Effects on Aquaculture Sustainability, Economy and Fish GIT Development. *Animals* **2021**, *11*, 604. [CrossRef] [PubMed]
178. Limbu, S.M.; Shoko, A.P.; Ulotu, E.E.; Luvanga, S.A.; Munyi, F.M.; John, J.O.; Opiyo, M.A. Black Soldier Fly (*Hermetia illucens* L.) Larvae Meal Improves Growth Performance, Feed Efficiency and Economic Returns of Nile Tilapia (*Oreochromis Niloticus* L.) Fry. *Aquac. Fish Fish.* **2022**, *2*, 167–178. [CrossRef]
179. Ouko, K.O. Socio-Economic Efficiency of Black Soldier Fly (*Hermetia illucens* L.) Larvae Meal for Aquaculture Production. Ph.D. Thesis, Jaramogi Oginga Odinga University of Science and Technology, Bondo Town, Kenya, 2023. Available online: <https://agris.fao.org/search/en/providers/124791/records/676540f550e69ae818389e53> (accessed on 1 July 2025).
180. Auzins, A.; Leimane, I.; Reissaar, R.; Brobakk, J.; Sakelaite, I.; Grivins, M.; Zihare, L. Assessing the Socio-Economic Benefits and Costs of Insect Meal as a Fishmeal Substitute in Livestock and Aquaculture. *Animals* **2024**, *14*, 1461. [CrossRef]
181. Maroušek, J.; Strunecký, O.; Maroušková, A. Insect Rearing on Biowaste Represents a Competitive Advantage for Fish Farming. *Rev. Aquac.* **2023**, *15*, 965–975. [CrossRef]
182. Ramzy, R.R.; Goenka, V.; El-Dakar, M.A.; Lee, J.S.H. Assessing the Environmental Impacts of the Black Soldier Fly-Based Circular Economy and Decentralized System in Singapore: A Case Study. *Sustainability* **2025**, *17*, 6115. [CrossRef]
183. Vala, R.B.; Borichangar, R.V.; Solanki, H.G.; Patel, M.R.; Parmar, A.M.; Varma, A. Insect Meal: An Emerging Eco-Friendly Approach for Sustainable Aquaculture Feed Industry. *J. Exp. Zool. India* **2024**, *27*, 1549–1559. [CrossRef]
184. Eide, L.H.; Rocha, S.D.C.; Morales-Lange, B.; Kuiper, R.V.; Dale, O.B.; Djordjevic, B.; Hooft, J.M.; Øverland, M. Black Soldier Fly Larvae (*Hermetia illucens*) Meal Is a Viable Protein Source for Atlantic Salmon (*Salmo Salar*) during a Large-Scale Controlled Field Trial under Commercial-like Conditions. *Aquaculture* **2024**, *579*, 740194. [CrossRef]
185. Cho, J.-H.; Bae, J.; Hwang, I.J. Effects of Black Soldier Fly (*Hermetia illucens*) Pre-Pupae Meal on the Growth, Stress, and Immune Responses of Juvenile Rainbow Trout (*Oncorhynchus Mykiss*) Reared at Different Stocking Densities. *Aquac. Rep.* **2022**, *25*, 101202. [CrossRef]
186. Nekrasov, R.; Ivanov, G.; Chabaev, M.G.; Zelenchenkova, A.A.; Bogolyubova, N.; Nikanova, D.; Sermyagin, A.; Bibikov, S.; Shapovalov, S. Effect of Black Soldier Fly (*Hermetia illucens* L.) Fat on Health and Productivity Performance of Dairy Cows. *Animals* **2022**, *12*, 2118. [CrossRef]
187. Huseynli, L.; Parviainen, T.; Kyllönen, T.; Aisala, H.; Vene, K. Exploring the Protein Content and Odor-Active Compounds of Black Soldier Fly Larvae for Future Food Applications. *Future Foods* **2023**, *7*, 100224. [CrossRef]

188. Siddiqui, S.A.; Harahap, I.A.; Osei-Owusu, J.; Saikia, T.; Wu, Y.S.; Fernando, I.; Perestrelo, R.; Câmara, J.S. Bioconversion of Organic Waste by Insects—A Comprehensive Review. *Process Saf. Environ. Prot.* **2024**, *187*, 1–25. [\[CrossRef\]](#)
189. Rushikesh, J.; Miles, L.; Twinkle, M.; Madhu, R.; Vendra, R.; Ruti, M.; Haldar, S.; Kumar, K.; Anjlina, D. Black Soldier Fly/Larvae: A Weapon for Solid Waste Management and Alternative Feed for Poultry and Aquatic Industries. *Int. J. Pharma Bio Sci.* **2020**, *10*, 113–120. [\[CrossRef\]](#)
190. Vauterin, A.; Steiner, B.; Sillman, J.; Kahiluoto, H. The Potential of Insect Protein to Reduce Food-Based Carbon Footprints in Europe: The Case of Broiler Meat Production. *J. Clean. Prod.* **2021**, *320*, 128799. [\[CrossRef\]](#)
191. Invertebrate Welfare—April 2020. Available online: <https://www.invertebratewelfare.org/newsletter/2020-04> (accessed on 5 June 2025).
192. López-Gámez, G.; del Pino-García, R.; López-Bascón, M.A.; Verardo, V. From Feed to Functionality: Unravelling the Nutritional Composition and Techno-Functional Properties of Insect-Based Ingredients. *Food Res. Int.* **2024**, *178*, 113985. [\[CrossRef\]](#)
193. Lee, C.G.; Silva, C.A.D.; Lee, J.-Y.; Hartl, D.; Elias, J.A. Chitin Regulation of Immune Responses: An Old Molecule with New Roles. *Curr. Opin. Immunol.* **2008**, *20*, 684–689. [\[CrossRef\]](#)
194. Caligiani, A.; Marseglia, A.; Leni, G.; Baldassarre, S.; Maistrello, L.; Dossena, A.; Sforza, S. Composition of Black Soldier Fly Prepupae and Systematic Approaches for Extraction and Fractionation of Proteins, Lipids and Chitin. *Food Res. Int.* **2017**, *105*, 812–820. [\[CrossRef\]](#)
195. Vargas, A.; Randazzo, B.; Riolo, P.; Truzzi, C.; Gioacchini, G.; Giorgini, E.; Loreto, N.; Ruschioni, S.; Zarantoniello, M.; Antonucci, M.; et al. Rearing Zebrafish on Black Soldier Fly (*Hermetia illucens*): Biometric, Histological, Spectroscopic, Biochemical, and Molecular Implications. *Zebrafish* **2018**, *15*, 404–419. [\[CrossRef\]](#)
196. Zarantoniello, M.; Randazzo, B.; Truzzi, C.; Giorgini, E.; Marcellucci, C.; Vargas, A.; Zimbelli, A.; Annibaldi, A.; Parisi, G.; Francesca, T.; et al. A Six-Months Study on Black Soldier Fly (*Hermetia illucens*) Based Diets in Zebrafish. *Sci. Rep.* **2019**, *9*, 8598. [\[CrossRef\]](#)
197. Tang, C.; Yang, D.; Liao, H.; Sun, H.; Liu, C.; Wei, L.; Li, F. Edible Insects as a Food Source: A Review. *Food Prod. Process. Nutr.* **2019**, *1*, 8. [\[CrossRef\]](#)
198. Lalander, C.; Lopes, I. Advances in Substrate Source Composition for Rearing Black Soldier Fly Larvae as a Protein Source. In *Burleigh Dodds Series in Agricultural Science*; Burleigh Dodds Science Publishing: Cambridge, UK, 2024; ISBN 978-1-80146-584-7.
199. Niassy, S.; Ekesi, S.; Hendriks, S.; Haller-Barker, A. Legislation for the Use of Insects as Food and Feed in the South African Context. In *Edible Insects in Sustainable Food Systems*; Springer Nature: Cham, Switzerland, 2018; pp. 457–470, ISBN 978-3-319-74010-2.

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