fishes

Review

Success of Aquaculture Industry with New Insights of Using Insects as Feed: A Review

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Abstract: Most of world's fish and seafood are produced by aquaculture, which is one of the biggest contributors to the world's food security. The substantial increase in prices of conventional feed ingredients and the over-exploitation of natural resources are some of the biggest constraints to aquaculture production. To overcome this stress, different approaches and techniques are used, among which the use of non-conventional feed ingredients in the aquaculture sector is the most recent approach. Different non-conventional feed ingredients such as plant-based products, algae (both micro and macroalgae), single-cell protein (bacteria and yeast), and insect meal are currently used in aquaculture for sustainable food production. Amongst all these novel ingredients, insects have greater potential to replace fishmeal. The existence of about 1.3 billion tons of food and agriculture waste from the food chain supply poses a serious environmental threat. Insects are tiny creatures that can thrive on organic waste and thus can convert the waste to wealth by the bioconversion and nutritional upcycling of organic waste. Insects have the potential to recover nutrients from waste aquaculture products, and many fish species feed on insects naturally. Therefore, employing insects in the aquaculture sector to replace fishmeal is an eco-friendly approach. The present review briefly highlights emerging non-conventional feed ingredients, with special attention given to insects. The current review also focuses on the nutritional value of insects, factors affecting the nutritional value of insects, potential insects that can be employed in the aquaculture sector, the physiological response of fish when fed with insect meal, techno-functional properties of insect meal, and emerging approaches for addressing possible downsides of employing insect meal in fish diets. Finally, it suggests avenues for further research into these inventive fishmeal replacements.

Keywords: feed; insects; aquaculture; innovation; sustainability

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1. Background

The largest sector of food production is aquaculture, which has the potential to contribute to sustainable food production in the future. In 2018, the aquaculture sector, which is expanding, produced 114.5 million metric tons of live weight [1]. By supplying the world's expanding population with high-quality food, aquaculture is essential to ensuring food security [2]. Making sure that everyone has access to enough food at all times is known as food security. While the global population is growing by 1.6 percent per year, the demand for seafood is rising at a rate of 3.1% annually. At a rate of 2.1 percent per year, the aquaculture industry is expanding more quickly than other areas of animal production, such as livestock [1]. This might be because the aquaculture and fisheries sectors generate more economy through production, selling, and marketing [3,4].

Despite the fact that aquaculture has many advantages for the availability of food, its sustainability depends on a variety of factors, including knowledge, experience, the regulatory environment, the ecological conditions for the growth of cultured species, and the presence of a sizable market for the sale of aquaculture products [5]. Currently, 50% of world fish production is generated from aquaculture, and it is one of the biggest suppliers of high-quality protein in terms of quantity and quality [6]. Organisms from terrestrial and aquatic environments provide about 43% of the world's protein and play a key role in preventing malnutrition, especially in developing nations [1]. Aquaculture production, like other types of terrestrial farming, is fully dependent on the availability of nutrients as feed [6].

Fishmeal has frequently been replaced in aquaculture with plant proteins. Previous research has shown that plant-based diets are unfavorable for fish growth and health, and this could be because of the presence of anti-nutritional substances (ANFs) [7–9]. Among plant-based diets, soybean is considered the best to replace fishmeal due to its cost-effectiveness and nutritional value [10]. However, the addition of high quantities of soybean meal in the fish diet has been shown to negatively impact growth, gut and liver integrity, intestinal microbiota composition, and immunological response in various carnivorous fish species [11–13]. When the salmonids were fed with SBM-based diets, severe gut health impairment with enteritis and increased inflammatory influx was observed in fish [13]. The researchers were therefore forced to create new aquafeeds with innovative feed ingredients that can replace fishmeal and minimize the detrimental effect caused by using vegetable protein because they were aware of the negative effects of utilizing a plant-based diet, even at a low inclusion level [14–16].

1.1. Emergent Non-Conventional Feed Ingredients

The aquaculture sector is one of the major contributors to food security worldwide [2], but the increased food demand has compelled scientists to look for novel and non-conventional feed ingredients such as algae, land animal by-products, single-cell proteins, and insects [17].

Bacteria and yeast have the highest potential to replace fishmeal due to their good nutritional value. Bacteria and yeast have good AA profiles comparable to fishmeal and the protein content ranges from 50–80% and 45–55%, respectively. They also have great potential to be utilized as raw materials and functional feed additives [18]. Microalgae have good nutritional profiles, which have emerged as good candidates for use in aquaculture [19,20]. Algae can promote growth, stimulate the immune system, and enhance fish color, in addition to utilizing waste-derived nutrients such as nitrate, nitrite, and TAN (total ammonia nitrogen) [21]. Yadav et al. [22] conducted a study to evaluate the effect of dried chlorella species on the survival and growth of common carp (*Cyprinus carpio*). The fish fed with the microalgal biomass showed a great improvement in weight gain, lower FCR, and protein efficiency ratio [22]. A cost/benefit analysis showed a significant reduction in the cost of formulated feed compared to commercial feed, which can enhance the profit margin of fish farmers. This research highlights the importance of algae as a novel non-conventional feed ingredient. Using this strategy, the waste carbon dioxide can be further utilized to formulate alternative feed supplements.

Biofloc production is a reasonable strategy to reduce environmental impacts by contributing low emissions. The Biofloc production and efficiency depend upon different factors, such as the cultured species [23,24]. Debbarma et al. [25] reported Biofloc production's importance for managing aquaculture nitrogen wastes. The Biofloc production system showed the best performance in terms of growth, condition factor, digestive enzyme activity, and survival. The production cost is one of the biggest causes of the limitation of the applicability of SCP and other newly emerged non-conventional feed ingredients in aquafeed [26,27].

Designing the new, highly effective aquafeed diets by combining plant- and animal-based diets (insect meal/poultry by-product meal) may be a revolutionary technique [12]. Poultry by-product meal (PBM) is a cost-effective and sustainable protein source that is rich in essential amino acids and has high nutrient digestibility [28]. Different studies have been conducted to replace the vegetable-protein-based diet with an animal-based diet (insect meal/poultry by-product meal). Intestinal histological changes and inflammatory responses were reduced in gilthead seabream due to this novel strategy when the amount of vegetable protein in the fish diet was decreased. Incorporating insect meal into the diet of seabream had a favorable impact on molecular inflammatory markers [12]. Poultry by-product meal positively improved lipid absorption in the seabream diet. Zarantoniello et al. [29] examined the effect of conventional and novel feed additives, which included Louisiana red claw crayfish (*Procambarus clarkii*) meal (RCM) and dried microbial biomass from *Tetraselmis suecica* (TS) and *Artrhospira platensis* (AP), on rainbow trout (*Oncorhynchus mykiss*). The fish's development was unaffected by the vegetable protein sources, including 0.25 percent of conventional feed additives, and AP-based diets, but their severely compromised gut health condition marginally improved. The fish's general welfare and intestinal integrity were preserved by RCM and TS-based diets, but the fish's growth performance was poor. This might be because these diets contain certain biogenic amines, which could negatively affect nutrient uptake. Gaudioso et al. [11] evaluated the effect of poultry by-product meal and *H. illucens* meal on gut microbiota inflammatory and immune markers of fish when substituted with vegetal protein. When poultry by-product meal was added to vegetal protein meal (VM), the growth performance and microbiota composition were maintained as in FM. Meals made from insect and poultry by-products demonstrated better fish health and were recommended as the ideal replacement for plant-based proteins. In the case of insect meal, the aquaculture industry faced some cost-effectiveness issues. Therefore, it was recommended to use a combination of insect meal and poultry by-product meal for better fish growth performance. Another study conducted by Pulido-Rodriguez et al. [30] showed the positive effect on growth performance of red swamp crayfish when replacing vegetal protein with insect meal by-product. However, *Tisochrisis lutea* and *Tetraselmis suecica* (marine algae) were added at a low inclusion level, which badly affected the fish growth performance and increased the FCR value.

A feed with balanced nutrients is vital for improving fish growth and development. By 2020, fishmeal production was expected to rise to 70,969 thousand tons globally, a nearly 10-fold increase from 1995 [31]. The fishmeal ingredients used to prepare feeds are under a lot of stress as a result of these expanding numbers. According to studies, insects may be a feasible alternative to fishmeal in the near future, as they are a good source of macromolecules and micromolecules [32–35]. The substitution of fishmeal with insect meal is a unique concept in aquaculture. However, aquaculture practices currently employ a diverse range of insect species. This category of insects includes maggots (*Musca domestica*), black soldier flies (*H. illucens*), silkworm pupae (*Bombyx mori*), grasshoppers, and mealworms (*Tenebrio molitor*).

A significant effect has been observed in the growth performance of fish when fish are fed an insect-based meal. Tran et al. [36] reported that when aquatic animals were fed with *Tenebrio molitor* and pupal full-fat silkworm *Bombyx mori* they showed a substantial increase in Hedges' g value for SGR with the reduction in FCR. The growth performance of aquatic animals fed with insects vary according to the stage and species of both the insects and aquatic animals. It is documented in many studies that when fishmeal is substituted with more than 30% insect meal, a negative effect on growth performance is observed [37,38].

The nutritional profile of insects has a major role in deciding the substitution level of fishmeal. The protein part of insects' diets ranges from 50–82% (dry matter basis), comparable to fishmeal ranging from 60–72% by weight. Insect meals are rich with essential amino acids, but different species have observed minor variations depending upon their orders. Hydroxyproline and taurine are unique ingredients in insects, absent in a plant-based diet but present in fishmeal [39]. The insect species are enriched with saturated fatty acids and less in the concentration of PUFAs. On average, the n-6/n-3 ratios in terrestrial insects are three times higher than in aquatic insects [40,41]. Fishmeal and fish oil are the main components of fish feed.

To preserve the sustainability of food, new protein substitutes must be used in replacement of fishmeal and fish oil due to their scarcity [42]. Although there is literature on the nutritional value of insects, there is a lack of information for a thorough assessment of the factors influencing that nutritional value. The challenges with employing insects as a feed for aquaculture to address fishmeal scarcity are discussed in this review.

1.2. Ecological Advantages of Using Insects in Fishmeal Diet

Environmental issues such as the overuse of natural resources, loss of biodiversity, and rising pollution levels directly affect global climatic conditions. This fact is evident from the scientific reports and data published in the last decades [43]. Different strategies and approaches have been applied to combating environmental problems, among which the concept of bioeconomy is the most prominent. The concept of bioeconomy focuses on utilizing food waste or algae [44].

As the world population increases rapidly, there is a need for a constant supply of protein with reduced environmental impacts [45]. Recent research suggested that insect-based meals could positively impact the environment by selecting a suitable diet. Incorporating yellow mealworms into the diet of rainbow trout decreased the net primary production use. Still, it did not lower the land use, global warming potential (GWP), eutrophication, and energy demand [46]. However, different results have been achieved in the case of *H. illucens*. When *H. illucens* is added to the arctic char diet, it reduces the environmental impacts by reducing abiotic depletion, GWP, acidification, and land use [47].

1.3. Waste to Wealth Concept

Agro-industrial waste's continuous production and proper disposal are major environmental issues. Still, the improved nutritional value of these agro-industrial wastes is paving the way for these wastes to be valorized in animal/fish feed [48]. Jayan et al. [49] proposed this concept by valorizing castor cake or meal by standard processes. The growth and nutrient utilization indices of *L. rohita* were significantly improved when fed with castor oil protein isolates. The biodegradation of plastic is also one of the biggest environmental problems. Using insects in the biodegradation of plastic is a novel approach. *Tenebrio molitor* has ability to biodegrade plastic waste. Both forms of *Tenebrio molitor* larvae and imago are plastic eaters. Bulak et al., 2021, also reported that *Tenebrio molitor* could actively degrade plastic waste.

Aquafeed has a finite shelf-life and is easily subjected to rancidity due to the peroxidation of lipids [50]. The oxidated lipids have a detrimental effect on the feed quality, reducing the palatability and nutritional value of feed [51]. Several insect species have shown the potential to recover the nutrients from expired fish feed. The black soldier fly has great potential to recover nutrients from expired fish feed [52].

Moreover, the black soldier fly is also considered an ideal candidate for converting waste into protein-rich biomass that can be used as animal feed [53,54]. This method relies on the black soldier fly larvae to feed on the wastes, which will reduce it to 50–80% (wet weight) residue and yield useable and high-quality biomass at a rate of 20–30% (solid basis) [55]. Black soldier fly larvae fed on waste are a good source of protein and are used as feed for fish [39], and the residue can be used as fertilizer for soil [56].

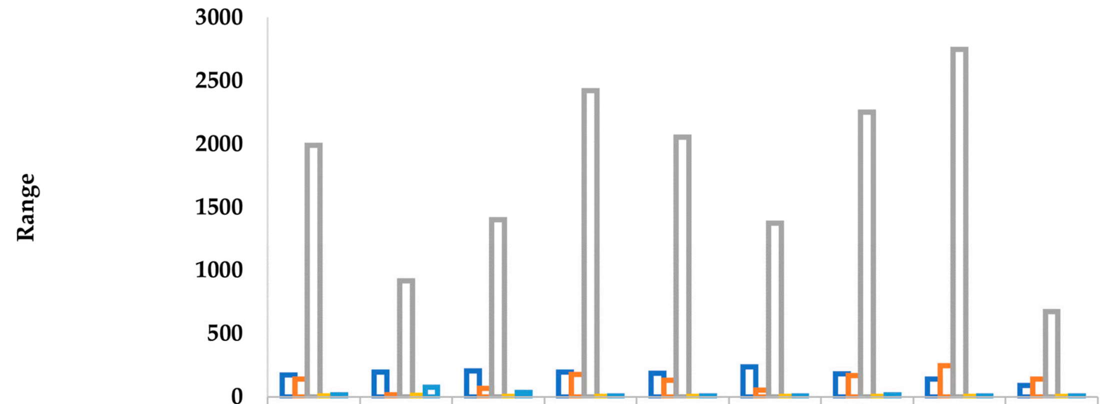
Insects are simple to grow and can be produced in large quantities with little need for water or land [39,57]. They grow quickly due to their fast reproduction rate [53,58] and have high feed conversion efficiency [57,58]. Insects can be grown on organic food waste, and they can convert this waste into protein and fat-rich biomass [59]. Additionally, this approach reduces environmental problems related to the reuse of food waste [53].

2. Nutritional Value of Insects

There are around one million insect species around the globe, and they are essential to the integrity of food chains and ecosystems. Although the majority of Europeans still view insects as harmful pests, several insect species are used as food in 100 different countries [33,60]. Insects are the largest class of arthropods and have been used as a food source for humans throughout history. Numerous insect species can be used as food, but only a few have been domesticated, such as silkworms and honeybees [61]. Insects, a high protein source, are also thought to be an excellent substitute for fishmeal for many freshwater and marine fish as aquaculture production rises day by day. Due to their adequate protein content, amino acid composition, and digestibility, animal by-product meals (AM) can be used in aquaculture instead of fishmeal [62].

Among the plant proteins, soybean meal is one of the most logical alternatives for high-quality fishmeal due to its high protein value, healthy amino acid profile, and low price [63]. Plant-based protein diets have been extensively studied in the past few years as a protein source for aquafeed formulations [64–66]. Plant-based diets are more economical as compared to animal proteins, but they have many limitations that make their substitution with fishmeal questionable, such as the absence of some vital amino acids, low palatability, the presence of anti-nutritional factors, and competitive prices with other food production sectors [66–68]. Additionally, essential components such as taurine and hydroxyproline which are rich in fishmeal are lacking in plant-based substances [69,70], whereas a variety of insect species contain high levels of taurine [71]. Taurine is the essential ingredient for the growth of brood stock and juvenile fish. A taurine-deficient diet results in increased demand for vitamin E and C, particularly in the larvae of marine water fish [72]. The insufficiency of taurine may cause serious psychological abnormalities, green liver disorder, and stunted growth [73]. Fish's principal physiological and behavioral responses are associated with taurine availability in the diet, including the survival rate [74], growth, immune response, and antioxidant activity [71].

As a result, interest in insect meal (IM) as a feasible feed alternative in fish aquaculture has developed dramatically. Insects are a rich source of energy due to macronutrients and micronutrients in sufficient amounts, making them the best suitable fish food [57,75]. It has been discovered that insects contain an adequate level of crude protein similar to soybean meal but slightly less than fishmeal by comparing the nutritional value of several insect orders, soybean meal, and fishmeal. The quality of protein depends upon the presence of essential amino acids, so fishmeal is used as an aquatic feed due to its healthy amino acid profile. Fishmeal is considered a source of high-quality protein because it contains a high amount of digestible essential amino acids, including lysine and methionine, which are thought to be absent in grains, the primary source of animal feed [76]. The amino acid composition of many insect species is currently unknown. With an adequate amount of methionine and lysine, Diptera's amino acid profile is comparable to fishmeal. Some insect species even have a higher amount of EAA than fishmeal, such as histidine and threonine in Diptera and leucine in Coleoptera and Orthopterans. Insects have a high level of polyunsaturated fatty acid n-6, lower than soybean meal but higher than fishmeal [77,78]. One critical point is that nutritional composition varies among the species. Their nutritional composition also varies according to order, diet, and developmental stage [79], as shown in Figure 1.



	Black soldier fly	House fly (A)	House cricket (A)	Super worm (A)	Mealw orm (L)	Mealw orm (A)	Giant mealw orm (L)	Waxw orm (L)	Silkw orm (L)
Protein (g/kg)	175	197	205	197	187	237	184	141	93
Fat (g/kg)	140	19	68	177	134	54	168	249	144
Calories (kcal/kg)	1994	918	1402	2423	2056	1378	2252	2747	674
Thiamin (mg/kg)	7.7	11.3	0.4	0.6	2.4	1	1.2	2.3	3.3
Riboflavin (mg/kg)	16.2	77.2	34.1	7.5	8.1	8.5	16.1	7.3	9.4

Figure 1. Nutritional value of potential insects used as fish feed. Reproduce from sources [80,81] (L = larvae; A = adult).

2.1. Proteins

Insects are an excellent source of protein since they contain a good proportion of amino acids; their levels of protein range from 25 to 75 percent (DM) [82–85]. A protein factor (Kp) of 6.2 can be used to calculate crude protein content by multiplying nitrogen content by protein. In order to fulfill fish nutritional demands, we advise using Kp modification based on the quantity of amino acids when calculating insect-containing practical feed compositions [86]. Hung et al. [87] studied that increased protein content shown among the treatments does not seem to be important for the observed growth performance improvement. The erroneous measurement of amino acids and amino acid loss due to methodological difficulties such as hydrolysis might result in incorrect calculations of crude protein [88]. The nitrogen of chitin is the main factor in the over-estimation of protein [89]. When insect protein is compared with plant and meat proteins, it is found that insects contain a substantial amount of good-quality protein due to balanced amino acid proportions [90,91]. Protein content varies amongst different orders due to different factors, and Orthoptera has the maximum protein values, ranging from 60 to 77% [92–94]. The crude protein ranges from 40 to 50% in Diptera, such as in the case of larvae of *Musca domestica* where CP was 46.9% and in house fly where it was 37–57% [92,95]. *Holotrichia parallela* is an edible beetle with a protein content of about 66% and an amino acid score of 87 and 100, with threonine as a limiting amino acid [96]. The protein level of *T. molitor* larvae is 46% [97], *H. illucens* 39% [98], *A. domesticus* 64–71% [99], *L. migratoria* 48–52% [100], *B. mori* 48–55% [101], termites 20–43% [102,103], beetle species 26–50% [102,104], and grasshoppers 26–45% [102,103].

It has been found from recent studies that usually an animal-based diet contains 40% of essential amino acids, but the range of essential amino acids in edible insects is about 46–96% [105]. House cricket meal contains some essential amino acids even at a higher concentration than plant- and other animal-based meals. House cricket meal also meets all the amino acid requirements recommended by the WHO (World Health Organization) [106–108]. Leucine content in Orthoptera is similar to animal-based protein but greater than soybean [106]. Another important amino acid found in greater quantities in insect proteins than in plant proteins is lysine [105]. Beef and eggs are good sources of methionine, serine, and tryptophan, which cannot be found in adequate amounts in some edible insects such as house crickets [107]. The silkworm is an edible insect containing 17 amino acids, with all essential amino acids. The content of essential amino acids is 47% in silkworm pupal protein, according to the recommendation of the WHO. In both male and female silkworm pupae, lysine was the amino acid that was most prevalent [109]. Numerous research studies have indicated that protein and AAs act as mediators of the trade-off between growth and immune protection. They are considered growth-limiting nutrients, particularly in those insects that feed on plant material.

2.2. Carbohydrates

Chitin makes up between 5% and 20% of the dry weight of insects [110,111]. It is a polysaccharide that is present in the exoskeleton of many insects in varying amounts and makes up 6.71–15.98% of carbohydrates [112]. Chitin is impermeable in a liquid medium and is the most common carbohydrate in biomass after cellulose. Carbohydrates are a rich source of nitrogen and carbon [113,114]. Generally, carbohydrates computed as nitrogen-free extract are found in minor levels in insects [83,85]. Some of the carbohydrate levels of edible insect species are described in the following; yellow mealworm larvae have a carbohydrate content that ranges from 1–7% [115], *Rhynchophorus phoenicis* larvae 5.53% [116], *R phoenicis* 20.23%, *Heteroligus meles* 20.10% [104], *Gynanisa maja* larvae 10.70%, *Ruspolia differens* 8.40%, *Macrotermes falciger* 32.80% [103], *H. illucens* 10–20% [98], *Locusta migratoria* 4–5.5% [100], and *Bombyx mori* 23% [101]. However, these levels are probably due to food left in the gastrointestinal tract.

2.3. Lipids

Researchers have realized that certain insects contain a lot of lipids. Insects can therefore be used to increase lipid intake. When 20% ground yellow mealworm larvae were used with wheat flour to generate extruded cereals, the lipid content of the final product increased from 0.9 to 5.4% [117]. Insects contain a significant concentration of unsaturated fatty acids, which must be examined during the preparation and preservation of insect meals [118]. Triacylglycerols account for approximately 80% of lipids, which is a reservoir of energy during periods of heavy energy consumption. Orthoptera, Lepidoptera, Blattodea, Isoptera, and Coleoptera have average lipid contents of 13%, 28%, 29%, 32%, and 33% dry weight, respectively [119]. Insects at larval and pupal stages have more lipids than adults [111]. The lipid content of *T. molitor* larvae is 33% [97], *H. illucens* larvae 38% [98], *L. migratoria* 19–20% [100], crickets 12–25% [120], termites 22–43% [102,103], beetle species 21–32% [102,104], *A. domesticus* 18–22% [99], *B. mori* 19% [101], and grasshoppers 3–49% [102,103].

Phospholipids are commonly found in nature and are responsible for maintaining the structure of membranes [121]. The phospholipid concentration of lipid content is about 20%; however, it changes with life stage, insect order, and species [121,122]. In insects, lipid content comprises a comparatively high concentration of C_{18} fatty acids, including oleic, linoleic, and linolenic acid [121]. The palmitic acid level is slightly higher than other lipids, and the lipid profile is greatly influenced by the diet fed by insects [90].

Insects are rich in n-6 fatty acids but deficient in n-3 fatty acid contents. However, this n-6/n-3 ratio is unsuitable for human health [123]. Therefore, different strategies are being employed to improve the fatty acid profile of insects. The content of n-3 fatty acids can be increased by using a suitable substrate; thus, the nutritional value of insects can be improved. Different factors also affect the fatty acid profile of insects and substrates, such as the rearing environment. This fact was also supported by Ruschioni et al. [124], who reported that levels of linoleic (C18:2n6) and alpha-linolenic (C18:3n3) acids varied amongst the insects even when they were reared on the same substrate. PUFAs are abundant in edible insects, commonly known as linolenic and linoleic acids [125]. However, the insects do not contain eicosapentaenoic acid (EPA) or docosahexaenoic acid (DHA), which are necessary for the health of human beings [125]. Lauric acids are one of the most important medium-chain saturated fatty acids in most insects. HI contains a substantial amount of lauric acid, which has antimicrobial properties and thus can modulate the intestinal health of host organism [126].

2.4. Vitamins

Insects have a range of vitamins that are either water-soluble or lipophilic [127,128]. A variety of insects having thiamine were listed by [90]. Its concentration varies between 0.1–4 mg per 100 g (DM). Riboflavin, also known as vitamin B_2, is found in edible insects and plays an important role in metabolic function. The yellow mealworm and the house cricket *Acheta domesticus* have high contents of vitamin B_{12}. Many other species that have been studied possess only trace quantities of this vitamin [90]. Insects often have low quantities of retinol but high levels of biotin, pantothenic acid, and riboflavin. Another important vitamin, folic acid, is identified in significant concentrations in different insects [119]. This trade-off is thought to focus on dietary nutrients, a significant idea in studying nutritional immunology [129,130].

2.5. Minerals

Edible insects are a good source of minerals such as zinc, sodium, potassium, iron, magnesium, copper, calcium, manganese, and phosphorous [131,132]. A substantial amount of iron is found in the moth *G. belina* (31–77 mg per 100 g of dry matter) and *Locusta migratoria* (8–20 mg per 100 g of dry matter) [133]. Similarly, a good quantity of zinc is found in caterpillars of mopane (14 mg per 100 g of dry matter) and *R. phoenicis* (26.5 mg per 100 g of dry matter) [90]. Hyun et al. [134] reported that edible insects such as the grasshopper *Oxya chinensis* contain very little heavy metal that is safe for human consumption. The solubility of iron was found in the following order in different insects: cricket > mealworms > grasshopper = buffalo worms > sirloin beef. Grasshoppers, crickets, and mealworms are reported to have high solubilities for Cu, Mn, and Zn. Similarly, the high solubility of Ca and Mg were reported in mealworms [135].

Kosečková et al. [136] examined the mineral content of the house cricket, yellow mealworm, desert locust, and super worm. All these insect species were reported to be good sources of iron. They reported that a good quantity of Zn, Cu, and P was found in house crickets, yellow mealworms, and desert locusts, even greater than the DRV (dietary recommended values). These insect species are all very low in Cd and Pb content, indicating that eating them poses no risk. Eating insects can increase zinc, sodium, phosphorus, potassium, calcium, iron, copper, manganese, and magnesium availability in terms of mineral nutrition [137]. Mopani or mopane, a caterpillar of moths, contains an iron concentration of 31–77 mg per 100 g DM. The ranges of different minerals (mg/kg) in *T. molitor* are Ca (349.2), P (5600–5700), Mg (1290–1416), Zn (95–101), Fe (60–64), Cu (11.4), Mn (7.0), B (20.3–24.2), and Mo (0.6), and in *B. mori* Ca (987.2), P (8550–8860), Mg (2400–2600), Zn (130–151), Fe (49–50), Cu (9.3–9.5), Mn (16.2–17.6), B (10–18.8), and Mo (0.2) [101].

2.6. Functional Properties of Insect Meals

Insect proteins have many favorable characteristics that make them fit to be used as food and feed. However, it is very important to evaluate the functional properties of insect protein before their substitution in any food and feed [138]. Depending upon insect protein's techno-functional properties, which include solubility, water and oil holding capacity, gelling, and emulsification, different food processing methods can be applied to improve the quality of insect-based food [139]. Several studies have been conducted to investigate the improvement in the functional properties of insect protein by applying suitable processing strategies [138]. Drying, defatting, and extraction are the different processing methods commonly used to improve the functional properties of edible insect proteins [140]. By enhancing the protein content, fractionation processing enhances the functionality of insect proteins [138,141–143]. Kim et al. [142] reported that the functional properties of *T. molitor*, *P. brevitarsis*, and *Allomyrina dichotoma* increased with protein content. Another important method for increasing protein functionality is enzymatic hydrolysis [138,144]. Purschke et al. [145] examined the effect of enzymatic hydrolysis on the functional properties of *L. migratoria*. They observed the different changes in functional properties of *L. migratoria* by applying hydrolysis conditions. The functional properties of *L. migratoria* (solubility, gelling, foaming, and water and oil holding capacity) were increased with the decrease in the molecular weight of protein.

There was no difference in the protein functionality, but a reduction in emulsifying activity was observed with the application of enzymatic hydrolysis [146]. Mintah et al. [143] examined the enzymatic hydrolysis of soldier flies that improved the dispersibility, turbidity, and particle size by changing the protein secondary structure. Lipids and chitin removal also improve foaming and emulsifying properties, respectively.

3. Factors Influencing the Nutritional Value of Insects

3.1. Insect's Species

An insect's species and order affect its nutritional value. The majority of the insects studied have a significant amount of protein [123], almost similar to soybean meal but inferior to fishmeal [147]. Usually, Orthoptera has a higher CP, between 50 to 55 g/100 g [148], Diptera amino acid content is analogous to fishmeal [92], and Coleoptera has a better amino acid profile than soy meal [149], although not comparable to fishmeal. The ratio of amino acids varies widely amongst the various insect orders, plant meals, and fishmeals. Histidine and threonine are more deficient in insect meals than in fishmeals out of all the essential amino acids. However, insect meals contain a sufficient level of tyrosine, lysine, and methionine compared to soy meals. Diptera has a similar amount of histidine, lysine, and threonine as fishmeal. Diptera contains a higher level of phenylalanine than soybean meal and fishmeal, but the methionine level is comparable to fishmeal. Leucine is abundant in the orders Orthoptera and Coleoptera, but deficient in the order Diptera. The percentages of tyrosine and valine are higher in Orthoptera, Coleoptera, and Diptera than in fishmeal [150,151]. Some of the values of the amino acids in different edible insects are presented in Figure 2 and Table S1.

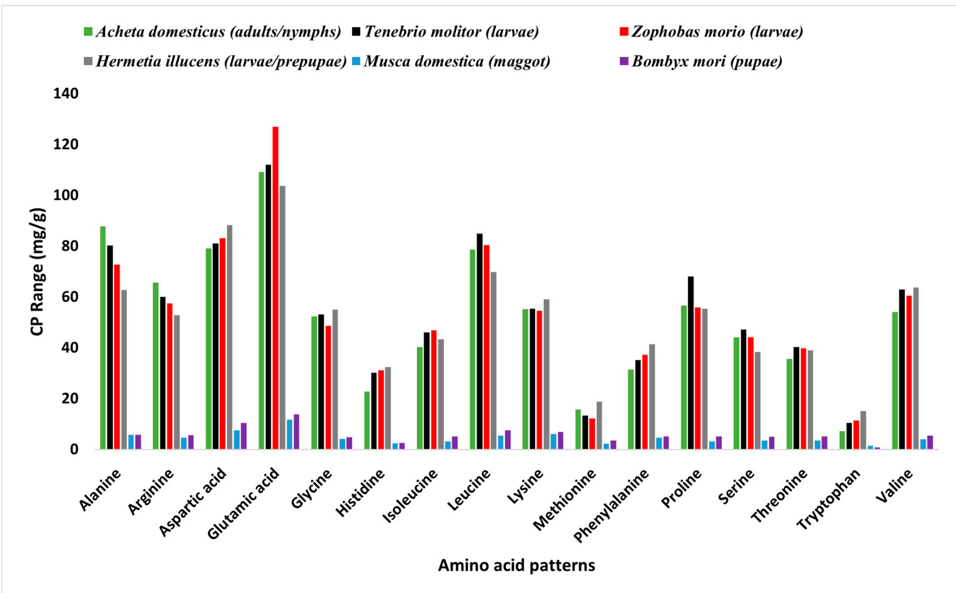


Figure 2. Patterns of amino acids (mg/g CP) of six commonly used edible insect species. Sources [80,82,152–155].

3.2. The Developmental Stage of Insects

An insect's developmental stage may also have an impact on how nutritious it is. With advanced developmental stages, it has been demonstrated that the protein content is generally increased. On the other hand, lipid content is the reverse. The orthopteran species is a high-protein species in its adult form. In Diptera, CP levels range from 40 to 50% in larvae and 50–62% in pupae in several species [150]. In general, larval stages have higher lipid contents than adults. At various phases of development, the lipid percentage in *A. domestica* varies between 14% and 22% [152]. Five-day-old larvae of the black soldier fly contain a maximum percentage of crude protein which is about 61%, and as the insect becomes older its crude protein content gradually declines [156].

The pupae of most insects contain a sufficient amount of saturated fatty acid but a lower amount of unsaturated fatty acid, however, adults behave differently [157]. Ademolu et al. [158] investigated differences in the nutritional composition of distinct post-embryonic developmental stages of the grasshopper *Zonoceros variegatus* nymphs and adults. There is an increase in protein content but a decrease in lipids from nymphs to adults. Similar to this, several Blattodea species show a correlation between developmental stages and higher protein and lower lipid levels [159]. One of the most significant features of insect development is the distinction between larvae and adult forms. Larvae and adults show diverse amino acid profiles; for example, yellow mealworm (*Tenebrio molitor*) adults are rich in protein and chitin, whereas larvae are rich in lipids [160,161].

3.3. Diet

Diet appears to affect the lipid composition of insects. Larvae and adults may consume a diverse range of diets, nonetheless, pupae usually do not, explaining the differences in amino acid, lipid, and mineral contents [162]. For example, in male bees amino acid, protein, and mineral contents vary with the development stage [157]. The orthopteran breeds in the wild have an 8.2% lipid content, while orthopterans bred in captivity have greater contents.

According to Barroso et al. [163], saturated fatty acids are abundant in terrestrial insects but they are deficient in polyunsaturated fatty acids, limiting their use as feed. In this study, the diet composition of BSFL was altered to improve lipid composition. This study suggests that diet-fed larvae contained three times more n-3 fatty acids and a reduction in the n-6: n-3 ratio compared to the control diet group. Dietary manipulation could quickly affect the lipid composition of the experimental larvae group. Van Huis et al. [164] prepared experimental diets from different organic products. Three types of edible mealworms were fed these diets to examine the effects of the experimental diet on the nutritional composition of the insects. Larval growth and survival rates as well as the protein and carbohydrate contents of experimental meals differed. The manipulated diet improved the FCE, crude protein, lipid composition, weight gain, and survival. Zarantoniello et al. [165] studied the rearing of BSF on coffee and *Schizochytrium* sp., and they found significant results in improving the FA profile of zebrafish larvae. The nutritional addition of BSF meal significantly impacted the fatty acid classes of the zebrafish larvae fed on the various diets. For example, the proportion of SFAs increased when insect meal was added to the diets, but the percentages of MUFAs and PUFAs frequently reduced as BSF inclusion levels increased. The higher inclusion of the BSFL in the diet reduces the n-3 and increases the n-6 FA. Chemello et al. [166] explained the effect of BSF mixed with *Schizochytrium* and stated that oocyte maturation stages, fish stress responses, and spawning and hatching success were all negatively impacted by higher replacement levels (BSF 75% and BSF 100%).

3.4. Processing of Insects

The ability of insect meal to replace fishmeal depends not only on the nutrition of insects but also on the bioavailability of nutrients. Many insect species have very high lipid levels. Different processing techniques are applied, including mechanical pressure for the defatting of insects by using different organic solvents such as petroleum ether. These processing methods can improve the protein content of IM further by generating various combinations of free amino acids (AAs) and decreasing the amount of undesirable lipids [167].

Insect meals have low palatability, which can be attributed to various factors, including chemical or biological contamination, anti-nutritional factors such as flavonoids and terpenoids in insect feedstuffs, and high monounsaturated fatty acid [92]. All these factors make insect meals susceptible to oxidation and subsequent rancidity problems. Drying, hydrolyzing, ensiling, and defatting are the different processing methods that can improve fish nutrition by improving the nutrient availability, digestibility, palatability, and composition of insect meal [168]. The processing technique of edible insects can affect their nutritional content. Toasting and solar drying of grasshoppers decreased their protein digestibility and niacin content, but winged termites retained their riboflavin and retinol content [169]. The processing step directly affects the protein quality and content of insect extracts. The nutritional composition of the mopane caterpillar was improved in terms of digestibility and crude protein after degutting, but the roasting resulted in decreased crude protein level and digestibility of the insect [170]. Thus, exploring and developing efficient processing procedures to enhance insect meal commercialization and consumer acceptability is necessary [131].

Fermentation, drying, extraction, enzymatic modifications, and thermal processing are the most common methods that improve insect meal quality, flavor, and texture. It is interesting to note that different insects react to processing methods differently, demonstrating various outcomes for in vitro digestibility [171]. Pre-processing technologies are the first steps in the processing of edible insects. These initial steps are normally performed before food production and are stated as pre-processing phases. Insect degutting, drying, and defatting are pre-processing steps [172,173]. Protein extractability is frequently improved with defatting. This pre-processing stage is completed in some studies following measurements of other protein-related parameters impacted by defatting [142,174]. Additional innovative processes, including pulsed electric field, ultrasound, cold plasma, and high-pressure processing, are extensively applied to replace standard operations and can be used as a pre-processing step [175]. These techniques improve the product's quality, digestibility, and preservation capacity [138,176]. At the industrial level, protein extraction is performed by utilizing different enzymes and organic and inorganic solvents. Newly emerging processing techniques are currently utilized to extract chitin, protein, and lipids in edible insects. The extraction rate varies among the insect species and can affect the extraction yield and insects' physical, chemical, functional, and bioactive properties [174]. A layout of the processing techniques is illustrated in Figure S1.

3.4.1. Enzymatic Hydrolysis

Enzymatic hydrolysis is principally performed to understand the bioactive properties of edible insect hydrolysate after stimulation of digestion in the gastrointestinal tract [177], specifically angiotensin-converting enzyme inhibition [178] and antioxidant capacities [179]. Techno-functional properties of enzyme hydrolysates also change during the processing, and this area needs to be investigated further. In the case of the locust *L. migratoria* L. [145], techno-functionality was increased by utilizing different food-grade proteases alone or in combination with varied enzyme–substrate ratios.

3.4.2. Drying and Thermal Processing

Drying is one of the best processing techniques that increases the shelf-life of insect meals. This processing technique ranges from conventional methods such as sun drying to contemporary methods, including microwave-assisted drying and freeze-drying. Drying stops food spoilage by reducing the water content, inhibiting the enzymatic and microbial reactions. Microbial growth depends upon the availability of water content; when the water content is low, microorganisms stop growing [172]. As the drying process reduces the water content, there is an increase in the concentration of dry matter, which does not damage the physical and chemical properties of insect meal and thus increases the shelf-life [180].

Thermal processing is also a widely used technique in the food production industry that inhibits microbial reactions and extends the shelf-life of insect meals [181]. Thermal processing induces physical and chemical changes without damaging the quality of food [182]. Different types of thermal processing such as hot air drying and oven-assisted boiling show the highest result in maintaining the quality and standard of mealworm larvae [183]. Thermal processing can process the silkworm larvae into a yellowish powder by using warm water, drying, and grinding. Thermal processing can also damage some important bioactive compounds [184] and the nutritional content of insect meals [185]. Thermal processing increases the bioavailability of biomolecules by increasing the process of protein hydrolysis [186]. When *A. domesticus* and *T. molitor* are heated at 200 °C for 10 min, improvements in the nutritional value and AA profile were observed [187].

3.4.3. Fermentation and Antibiotic Resistance

Recently, fermentation technology has been used to produce insect meal, increasing the nutritional value and quality of the meal [188]. Considerable literature is currently available on fermented insect meal, including other insect strategies such as feed additives and biofuel [189]. A particular culture of microorganisms is utilized to ferment the biomolecules in the substrate during the fermentation of the insect meal, improving its nutritional value and digestibility. Antibiotic-resistant bacteria can undoubtedly come from insects [190,191]. However, there are currently not many studies that have been published that demonstrate how frequent antibiotic resistance is in edible insects [192–195] and the antibiotic-resistant (AR) genes in different edible insects. The existence of transferable AR genes in edible insects has not yet been precisely linked by studies to rearing conditions. Additionally, no research has been conducted to ascertain the loads and dynamics of antibiotic resistance in certain microbial communities associated with edible insects. This aspect of edible insect processing needs much attention for the healthy production of food and feed.

4. Potential Insects Used as Fishmeal

Over the last two decades, numerous studies have been conducted to lower the demand for fishmeal, fish oil, and their by-products in the aquaculture industry [196], which resulted in increased incorporation of plant-derived ingredients in fish feed [197]. However, compared to fishmeal-based diets, adding these substances to aquafeeds imposes greater pressure on water and land resources [197] and generates more waste [198]. Several protein alternatives have been examined for fish feed, insect meal, and fishery by-products, showing the greatest potential to fulfill aquafeed's protein requirements in the next decades [18]. For several aquatic species, the successful incorporation of insect meal preference to fishmeal in the diet of many fresh and marine water fish has been widely reviewed [39,199,200].

4.1. Black Soldier Fly

The black soldier fly (BSF) (*Hermetia illucens*) is one of the best options currently used as an alternative source of protein in the aquaculture diet. It is one of the extensively investigated insect species due to its healthy nutritional value [199]. The insect's balanced nutritional composition makes it an ideal and possibly significant alternative to fishmeal, and the larval form is what is used to prepare BSF meals.

Bioactive compounds with nutraceutical properties, such as lauric acid, chitin, and antimicrobial peptides, are present in the BSF larvae meal. These compounds are very important for improving the growth of the fish [201]. Previous research suggests that these chemical compounds have either prebiotic or probiotic properties; they are fermented by beneficial commensal bacteria in the intestine and produce metabolites that improve the host's health [202,203]. Black soldier fly (BSF) larvae growth as fish feed is a promising approach, since it uses organic wastes while also being safe for humans and animals [201,204]. BSFLM also has an amino acid profile comparable to fishmeal [39], making it a good candidate for long-term mass production. Many experimental studies have indicated that substituting FM with BSFLM in aquaculture has no adverse impact on fish development [205–208]. One of the best features of BSFLM is that it can utilize organic wastes as the substrate, such as animal dung [209,210] and plant waste, which includes vegetables and fruit wastes [211], algae [212], and fish [163,213]. The inclusion of fish offal in the BSF diet causes black soldier fly prepupae to absorb different lipids. In the modified prepupae, omega-3 fatty acids are found in reasonable amounts, which could be used as feed for carnivorous fish and other animals. Furthermore, this insect species may offer new approaches for reducing and recycling fish offal using different processing operations.

BSFL meal was found to have a greater growth response and feed conversion ratio than FM in Nile tilapia [214]. Previous studies have shown that when BSFL meal is included in the diet of blue tilapia, *Oreochromis aureus*, it shows positive results. The replacement of FM with BSFLM for different inclusion levels greatly increases *O. niloticus* growth without causing detrimental effects. It has also been studied that BSFL meals can completely replace FM [215]. It is obvious from previous research that in yellow catfish, FM can be substituted for up to 20% of the diet [216]. There were no remarkable changes in sea bass growth, feed consumption, survival, and hematological parameters when the fishmeal was partially replaced with black soldier fly meal. Additionally, it was discovered that switching from fishmeal to BSFM at 50% for eight weeks reduced feed costs by 15.5% compared to fishmeal pricing [217]. The HI has good protein solubility, water binding capacity, and lipid binding capacity [174].

4.2. Common Housefly

Housefly (*Musca domestica*) maggot meal has a high nutritional value as an insect protein source. The housefly contains a substantial amount of proteins, lipids, and carbohydrates similar to fishmeal, improving fish growth [53]. It also comprises several biologically active compounds such as antimicrobial proteins, lectin, and chitin [218]. Maggot meal shows good potential to replace fishmeal, as the housefly has a fast reproduction rate, balanced nutrient proportion, and simple processing method [219]. Energy, protein, and micronutrients EAAs and FAs are abundant in housefly larvae. Housefly larvae are less expensive, have healthy nutritional contents, and are easier to produce than other alternative animal proteins. HFL meals, high in lysine, threonine, and methionine, can supplement protein-deficient cereals and legume-based feed for aquatic animals [220].

Houseflies can quickly digest food waste and cattle dung waste, which is organic, using nutrients from waste to reduce the volume of waste in its entirety. Maggot meal enriched with protein and oil from dried fly larvae could be used as important cattle and aquaculture fodder [150]. The fish efficiently absorb maggot meal, and its inclusion in tilapia diets appears to have no oxidative-stress-inducing effect on fish metabolism. It can be used effectively as a rich source of protein for the growth of tilapia fingerlings [151]. Wang et al. [221] observed the effects of four experimental diets supplemented with 25%, 50%, 75%, and 100% *M. domestica* (MD) larva meal on Nile tilapia. About 75% of MD meals can be included in the diet of fish without causing substantial adverse effects on the growth and development of fish. Adding maggot meal (MM) slightly enhanced fillet quality by making them tougher. It is also worth noting that several experimental diets significantly improved water quality compared to the control diet. Several investigations, including MM-based feeding experiments in different fish species, have been conducted over the last decade. Maggot meal can replace 100% fishmeal in the diet of Nile tilapia fingerlings [222] and African catfish [95] without damaging growth or nutrient utilization ability or causing oxidative stress [151,222]. Partially substituting FM diets with blowfly (*Chrysomya megacephala*) MM increased juvenile tilapia growth, feed efficiency, and survival [223].

Feeding tests were conducted on juvenile Asian bass to evaluate physiological responses to growth and fillet composition to dietary FM partly supplemented with housefly-maggot-based meal. According to the research, replacing dietary FM with up to 300 g/kg of housefly maggot meal might be achieved without harming development [224]. An eight-week rearing experiment on swamp eels (*Monopterus albus*) indicated that supplementing the food with housefly larvae had positive influences on the swamp eels' development and immunity [225]. In conclusion, several feeding studies on various aquaculture species have shown that adding housefly maggots to fish diets may boost growth and FCR while limiting physiological stress. Feeding fish diets with housefly maggot meal is also less expensive. It is a different protein source that may be used to replace FM in aquafeeds, depending on its nutritional content, availability, growth potential, and feed efficiency. This is especially helpful in underdeveloped nations when FM imports are expensive.

4.3. Mealworm

The yellow mealworm (*Tenebrio molitor*) is a fast-growing and rapidly reproducing insect that feeds on bread and cereals. In *T. molitor* (TM), the protein content varies between 47% and 63% and lipid content between 31% and 41%. The amino acid profile is in accordance with the nutritional demand of aquatic animals [120]. Mealworms are simple to produce, have a low environmental impact, have easily manipulable nutritional content, and are highly efficient.

Recent research has shown that TM meal is an innovative protein source that can partially substitute FM in chickens [226] and aquatic species [53]. A percentage ranging from approximately 33 to 74 of FM can be replaced by TM larvae without harming the growth of gilthead seabream [227]. They also reported to have tremendous potential for replacing FM in cattle and fish [39,53,228]. It is evident from previous studies that mealworms can substitute the fishmeal of rainbow trout [229], European sea bass [230], gilthead seabream [227], and blackspot seabream [231].

An approximately 35 percent substitution of yellow mealworm may replace fishmeal in European sea bass without slowing fish growth, whereas a 70 percent of fishmeal substitution reduces fish growth [230]. According to previous studies, higher inclusion levels of mealworms in rainbow trout meal had no negative effect on weight gain but enhanced the protein content and lowered the lipid content compared to the control group [229]. A 100% replacement of fishmeal with yellow mealworm meal enhances the Pacific white shrimp lipid content but does not affect the growth rate and feed conversion ratio [232]. When a considerable amount of the fish feed is replaced with a mealworm in common catfish fingerlings and African catfish, its growth retards [233]. The HI has good protein solubility, water binding capacity, and lipid binding capacity [174]. Insects have substantially greater phosphorus levels than calcium levels. They have higher phosphorus content than mammals. Mealworms lack calcium, so primarily feeding fish with mealworms might result in calcium deficiencies and body deformities. Despite this, the mealworm insect is an excellent choice to replace fishmeal [53].

4.4. Cricket

Crickets (*Acheta domesticus*) belong to the Orthoptera order, having a good amount of crude protein ranging from 55–73% and a sufficient amount of indispensable AA except lysine and methionine, which can be supplemented in the feed [80,92]. Cricket food is high in proteins and lipids and contains vitamins and minerals [234]. Cricket meal contains a significant amount of crude protein (64.9%) and lipids (17.4%) with a good proportion of amino acids, including lysine and methionine, which are deficient in a plant-based diet [235]. Recent studies reported that 8.7% of chitin is present in cricket meals, and its supplementation in the fish diet improved the interaction of chitosan glucosamine with bacterial cell walls; in addition, the consequent alterations in the permeability of cell walls reduced the bacterial population [236,237].

Due to their excellent nutritional value, live crickets are currently sold at the commercial level in big pet stores and markets as fish bait or supplemental feed for differential ornamental fish species. Cricket meal can substitute up to 100% of fishmeal in African catfish, showing better results than the control diet [238–240]. It has the potential to partially or completely replace fishmeal in fish feed [235,241]. A recent study investigated whether substituting insects (house cricket and super worm in equal proportions) for FM in perch feed could affect fish survival, growth parameters, and fatty acid composition [242]. Cricket meal might contain any xenobiotic ingredient, thereby altering enzyme activity.

Hanan et al. [243] described meat quality and the fatty acid profile of the insects *Zophbas morio* and *A. domestica*. These species were specifically selected for their simple breeding, standardization, and higher AA, FA, and vitamin contents. Only super worms and crickets possessed a significant concentration of vitamin A for the animals that feed on insects [82]. Fishmeal can be substituted with up to 50% cricket meal in red Nile tilapia without significantly affecting growth performance or feed consumption.

4.5. Locust

Locusts (*Locusta migratoria*) are generally produced to feed domestic and zoo animals and have also been studied for cattle feeding. They vary greatly in protein composition (29 to 70% on a dry matter basis) and lipid content (4 to 22% on a dry matter basis) [53,244]. Locusts are among the most commonly consumed insect species globally, but they have also been utilized as a supplementary protein source for chickens and fish [131]. Aquaculture development in Africa and Asia and the search for alternate protein sources led to feeding experiments with locusts and grasshoppers for catfish and tilapia [245].

A 50% inclusion level of locust meal yielded the optimum results in Nile tilapia in terms of growth. As a result, it is recommended that locust meals at a 50% inclusion rate can be added to the diet of tilapia fish without impairing fish growth. When about 20% of adult Orthoptera (grasshoppers or locusts) was added in the diet of catfish and tilapia, it did not affect catfish or tilapia digestibility or growth [246,247]. However, the use of locust meal as an alternative source of protein in aquaculture diets is still understudied, and no data on its use as feed for marine fish species are known [246,248].

4.6. Silkworm

The silkworm (*Bombyx mori*) (SW) is believed to have originated in China more than 4000 years ago [249]. Its pupae are the primary by-product of the silk industry, with about 8 kg of pupae produced for each kilogram of silk. Silkworm meal is prepared by properly grinding and drying boiled cocoons of silkworm larvae. SW meal is obtained by drying and grinding the larvae's uncoiled boiled cocoons, containing 56% protein and a substantial amount of essential amino acids [250]. Kurbanov et al. [251] investigated the effect of substitution of fishmeal with silkworm pupa protein on the growth and feed utilization ability of African catfish (*Clarias gariepinus*) fingerlings. Five isonitrogenous diets containing approximately 40% crude protein and different levels of fishmeal replacement (0–100%) were fed for 40 days at 5% live fish body weight. The growth rate and feed utilization efficiency of fingerlings fed diets with a 50:50 mixture of fishmeal and SPP were significantly higher than those fed diets containing SPP or fishmeal alone. The fishmeals of different fish species have been substituted with silkworm pupae meal and promising results were obtained, thus showing the good potential of silkworms to replace fishmeal. About 10% SWM can be successfully substituted in the diet of chum salmon and olive flounder [252].

The snakeskin gourami diet can be substituted with up to 15% SWP (silkworm pupae) without adverse effects on growth, but a 22% inclusion level of SWPM decreases growth rate and protein digestibility [253]. A 30–50% successful inclusion of defatted or non-defatted SWP can be achieved in rohu, common carp, mahseer, and rainbow trout [254,255]. A total FM replacement without adverse effects on growth has been observed in common carp and Japanese sea bass [256]. Some fish species show negative responses even when a low level of SWM is incorporated into their diet. In tilapia, a 5% inclusion level drastically decreased growth and development [257]. Jian carp also showed reduced digestive enzyme activity, heat shock protein activities, and increased oxidative stress when the diet was incorporated with about 8% of SWPM [258]. In walking catfish, the protease activity result is comparable to FM when 58% FM is substituted with SWP meal. SWP appears to be a potential source of protein for fish diets in general, except for Nile tilapia and Jian carp gourami. SWP meal was found to be an advantageous sustainable feed element in carp diets, with benefits for boosting growth performance and specific physiological markers, according to an eleven-week feeding research on *Cyprinus carpio* [259]. In the rainbow shark (*Epalzeorhynchos frenatum*), feeding experiments revealed that SPM could substitute up to 30% of FM in the diet [260].

5. Insects as Feed for Crustaceans

Fishmeal is a commercial diet for rearing prawns and shrimp because of its high protein content, favorable amino acid and fatty acid profiles, high digestibility, and palatability [205]. Farm animals' diets have recently begun to include insect larvae meals, and previous studies showed that insect meals are a promising addition to the diets of farmed crustaceans [205,232].

5.1. Shrimp

Studies have found different results comparing the growth rate performances of commercially produced shrimp and fish fed with FM substituted with insect meal. This could result from changes in meal preparation methods or diet formulation. The nutritional value of animal protein meals is influenced by the processing technique and the quality of the raw materials [261]. For example, research on rainbow trout showed that the BSF larval diet could replace 50% of fishmeal without impairing growth performance. However, a decrease in protein utilization efficiency was reported in shrimp [262]. Without impairing shrimp growth, a full-fat BSF (*H. illucens*) meal can substitute up to 25% of fishmeal [205]. Like this study, subsequent studies on *T. molitor* full-fat meal-based diets found that when methionine was added in adequate amounts, Pacific white shrimp's nutritional value and growth performance were on par with or even superior to those of FM-based diets [167,232].

Motte et al. [263] reported that utilizing TM meal in shrimp diets significantly enhances growth when paired with FM without affecting shrimp survival or feed consumption, even when TM replaces 100% of FM. Moreover, this insect meal's very important key feature is that it improves the immune system and resistance to infection, leading to increased shrimp survival. Improving immunity is critical when shrimp production intensity is very high, causing stress and increasing sensitivity to illnesses. TM meal has good potential as an efficient feed source for commercial shrimp farming. The 50% substitution of fishmeal with mealworms for the shrimp diet is ideal for boosting shrimp growth performance, while having no negative effects [167]. TM is a suitable replacement for FM that has no negative effects on the expression of important digestive enzymes, gut microbiota, or the Pacific white shrimp's immune system [264].

5.2. Prawns

Efforts have been made to supplement the diet of prawns with insect meal. A recent study examined the effect of replacing the diet of prawns with insect meal [265]. The insect meals were prepared from the larvae of three insects: house fly, BSF, and mealworm. Incorporating the black soldier fly into the fishmeal diets of prawns resulted in considerably higher prawn growth rate and survival. The shrimp survival rate was significantly reduced when fed a diet consisting of house fly larvae, but growth performance was incomparably higher. Insect inclusion in plant-based foods had little effect on growth performance, while survival was greater in the TM and HI inclusion diets. When TM and HI were added to fishmeal and plant meal diets, they increased the protein content of the prawns' muscles. Langer et al. [266] studied the consequences of replacing fishmeal with silkworm pupae, soybean meal, and earthworm meal in the freshwater prawn *Macrobrachium dayanum* for 90 days. The diet including silkworm pupae showed the second best result, closely followed by fishmeal.

Two studies investigated the utilization of seven diets for prawns farmed at suboptimal temperatures [267,268]. All seven diets supplied to the juvenile prawns were quickly devoured. Shrimp- and silkworm-based meals provided the best growth and survivorship, while fishmeal- and black soldier fly larvae meal (BSFLM)-based diets provided the poorest growth. Survival rates were comparable for diets based on soybeans, crickets, mealworms, and fishmeal. BSFLM inclusion in the diet caused the mortality in prawns after 1 day of feeding, which might be due to some antimicrobial or toxic compounds produced by BSFL. Similarly, as the termite meal inclusion level increased in the diet, decreasing order in growth was observed in prawns. Partial replacement of FM with 35% TM in prawns showed positive results but was lower than FM. Termite meal cannot replace fishmeal as an alternate protein source for *M. rosenbergii* juveniles. However, it can be added to the diet of prawns for amino acid supplementation since its addition can improve the growth rate [268].

6. Physiological Responses of Fish Using Insects as Fishmeal

Diet formulation is the key factor for sustainable fish production, as the composition and nutrition of the diet will directly influence the fish growth performance and health status [269]. An accurate and detailed examination of the organs involved in digestion and absorption of feed, immunological response, and metabolic processes should be conducted while testing new dietary formulations [270]. It is generally known that insects contain bioactive substances such as chitin, which, at specific concentrations, can strengthen fish immune systems and promote the diversification of the gut flora of fish [271]. Recently, scientists have been working on new aquafeed formulations such as insect meal and examining their effect on the physiological response of different fish species. A review of some of these studies is presented in the subsequent sections.

Recent research has shown that rainbow trout's inflammatory response can be lowered by including HI-based meal (*H. illucens* meal) in low-FM diets [272,273]. Additionally, it has been noted that HI-based meal positively impacts the intestinal physiology of various farmed fish species [274]. According to studies by Osimani et al. [275], Zarantoniello et al. [276], and Zarantoniello et al. [165], HI-based meals contain some bioactive substances, such as chitin and medium-short FAs. These useful substances have immune-stimulating, antimicrobial, and/or anti-inflammatory properties, which have positive and beneficial effects on fish gut health [277]. It is evident from recent research that the quality of the nutrients can affect the reproductive system (with an emphasis on oocyte quality). A good aquafeed composition is essential for brood stock's proper growth and development [270]. Chemello et al. [166] observed the physiological effect of different levels of BSF prepupae meal (0, 25, 50, 75, and 100%) on fish growth performance, lipid metabolism, stress response, and reproduction. For determination of the physiological response of fish to experimental diets, a multidisciplinary approach (biometric, gas-chromatographic, histological, and molecular analyses) was used. There was not any detrimental effect on physiological responses of fish when the fishmeal was replaced with 50% BSF meal in zebrafish. However, the inclusion of a higher level of BSF meal (75% and 100%) showed a negative effect on stress response, oocyte maturation, and spawning and hatching of zebrafish.

Sudha et al. [278] revealed the inclusion of different levels of BSFM in the catfish diet and its effect on the physiological response of catfish. When the fishmeal was replaced with 20%, 40%, and 60% diets, no significant difference in growth performance was observed compared to the control group. However, the inclusion of 100% BSFM in the diet of catfish showed a reduction in growth and feed efficiency. No significant differences in catfish's amino acid profile and hematological responses were observed when fed with different BSFM. The non-significant difference in the liver and intestinal amylase and lipase activity was observed in the inclusion of BSFM. Higher levels of BSFM (80% and 100%) significantly lowered the proximate body composition of fish and increased lipase activity. Fish fed with 80% and 100% BSFM showed increased congestion in the hepatocyte. Zarantoniello et al. [276] observed a significant growth and survival reduction when fish were fed with a diet containing 50% *H. illucens*.

Additionally, a 50% HI diet substantially decreased the hepatic lipid and glycogen content but increased hepatic *hsp* 70.1 gene expression. The inclusion of 50% HI in sturgeon's diet also badly affected gut histological morphometric parameters. Zarantoniello et al. [165] reported on the inclusion of insect meal and its effect on the physiological responses of fish. The different inclusion levels of BSF meal (0, 25, 50, 75, and 100%) in the diet of zebrafish showed a significant difference in the physiological response of fish. When the fish were fed with a high inclusion level of BSF meal (75 and 100%), severe hepatic steatosis was observed in the fish's liver. Inclusion of a high level of BSF meal resulted in a reduction in gut microbiota biodiversity, high lipid content, and significant upregulation of genes involved in immune response.

7. Challenges of Using Insects as Feed in Aquaculture

Chitin, a non-protein nitrogen molecule found in most insect cuticles, causes reduced meal digestibility and growth performance [279]. Increasing the chitin concentration in IM products to ensure a favorable response in fed species requires more investigation. Alkaline extraction may easily remove chitin [280], but it is costly and leaves chemical residues and contaminants [281].

In addition to the presence of chitin, a negative effect in the growth of aquatic animals is observed when insect meals are included in aquafeeds. This fact can be attributed to lower levels of fatty acids in the insect-based diets compared to the fishmeal control diet [13]. Many studies have reported that insects have lower levels of n-3 PUFAs [165], which results in lower n-3 PUFA levels in aquafeeds if substrates enriched with n-3 PUFAs are not used during the insect rearing. Zarantoniello et al. [276] found that a 50% substitution of fishmeal with BSFM caused a significant reduction in n-3 fatty acids, the result of which was a marked reduction in sturgeon weight and SGR observed when fed with BSF-substituted diets. In addition to fatty acids, insect meals are also deficient in some essential amino acids as compared to fishmeal, and manipulation of these components through the rearing substrate is still a big challenge [282].

Prices of insect meals are predicted to become competitive by 2023, but at present, IM prices are very high [283,284]. The main limitation of using insects is the existence of toxic compounds which can negatively affect fish physiologically, such as lowering growth and altering hematological parameters [285]. On the other hand, the substitution of FM and FO with *H. illucens* meal can reduce the content of some potentially toxic elements such as Ni, As, and Pb in fish feed, causing levels of harmful chemicals in animal feed to be below the permitted limit [286]. It is now widely acknowledged that dietary metal(loid) intake can cause chronic toxicity in aquatic species [287]. These pollutants can bioaccumulate or bio-magnify in food chains [288]. Consumption of PTE contaminates fish, thus is a major risk to human health. These PTEs should be examined in the environment and feed or food because of their hazard to feed/food safety and, eventually, human health. Non-defatted insect meals and oils show a dramatic change in FA profile, which shows huge variation in the quality of insect meal and its composition, limiting the usage of insects as feed ingredients.

Another important aspect of incorporating insect meal in aquaculture depends upon the aquaculture producer and consumer acceptance. Without consumer acceptance, adopting insects in the aquaculture sector is difficult. An accurate evaluation of factors involved in insects' production is also a big challenge, as it involves transitioning from the wild catching of potential edible insects from their habitats to their large-scale production. Intensive insect rearing requires intensive labor, as most commonly used insect-rearing methods are labor intensive. Scaling up the insect industry requires the availability of labor/staff, as only a few stages of insect rearing are automated. The safety risks (allergens, chemicals, and microbial hazards) of insect-fed animals are also increasing with the increasing demand for the inclusion of insect meals in the diet of aquatic animals [289]. The regulation of insect feed is also a critical issue for the insect-rearing industry. The regulations and guidelines regarding insect feed are different in different countries. For example, in several states of the United States, insect-based feed is allowed, while other states are waiting for FDA permission. There is a lack of proper guidelines, regulations, and legislation regarding insect rearing and consumption [290] (Figure 3).

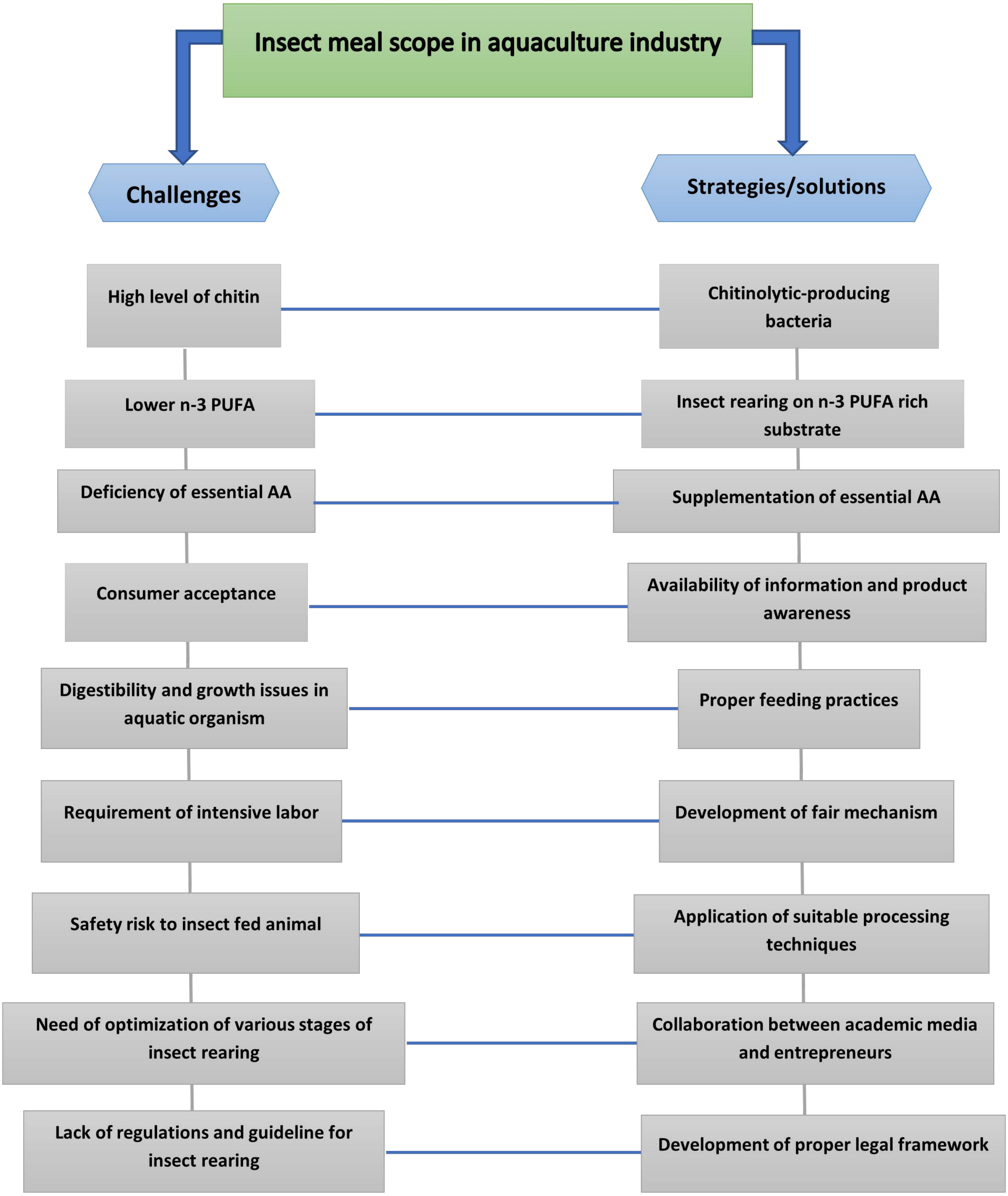


Figure 3. Challenges and solutions of insect-based meal in aquaculture industry.

8. Possible Solutions to Challenges in Introducing the Insects in Aquafeed

Chitin, which has a detrimental effect on the growth of fish, can be removed by supplementation with chitinase/chitinolytic-producing bacteria. This approach is very beneficial in inducing an immune response to fish and mitigating the environmental impact of fish waste [281]. Two major factors that can accelerate consumer acceptance and positive perception regarding the aquatic products produced through insect-based feed are the availability of information and product awareness [291,292]. To promote wider consumer acceptance, it is very important to reduce information asymmetry [292].

The environmental impact can be reduced by proper upscaling of insect production, and as a result, the insects can compete with conventional ingredients [293]. Environmental impact categories of *T. molitor* [46], *M. domestica* [294], and *H. illucens* [295] largely contribute to feeding produced from the insect-rearing industry. Therefore, providing a suitable substrate for insect rearing and increasing the efficiency of facilities will be major contributors to attaining insect meal's environmental benefits [293,296].

Another method for improving the amino acid content is defatting, but it requires intensive energy usage, increasing the environmental impact and feed cost [297]. It is better to add complementary raw material to insect meals or supplement the IM with deficient amino acids. Defatted mealworm and aquatic insect meals have higher arginine content than full-fat BSF diets [298,299]. As many AA compositions are found in insects, it is critical to analyze them before producing any insect-based feed [233,300]. More trials are needed to find a suitable feed to boost the omega-3 lipid content in insect meals, notably in HI, which tends to acclimate more easily to different diets [212,301].

Among the manufacturing techniques, extrusion can play a vital role in nutrition utilization [196]. The efficiency of extruded insect-based feed is also documented in recent studies [302,303]. Environmental impacts can be reduced by properly addressing feeding practices to minimize feed waste and FCR. Novel processing techniques are needed to address the safety concerns regarding insect feed consumption. It has been observed that various chemicals can be degraded if the insects are grown properly [289]. Preparing insect protein meal or dry pellets would save money and extend their shelf-life (relative to live food).

To optimize various stages of insect rearing, academic researchers and institutes collaborate with different EU companies to foster innovations. Studies have indicated that collaboration between academic media and entrepreneurs resulted in the development new innovative techniques. For example, a Dutch company has developed a centralized system for controlling oviposition in HI adult colonies with the help of olfactory triggers (web source). Larvae from the adult cages are transferred to a separate system by a newly developed automated device that allows counting larvae, dozing, and proper analysis. Breeding cages with pipes have also been developed to efficiently clean insect-rearing cages (web source). For promoting the insect business, there is a dire need to develop the proper legal framework to help the feed industry flourish fast (Figure 3).

9. Future Perspective

First, the insect industry must greatly increase its production capacity. Insect feed prices are currently too high. Fishmeal, high-quality SBM extracts, and soybean meal production volumes are thousands of times higher than insect meal protein and its by-products. By expanding the production scale, insect producers can compete on price and product stability with other protein sources. Industrialization and controlled manufacturing technologies will help shareholders to scale up the industry by reducing labor-intensive insect production [304].

Further cost–benefit research will need to be conducted regularly to determine the economic effects of adding insects to animal feed to see how these alternative protein ingredients affect total production costs. Additional research is needed on insect meal to modify and improve the digestive tract of the fed animal. Multiple approaches, including histomorphology, molecular biology, and histochemistry, will be advised to assess the gastrointestinal tract health of insect-fed organisms.

It is crucial to clarify and comprehend the factors behind consumer concerns about farm animal welfare worldwide. First, one rationale is that customers give farm animal welfare a higher priority than other traits when evaluating the quality of food [305–307]. One key reason consumers buy animal-welfare-friendly items is a correlation between better human health benefits and farm animal wellbeing [308–310].

The bioconversion technique for insect production is one of the sustainable solutions to food security. In this sense, waste is a valuable resource for producing high-quality protein (insect meal) for the food system. As a result, the technology produces zero waste and lowers the need for costly protein sources such as soy meal and fishmeal in aquafeed. Utilization of organic wastes for rearing edible insects is an attractive approach that would facilitate the SDGs promoting female entrepreneurs. This approach will help build sustainable and smart areas with reduced greenhouse gas emissions, indirectly reducing the carbon footprints. The potential of the insect meal industry to meet the increasing demand of the fish feed industry is unclear and data deficient. Research on this topic is limited to tiny plots or cages with immature or juvenile fish. More research is needed to verify that insects can be produced effectively and efficiently to feed young and adult fish.

Moreover, the insect's requirement level for different fish species varies according to stages and culture systems, and more studies are needed to fill this gap. This gap needs to be filled to commercialize aquaculture insects. The long-term sustainability impact of insect rearing is unknown. The data are not available for the proper understanding of production aspects of potential insects and the requirements and risks of their accidental release, which opens a new avenue for further research. Some insects have the potential to replace fishmeal completely, such as the BSF. However, the species-specific threshold limits the complete substitution of fishmeal with insect meal. Therefore, it is very important to explore new fractionation, separation, and biorefining schemes to extract useful products from insects.

Recent studies have demonstrated that different parts of insect's meal, such as meal, oil, pulp, and paste, can be used in aquaculture. The most literature is available on insect meal and, to some extent, oil. However, the data regarding the utilization of pulp and paste are scarce, and this area of research needs to be addressed. More collaboration is needed between the feed industry, government, academia, and local farmers to explore new insect protein sources and build efficient, cost-effective, sustainable rearing systems.

10. Conclusions

The present review analyzed that insects have good potential to replace fishmeal due to their nutritional value. Among the non-conventional feed ingredients, insects have the biggest potential to replace conventional feed ingredients. Proper processing technologies can further improve the nutritional value of insects. Insect-based diets showed a positive physiological response in many fish species. Insects have great potential to use agro-industrial and plastic wastes, thus contributing to combating pollution-related environmental problems. Our review also highlighted the challenges or hurdles in using insects in aquafeed, and possible solutions to these challenges were also addressed. However, more studies need to be conducted to determine the required level for aquatic animals, which varies from species to species and with developmental stages. Most of the studies on replacing fishmeal with insect meal focus on juvenile stages, not adult ones. For this reason, this area still needs to be investigated. It is important to scale up insect farming at the industrial level with standard, cost-effective, and eco-friendly facilities and to develop suitable substrates for insects to deal with nutritional and environmental issues.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/fishes7060395/s1, Table S1: Patterns of amino acids (mg/g CP) of six commonly used edible insect species. Sources [80,82,152–155]; Figure S1: The processing techniques of the insect's-based feed.

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