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Promoting Sustainable Food Security: Integrating Mealworms (*Tenebrio Molitor*) as a Nutrient-Rich Feed Source in Aquaculture

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Abstract: The limited availability and high pricing of fishmeal and fish oil have led to the exploration of sustainable alternatives for aquaculture nutrition. In addition to plants, the use of insects in aquaculture has gained significant attention as an alternative protein to fishmeal, serving as an alternative protein source for both fish and crustaceans. In the last couple of years, mealworm (*Tenebrio molitor*) larvae have received much attention because of their potential as an alternative protein supplement in aquaculture feed. Mealworms are well known for their high protein levels, well-balanced profile of amino acids (leucine and isoleucine), and good feed efficiency rate. This systematic review highlights the nutritional richness of mealworm meals, highlighting their potential as a protein replacement for fishmeal used in the diets of various farmed fish and crustaceans. Furthermore, this study explored the impact of integrating mealworm meals into the diets of fish and crustaceans by examining aspects such as growth performance, feed utilization, body composition, immune parameters, and antioxidant enzyme parameters. Furthermore, this study investigated various feeding substrates that may have an impact on the growth rate and nutritional composition of mealworm meal, as well as the effects of defatted and full-fat mealworms in the aquaculture feed industry.

Keywords: chitin; feed; food security; insect

促进可持续粮食安全：将黄粉虫(黄粉虫)作为水产养殖中营养丰富的饲料来源

摘要：鱼粉和鱼油供应有限且价格昂贵，这促使人们探索可持续的水产营养替代品。除了植物之外，昆虫作为鱼粉的替代蛋白质在水产养殖中的应用也引起了广泛关注，成为鱼类和甲壳类动物的替代蛋白质来源。在过去几年中，黄粉虫（黄粉虫）幼虫因其作为水产饲料中替代蛋白质补充剂的潜力而备受关注。黄粉虫以其高蛋白质含量、均衡的氨基酸（亮氨酸和异亮氨酸）分布和良好的饲料效率而闻名。本系统综述强调了黄粉虫粉的营养丰富性，强调了它们作为各种养殖鱼类和甲壳类动物饮食中鱼粉蛋白质替代品的潜力。此外，本研究通过研究生长性能、饲料利用率、身体成分、免疫参数和抗氧化酶参数等方面，探讨了将黄粉虫粉整合到鱼类和甲壳类动物饮食中的影响。此外，本研究调查了可能影响黄粉虫粉生长速度和营养成分的各种饲喂底物，以及脱脂和全脂黄粉虫在水产养殖饲料行业的影响。

关键词：几丁质；饲料；食品安全；昆虫

1. Introduction

The escalating demand for fish meal, coupled with a significant shortfall in global fish meal production, has intensified competition for its incorporation into the animal feed sector [1]. Consequently, fish meal has become the most expensive protein commodity in both animal and aquaculture feeds in recent times [1]. Moreover, projections indicate that by 2050, the global population will exceed 9 billion, creating an additional need for food, which is half of the current demand [2]. The demand for fish as an affordable protein source is increasing daily, owing to the rapidly growing human population. Research is being conducted to improve the commercial output while ensuring environmental sustainability. The most important factor in enhancing fish productivity is the quality of fish feed. Plant protein sources are challenging to use in feed because of the presence of anti-nutritional agents, non-starch polysaccharides, and less appropriate amino acid and fatty acid compositions in fish [1]. In response to environmental and economic considerations, the exploration of alternative and more sustainable protein options gained attention over the years, leading to the exploration of alternative and more sustainable protein options.

Recently, nutritionists have recognized insect meal as an eco-friendly protein source and have been extensively studied as a possible sustainable feed for aquaculture [3,4]. Factors such as the stage of metamorphosis, insect origin, and feeding habits greatly influence the nutritional composition of insect meals [5, 6]. Processing strategies have been shown to affect the nutritional quality of edible insects. Mealworms have become prominent insect species in the ongoing search for sustainable feed supplies for fish and crustaceans. Mealworms were chosen as the primary subjects of this review based on several critical factors.

Nutritional Composition: Mealworms have been used as a replacement for protein sources such as soybean meal and fishmeal in aquaculture feed. Mealworms are a rich source of high-quality protein containing all essential amino acids necessary for the growth and development of farmed shrimp and fish [6-8]. Their lipid profiles, including beneficial fatty acids, also support the dietary needs of aquaculture species. formulations owing to their high protein contents [9]. Mealworms also possess a well-balanced amino acid profile [10].

Environmental Sustainability: Mealworms can be produced using less land, water, and minimal greenhouse gas emissions [10]. Their cultivation involves converting low-value organic waste into high-value biomass, thus making them an environmentally sustainable alternative [2, 4]. The findings of this review have significant implications for aquaculture. By integrating mealworm-based feed, farmers can potentially**:**

- *Enhance Growth and Health:* The high protein content and beneficial lipid profile of mealworms can support optimal growth and improve the health of farmed shrimp, potentially leading to better yields and higher quality products [6].
- *Reduce Environmental Impact:* Shifting to insect-based feeds like mealworms could reduce reliance on

fishmeal, thereby alleviating pressure on wild fish stocks and contributing to more sustainable aquaculture practices [2, 8].

- *Improve Economic Efficiency:* With advancements in mealworm farming, production costs are decreasing, offering a more affordable alternative to traditional feed. This could lead to reduced feed costs, which constitutes a significant portion of the operational expenses in aquaculture [1–4].

This study aimed to examine existing research findings on the effects of mealworm meals on farmed fish and crustaceans, considering the growing interest in mealworms as a feed ingredient. This study focused on several aspects, such as growth performance, feed utilization, body composition, immunological parameters, and antioxidant enzyme parameters, to explore the potential of mealworms as a sustainable protein source in aquaculture.

2. *Tenebrio Molitor* Mealworm

Insect protein is a highly potent fishmeal substitute in feeds because it contains high levels of proteins and important amino acids [1, 3]. However, the nutrient content in insects is highly dependent on the stage of life and the species involved, namely larvae, pupae, nymphs, and adults. Insect-based meals have been used experimentally in some feeding studies as substitutes, which means that they can be selected if required. Among these insects are black army fly, silkworm, housefly, locust and mealworms because they contain a lot of protein, fats, vitamins and minerals but, on the other hand, possess low antinutritive factors [1, 5, 7, 9]. Additionally, fresh or dried mealworms have been used as fish feeds in aquaculture for many years. According to [11], mealworm beetles are native to Europe but are now found worldwide.

According to [12], mealworm larvae are readily available for commercial use and it is not difficult for them to reproduce themselves. According to [11], mealworms undergo four phases of development throughout their lives: eggs, larvae, pupae, and adults. Adults normally measure between 1.25 and 1.8 centimetres in length, while larvae often measure approximately 2.5 centimetres or more in length compared to adults. An average of 300–400 eggs were laid by female beetles, from which larvae emerged and develop over five–twelve days. The duration of the larval phase can range from 22 to 100 days [12].

Consequently, high protein levels, efficient conversion of feed, and well-balanced amino acid compositions have enabled the development of mealworms for commercial purposes. In addition, mealworm proteins are rich in amino acids such as leucine and isoleucine, which are required by the Food and Agricultural Organization for dietary provisions [13]. However, some essential amino acids are missing in mealworms, such as threonine, lysine, cysteine, histidine, and methionine. Analysis of the fatty acid composition showed that all stages of growth had high concentrations of linoleic acid (C18:2), oleic acid (C18:1), and palmitic acid (C16). These same acids were found at much higher levels in excreta than in any other phase, suggesting their use as an additional supplement in aquaculture feed. Moreover, pyridoxine, riboflavin folate, and vitamin B12 are abundant vitamins present in mealworms in rich proportions, whereas niacin is also available [5, 9].

In addition, [11] conducted a study in which they examined the nutrient composition of mealworm larvae, adults, exuvium, and excreta. They found that young worms had 46.44% protein, adults 63.34%, shed skins 32.87%, and waste 18.51% protein. This study showed that waste can also be used to obtain more protein in the cycle of reusing food. Meanwhile, [11] stated that live mealworms have a nutritional composition that includes 62% moisture, 20% protein, 13% fat, and 2% fiber, whereas the nutritional value of dried mealworms is comprised of 5% moisture, 6% fiber, 28% fat, and 53% protein.

Mealworm meal has been thoroughly evaluated for its impact on fish growth and nutrient utilization in various farmed fish species, such as African catfish [8], rainbow trout [3-4, 14-15], mandarin fish [16], European Seabass [17, 18], red seabream [19], olive flounder [14], humphead wrasse [20-21], and giant grouper [22], as well as crustaceans, such as white leg shrimp [6, 23-24], and giant freshwater prawn [7], to partially or completely replace fishmeal in aquaculture feed (Table 1).

In conclusion, mealworm use has tremendous potential for the implementation of sustainable aquaculture practices. This approach provides a feasible solution to the issues posed by traditional feed sources, while also adding to the adaptability and efficiency of the aquaculture industry.

3. Diverse Feeding Substrate Impacts Mealworm Growth Rate and Nutritional Composition

The variety of dietary decisions made by insects has a significant effect on the way they grow and perform in general. The shedding process of mealworm larvae may differ depending on the nature of their diet compared with that of other beetles [12]. Furthermore, mealworm diet supplementation can affect mealworm growth, survival, fecundity, development, nutrient composition, and feed conversion ratio [10]. Table 1 shows the effect of different feed types on the proximate composition of mealworms.

Mealworms, especially the superworm species, can only be fed wheat bran, but their complementary meals may include fresh potatoes, carrots, and cabbages to fulfil other nutrient needs [25]. According to [25], the weight of mealworms increased significantly when carrots, oranges, and red cabbage were provided. [10] also found that mealworms had differences in dry matter and nitrogen efficiency when carrots were used in their study, which helped to increase the development time for the mealworm. This was most likely caused by the plants' high moisture content (86.75%–90.39%).

Mealworm larvae are highly drought-tolerant and can actively absorb water from the air. Moreover, fresh plant material may provide important micronutrients and phytochemicals [25].

Table 1. Proximate composition of mealworm (The authors' elaboration)

Crude Protein (%)	Crude Lipid (%)	Moisture (%)	Crude Ash (%)	Feeding Substrate	Sample Preparation	Ref.
51	33	4	96.1	Wheat bran and carrot	Freeze Dried Mealworm	[27]
20	13	62		Carrot, lettuce seed and Chinese leaves	Live mealworm	[28]
57.57	26.80	59.53	3.90	Wheat bran	Undried	[29]
53.0	23.07	1.38	3.67	Wheat bran	High- Frequency Dried	
55.77	28.83	7.87	3.73	Wheat bran	Rack Oven Dried	
57.07	27.47	2.23	3.47	Wheat bran	Infrared Dried	
56.77	27.47	2.67	3.67	Wheat bran	Microwave dried	
55.50	28.43	5.47	3.63	Wheat bran	Freeze-Dried	
47.5	30.8	7.07	4.27	-	-	
17.6	13.8	64.01	1.5	Wheat bran	Freeze Dried	[25]
76.65	6.14	-	5.89	Mushroom spent corn stover	Dried	[30]
74.43	8.12	-	6.63	Highly denatured soybean meal	Dried	[30]
70.10	11.95	-	7.71	Spirit distiller grain	Dried	[30]
68.93	16.92	-	8.14	Wheat bran	Dried	[30]
46.4	32.7	5.3	2.9	Wheat bran and vegetables	Dried	[13]
44.72	42.28	2.43	3.69	Oat flake and Vegetable	Dried	[31]

Three samples of agricultural by-products: broccoli by-product, the tiger nut pulp and the grape pomace, were used in [26] to understand its impact on the larval development, the larval digestibility and the quality of the larval nutritional value. It was identified that the growth plus the nutritional composition were influenced by certain types of by-products as well as different portions of the by-products fed to mealworm larvae. Feeding the larvae with diets comprising only broccoli by-products was disadvantageous as it reduced both the yields and palatability of the larvae. However, the amino acid profiles of the larvae did not change significantly in response to the diets represented by these by-products, indicating that they might play a role in future insect farming. For the larval weight and feed conversion ratios, it can be seen that the fish that fed on the diet containing higher protein levels had better weight and feed conversion ratios for the larvae, while the fiber content increased the fat content and the ratios of feed conversion. In conclusion, the study also demonstrates the possibility that the by-product affects the proximate compositional change of mealworm larvae and stresses that agricultural by-products can be used as a potential source of protein in human diets [26].

Furthermore, in their study, [9] examined the impact of various diets on the composition of proteins and amino acids of mealworms, with specificity on the effects of protein quality and amino acid composition. The experimental diets, which used wheat bran as the control substrate, included pea protein, rice protein, sweet lupine, cassava, and potato flakes. These results indicated that supplementation with pea flour and rice flour protein was not beneficial in terms of high protein yield and lower lipid content in mealworms. Furthermore, cassava flour and wheat bran produced the highest amounts of amino acids and essential amino acids. It was also observed that dietary lipids and carbohydrates exerted a greater influence on larval composition than protein content, suggesting potential improvements in the formulation of artificial diets for mealworms [9].

In conclusion, adding fresh plant materials to the diet of larvae can enhance their growth rate and reduce the time required to reach harvestable weight, thereby improving the efficiency of mass mealworm production [25]. As suggested in [9], factors other than proteins, such as fat and carbohydrates, significantly influence the nutritional composition of mealworm larvae, indicating that high protein intake does not always result in a corresponding increase in larval protein content. However, [26] holds a different view, asserting that higher dietary protein generally leads to increased protein content in larvae, whereas fiber-rich diets reduce larval protein levels.

4. Defatted and Full-Fat Mealworm Inclusion in Feed

Insect-based diets can contribute essential minerals and vitamins to the nutritional needs of fish [5, 10]. Insects can have high lipid levels, up to 40% [6, 17]. Table 2 illustrates the potential contribution of full-fat mealworms to the diets of aquaculture species. However, this is unfavorable for fish nutrition because they contain minimal amounts of EPA and DHA [5]. Furthermore, elevated lipid levels in their composition pose a higher risk of lipid oxidation [17]. This may alter the lipid composition of fish, thereby affecting their sensory characteristics, but not in a severe way. Feeding insects with fishery by-products, microalgae, and seaweeds can improve the quality of n-3 fatty acids. The defattening technique aims to address the limitations of a high-fat insect diet and, at the same time, enhance the protein content in the resulting defatted product.

In recent years, insect producers have increased the production of defatted insect meal [15]. Table 3 presents previous studies that incorporated defatted mealworms into the diets of various aquaculture species. Defatting helps attain high yields of crude protein (CP) and better resistance to breakdown in comparison to full-fat insect meals [15]. Since the amino acid analysis of insect proteins indicates a better nutritional value for marine fish compared to the fatty acid profile of insect meal, and the combined analysis also indicates somewhat inferior values for marine fish, it is recommended to eliminate fat from insect meal [17]. The proteins could then be used in the formulation of fish feed or in industrial uses, whereas the lipids could be used in other processes where the content of n-3 HUFA is not required [17]. Chemical methods, such as the use of organic solvents, such as ethanol, acetone, or hexane, have been applied for the removal of fatty components [14]. Complete replacement of fishmeal with defatted mealworm meal has been reported in a hexane-ethanol solution [19]. The use of the petroleum ether extraction method in insect meal for defatting has resulted in an increase in the crude protein content of insect meal. Defatted insect meal has the potential to serve as a high-quality source of protein for fish feed, particularly given its favorable amino acid profile. However, further research is needed to fully evaluate the feasibility of using defatted insect meal on a large scale and to address any potential drawbacks or limitations associated with this approach.

Table 2. Inclusion of full-fat mealworms in fishes and crustaceans (The authors' elaboration)

Species	Inclusion of Full Fat Mealworm Meal (%)	Effect	Ref.
Giant Freshwater Prawn (*Macrobrachium Rosenbergii*)	12	Positive effects on growth performance and immunological parameter	[7]
White-leg Shrimp (*Litopenaeus vannamei*)	25	Lipid content rising and polyunsaturated fatty acid content falling.	[7]
	60	Increase in protein level in their hemolymph. Increase in body weight and feed efficiency	[6]
African Catfish (*Clarias gariepinus*)	80	Exhibited feed utilization and good growth.	[8]
Rainbow Trout (*Oncorhynchus mykiss*)	Up to 50	Can be included in the diet and fatty acid profile of rainbow trout fillets undergo significant changes.	[3, 4]
	12	Improved fish growth and feed utilization.	[14]
Mandarin fish (*Siniperca scherzeri*)	30	Increase in immune parameter	[16]

Table 3. Inclusion of defatted mealworms in fish and crustaceans (The authors' elaboration)

Species	Inclusion with Defatted mealworm meal	Effect	Ref.
Rainbow Trout (*Oncorhynchus mykiss*)	20%	No adverse effect on the fish growth, digestibility, or hepatic enzyme	[15]
White leg Shrimp (*Litopenaeus vannamei*)	50%	Improved growth performance parameter	[24]
European Seabass (*Dicentrarchus labrax L*)	80%	Did not compromise protein and lipids digestibility, growth performance, or nutrient balance.	[18]
Red Seabream (*Pargus Major*)	Up to 65%	Resulting in larger growth in fish.	[19]
	10%	Anti-bacterial disease capacity was obtained	[19]
Olive Flounder (*Paralichthys olivaceus*)	40%	Recommended inclusion to minimize adverse impacts on feed efficiency and nutritional value of the fillet lipid fraction.	[14]

5. Results

5.1. Effect on Farmed Fishes Growth and Feed Utilization

The inclusion of mealworms in fish has had a positive impact on the growth performance of farm fish such as rainbow trout, mandarin fish, grouper, European seabass, and olive flounder. The following are reported studies published by other authors.

5.1.1. Rainbow Trout

The potential of including mealworm insect meals in rainbow trout diets to partially replace fishmeal has been explored previously [4]. This study examined the impact of including insect meal on fish growth, protein utilization, and physiological state. The results showed no negative effects on these elements. Substituting fishmeal with mealworm meal improved protein digestion at the highest level, reduced the visceromatic index, and increased aerobic catabolism in fish. This leads to an increase in pro-oxidative conditions, but the levels of antioxidant enzymes increase to counteract it [4]. This study supports [14] findings of this study indicate that incorporating mealworms enhances rainbow trout growth performance and feed utilization by improving protein efficiency and reducing feed conversion ratios. However, elevated levels of 28% resulted in a minor decline in growth performance, possibly attributed to the high fat and chitin contents of mealworms [14].

It was observed that rainbow trout boosted FCR and improved amino acid levels when fed mealworm insect-based meals. The effects of replacing fishmeal with mealworm larval meal on the growth rate and nutrient digestibility of rainbow trout were studied in [3, 4]. To evaluate the effects of mealworms, the authors fed rainbow trout with a diet containing 0%, 25%, and 50% of mealworms, and changes in feed conversion ratio, protein efficiency ratio, specific growth rate, and survival rate were compared to the use of black army fly insect diets [4]. The literature review shows that the incorporation of mealworm meal to replace fish meal in rainbow trout diets has had a positive impact on growth and nutrition [4]. These findings have been supported by changes in the morphology of the intestine, which include increased villi height as well as better protein breakdown in diets containing mealworm meal. Contributions of [15] evaluated the potential of partially defatted mealworm as an alternative fishmeal source in the aquaculture industry. Apparently, the fish fed with defatted mealworms did not show any comparable changes in growth measures as the fish fed the standard diet containing fishmeal. A reduction in fishmeal inclusion rate in the diet of rainbow trout did not affect growth performance negatively, as there were no differences in weight gain and specific growth rate of trout between fish fed with partially defatted mealworm meal and fish fed on fishmeal.

5.1.2. Mandarin Fish

Incorporating up to 20% mealworm meal into the diet improved the growth rate and nutritional utilization of mandarin fish [16]. However, increasing it to 30% resulted in a slight decline in growth performance. Diets containing 10% and 20% mealworms resulted in significantly greater growth rates in fish than a control diet lacking mealworms [16].

5.1.3. European Seabass

A study on the effectiveness of feeding European seabass juveniles with mealworm larvae was conducted by [33], who attempted to determine growth performance. While conducting the study, they realized that supplementing up to 25% of the diet with full-fat mealworm larvae meal did not affect performance endpoints. The evaluated parameters of final body weight, weight gain, specific growth rate, and feeding rate decreased with an increase in the inclusion level of mealworm meal to 50% compared to the control diet containing 0% mealworm meal. However, the highest feed conversion ratios were recorded when European seabass was fed with a 30% inclusion level of mealworm meal. Incorporating up to 80% defatted mealworm meal as a substitute for fishmeal did not negatively affect protein and lipid digestibility, growth performance, or nutritional balance [18]. However, elevated amounts of defatted mealworm meal (100% inclusion) increased the hepatic lipid content, total cholesterol, and non-esterified fatty acids in the muscle. It also influences the expression of genes associated with food metabolism in the liver and muscle [18].

5.1.4. African Catfish

As discovered in [8], African catfish find mealworm meals to be very appetizing. It can substitute up to 40% of fishmeal in diets without affecting the growth performance or feed efficiency. Live mealworms were identified as an appropriate complete feed source for African catfish fingerlings. Combining mealworms with catfish pellets results in good development and feed utilization efficiency [8].

5.1.5. Gilthead Seabream

According to a previous study [32], mealworm larvae meal in gilthead seabream diets had significant effects on growth performance and nutritional digestibility. The experimental group was provided with a diet containing 25% mealworm meal. The group fed a diet containing 25% mealworm meal exhibited enhancements in final weight, specific growth rate, weight gain, and protein efficiency ratio. At the 50% inclusion level, nutrient digestibility was reduced, but it did not negatively affect growth performance [32].

5.1.6. Red Seabream

A study conducted by [19] substituted fish meal with defatted mealworm meal in red sea bream. Red seabreams fed diets with total substitution of fishmeal with defatted mealworm meal larvae exhibited greater development than those fed control diets with 65% fishmeal [19]. The study demonstrated that complete substitution of fishmeal with mealworms is achievable in red seabream by extracting the oil component from dried mealworms using organic solvents.

5.1.7. Olive Flounder

The growth rate of olive flounder decreased as dietary mealworm meal levels increased [14]. Feed utilization efficiency improved as the amount of dietary fishmeal replacement increased to 40% but declined at higher replacement levels [14]. The results showed negative linear and quadratic influences on nutritional digestibility. The study recommends replacing no more than 40% of fish meal with mealworm meals in the diets of olive flounder juveniles to maintain feed efficiency and nutritional value [14].

5.1.8. Giant Grouper

The use of graduated and purified oat or wheat gluten meals revealed that these can replace up to 30% of dietary fishmeal protein for large groupers without any negative effects on their growth rates [22]. The feeding trial consisted of four treatment diets: fishmeal-free diets and three diets containing 10%, 20%, and 30% fishmeal with mealworm meal (MWM) substitution for fishmeal protein [22]. Thus, the study findings highlighted that dietary treatments had no influence on weight gain, protein accretion, protein efficiency rate, feed conversion rate, cumulative mortality, or whole-body amino and fatty acid composition. This study also found that in-fish-out ratios decreased arithmetically as the levels of incorporated mealworm meal increased. Plasma triglyceride concentrations were also significantly lower at high replacement levels. The publication presented is relevant to this task as it describes the possibility of variation in protein content of mealworm meals due to changes in the nitrogen and chitin content of the mealworm components. As a result, up to 30% of MWM can replace the fishmeal protein used as feed for large groupers without significantly affecting the growth rate, in accordance with sustainable aquaculture [22].

5.1.9. Tilapia

However, not all fish species benefit from the addition of mealworm meal to their diet. As discovered in [34], the addition of mealworms to the diet of Nile tilapia reduced growth performance and nutrient utilization. Research indicates that fish-fed diets including mealworm meal exhibit decreased growth performance, feed conversion efficiency, and protein efficiency ratio in comparison to fish fed control diets consisting of fish meal and soy meal. Nutrient utilization and growth index were reduced in fish diets with mealworms, regardless of the amount of insect meal used [34]. Chitin in mealworm meals has been documented to have a negative effect on lipid utilization and retention, impacting Nile tilapia growth and nutritional indices.

5.1.10. Yellow Catfish

A previous study [35] examined the effect of feeding yellow catfish mealworm meal on the growth performance and immunological responses of fish. This study found that adding mealworm meal to the diet of young yellow catfish did not adversely affect their growth performance. In yellow catfish diets, mealworm meals can substitute up to 75% of fishmeal without significantly affecting fish growth [35].

5.1.11. Humphead Wrasse

Despite the limited scientific literature, particularly detailing the nutritional requirements of humphead wrasse (*Cheilinus undulatus*) in captivity, it is well established that its natural diet predominantly consists of small fish, mollusks, and invertebrates [20, 21]. These natural diets are particularly high in protein, which is essential for the growth and development of this species, similar to that of other marine fish. It has also been reported that protein-rich sardines and high lipid content of squid are necessary to support the maturation of humphead wrasse reared in captivity and able to release eggs [21]. Judging from the humphead wrasse’s natural and high preference for a high-protein diet, it is reasonable to incorporate their dietary needs in captivity, which would also be centered around protein-rich feed. Hence, one potential feed ingredient is mealworms, which are known for their remarkably high protein content [5, 21] and integrating mealworms into the diet of humphead wrasse in aquaculture settings could be a viable strategy to meet their nutritional requirements and promote their overall health and growth performance [2, 5, 20, 21].

Given the growing interest in sustainable aquaculture practices, the inclusion of alternative proteins such as mealworms instead of prey fish could help reduce reliance on conventional fish meal, thereby supporting responsible fish farming operations [14]. In addition, the use of alternative proteins can enhance the economic resilience of the aquaculture industry by suppressing fluctuations in global fishmeal supply and prices [2, 5]. As a result, the inclusion of mealworms as additional feed ingredients will certainly represent a forward-thinking approach in humphead wrasse aquaculture that contributes to sustainability, responsible resource management, and environmental stewardship [2, 5, 20-21].

5.2. Effect on Immune Response and Antioxidant Enzymes of Farmed Fishes

Mealworm meal has the potential to dramatically influence the immunological response and antioxidant enzymes of farmed fish; however, the extent of this influence is dependent upon the species of fish and the amount of mealworm meal included in the diet.

5.2.1. Rainbow Trout

The effects of fishmeal replacement with *Tenebrio molitor* on the innate immune response and intestinal antioxidant enzymes in rainbow trout were investigated in [17]. Hence, the study shows that incorporating fish meal worms for feeding results in enhancement of the antioxidant enzymes in the intestinal part and reduction of lipid peroxidation in both the proximal and distal intestinal tracts of rainbow trout fish. Moreover, a study on the effect of dietary mealworm larvae on the immune response in rainbow trout proved that larvae could improve the antibacterial activity of fish serum, particularly against negative bacterial stains [17]. In a study by [14], it was found that fish fed mealworm meals had enhanced nonspecific immune levels, as indicated by increased MPO and lysozyme levels. Dietary treatments in a study conducted by [14] indicated that fry-fed diets with mealworm meal affected the levels of aspartate aminotransferase (AST), alanine aminotransferase (ALT), alkaline phosphate (ALP), albumin (ALB), total cholesterol (TCHO), total protein (TP), and total bilirubin (TBIL) of the rainbow trout. The changes in blood and immune responses are evidence that the incorporation of mealworm meals has both positive and negative impacts on the health and immune response of rainbow trout. [4] found that mealworm meal, which was added to the formulation as a functional ingredient, was capable of exerting protective effects against tissue injury and enhancing immunological and antioxidant status in rainbow trout.

5.2.2. Mandarin Fish

Blood lysozyme and glutathione peroxidase activities tended to increase as dietary mealworm meal levels increased in mandarin fish [16]. Fish fed a diet containing 30% mealworms showed significantly elevated levels of immunological markers compared to those fed a control diet without mealworm meal. Increasing dietary mealworm meal levels resulted in elevated blood superoxide dismutase and glutathione peroxidase activities, which are crucial for neutralizing excessive superoxide radicals and regulating reactive oxygen species balance in fish [16].

5.2.3. European Seabass

European Seabass exhibited notable anti-inflammatory reactions, including ceruloplasmin, myeloperoxidase, and nitric oxide, after being fed mealworm meal, as shown in [17]. The antibacterial activity against gram-negative bacteria was not considerably affected, but the lysozyme antibacterial activity and serum trypsin inhibition, linked to anti-parasite effects, were notably improved [17].

5.2.4. Red Seabream

Thus, it was concluded that the use of red seabream-fed diets with mealworm larvae led to increased resistance to the formulated diets to negative impacts of harmful microorganisms [19]. In the challenge test with pathogenic *E. tarda*, actinopterygian fish fed diets containing mealworms as a partial replacement for fishmeal had a significantly higher survival rate than those fed the control diet. Essentially, red seabreams modify their immunity and demonstrate a higher level of resistance to bacterial infections when consuming a diet containing 10% defatted mealworm larvae. The mealworm is thought to have immunostimulatory properties, and it is believed to have chitin or unknown polysaccharides, which can be very important in increasing disease resistance in cases of illness. In the case of the red seabream mealworm, it is evident from [19] that their feed can enhance the resilience of the larvae against bacterial diseases.

5.2.5. Olive Flounder

[14] also found that feeding young flounders diets containing high amounts of MW noticeably affected some immune factors. The study reported that the optimum inclusion level of mealworm meal was up to 40% substitution of fish meal, which had immunostimulatory effects, as evidenced by the reduction in MPO activity when fish meal protein was replaced. In addition, the activity of succinate dehydrogenase enzymes was typically elevated as the MW level in the diet increased. The present investigation revealed that supplementing MW in the diet enhances the immune function and antioxidant capacity of the fish [14], according to the studies conducted.

5.2.6. Yellow Catfish

Supplementing yellow catfish diets with mealworm meal increases plasma superoxide dismutase (SOD) activity and decreases malondialdehyde (MDA) levels [35]. This study showed that adding mealworm meal to the diet improved the antioxidant abilities of yellow catfish, leading to increased SOD activity and decreased MDA levels. Mealworm meal supplementation enhanced the antioxidant capabilities of yellow catfish by improving cellular free radical metabolism and removing lipid peroxidation, as indicated by a previous study [35]. An inclusion level of at least 18% mealworm meal per 100 g of feed is recommended to improve the immune response and disease resistance of yellow catfish [35]. This level of inclusion has been shown to significantly enhance the innate and adaptive immune responses of catfish as well as increase their resistance to bacterial infection, tissue damage, and immunological reactions. Research by [35] suggests that incorporating > 18% mealworm meal in the diet is recommended for yellow catfish to benefit from positive impacts.

5.3. Effect on Body and Fillet Composition of Farmed Fishes

The inclusion of mealworms in rainbow trout diets can affect the nutritional composition of fillets, especially the protein, lipid, and fatty acid profiles [4]. They observed changes in the fatty acid profile of rainbow trout fillets, and the n-6 fatty acid ratio decreased linearly, increasing the number of mealworms in the feed. According to [4], they also observed a decrease in omega-3 fatty acids in fillets as the percentage of insect meal in the feed increased.

However, research has demonstrated that the use of insect meal in fish diets has some undesirable effects. The fatty acid profile of rainbow trout fillets significantly changes when fishmeal is partially replaced with mealworm larvae meal in the diet [3]. The levels of essential omega-3 fatty acids, eicosapentaenoic acid (EPA), and docosahexaenoic acid (DHA), as well as the thrombogenicity index (TI), decreased, whereas PUFA/SFA and n3/n6 gradually decreased with an increase in mealworm meal in the diets [3]. These undesirable effects should be overcome in future research [4].

In line with the study in [3], a recent study [15] demonstrated that the apparent digestibility coefficients (ADC) of dry matter, ether extract, and gross energy were not affected by the inclusion of dietary defatted mealworm meal in rainbow trout diets. However, the ADC of crude protein was negatively affected by the inclusion of mealworm meal, showing a decreasing trend as the level of mealworm meal increased [15].

Moreover, [16] found that the body composition of juvenile mandarin fish fed diets containing mealworm meal did not show any definite pattern of change. No significant changes were observed in the carcass composition of fish. The fillet composition, specifically the fatty acid profile, reflected the diet composition; fish fed diets with mealworm meal had higher levels of saturated and monosaturated fatty acids and lower levels of omega-3 polyunsaturated fatty acids than those fed a control diet without mealworm meal [16].

Furthermore, mealworm larvae meal in European seabass diets has been shown to affect the whole-body composition and fatty acid profile [33]. In a study conducted by [33], the authors stated that mealworm meal did not contribute to any significant changes in the whole-body composition of fish, apart from the ash content. However, changes were observed in the fatty acid profile, particularly in the fatty acid profiles, with an increase in C18:C20:5n3, an increase in C20:4n6, and a decrease in C20:5n3 in broiler chickens fed the experimental diets, which was accompanied by a reduction in the n3:n6 polyunsaturated fatty acid ratio. This suggests that the use of mealworm meal in the diets of European seabass can bring about changes in the layouts of fatty acids in the fish, which in turn may affect the nutritional characteristics of the fish.

In addition, a significant shift in the muscle and liver fatty acid profiles of Nile tilapia fed mealworms compared to those fed fishmeal and soymeal diets was identified by [34]. The muscles of fish fed mealworms contain significantly lower levels of n-3 fatty acids and a less desirable n-3: n-6 ratio. The n-3: n-6 ratio was different in the liver depending on the three diets, as a statistically significant relationship was observed with fish liver. The results of this study indicated that based on the trend in the fatty acid profile of the fish fed with the diet containing mealworm, the values obtained showed an increase in the monounsaturated fatty acids and a reduction in the saturated fatty acids compared to the fish fed with fishmeal diets. In addition, the analyzed diets, which included mealworm, fishmeal, and soybean meal, had a significant effect on DHA concentration in the fish muscle tissue and fish livers lacking EPA in the Nile tilapia fed mealworms or fishmeal.

Finally, [14] observed the comparative effects of mealworm meal inclusion in the diet on the flare of the whole body and fillet, moisture, crude protein, and crude lipid contents, all of which impacted the flounder. Specifically, the outcome highlighted that the dietary mealworm meal content had a negative linear relationship with the proximate composition, with a decrease in the lipid content of the fillet. Additionally, the study observed significant positive linear and quadratic trends between fillet c18. The current study aimed to establish a relationship between dietary consumption of *M. domestica* meal, specifically its C18:1n-9 (oleic acid) and C18:2n-6 (linoleic acid) concentrations, where the OA and LA levels increased progressively with the levels of the consumed *M. domestica* meal. Furthermore, the fillet n3/n6 ratio and AI decreased in rats fed a diet containing mealworm meal, while the fillet TI and HUFA/Omega-3 fatty acid ratio improved in a positive control manner by increasing their values. Furthermore, the fillet Σn3/Σn6 ratio and atherogenic index demonstrated significant decreasing trends with the dietary inclusion of mealworm meal, while the fillet thrombogenic index and hypocholesterolemic fatty acid ratio exhibited significant positive trends with increasing values. These findings suggest that incorporating mealworm meal into the diet can have a significant impact on the proximate composition of the whole body and fillet of olive flounder, particularly in terms of lipid content and fatty acid profile [14].

5.4. Inclusion of Mealworm-Based Feed in Crustaceans

The inclusion of mealworms in crustaceans such as white-leg shrimp and freshwater lobsters has been studied by several researchers. Similar to fish, the inclusion of mealworm meal in crustaceans can affect growth performance, feed utilization, immune responses, and antioxidant responses.

5.4.1. Immune and Antioxidant Responses

Previous research by this laboratory [6, 23] has confirmed that feeding WL shrimp with M. brunipes has a positive effect on immune responses, hemolymph biochemical indices, and growth characteristics. Replacing fishmeal with the same percentage of "mealworms" could have a significant impact on the shrimp's immune cells, as identified by [23]. Regarding the changes in the level of lysozyme (LZM) activity with an increase in the proportion of mealworms in the diet up to 60%, enhanced activity of this enzyme, which is an important part of the non-specific immune response (NSIR), was observed. As demonstrated in the above findings, dietary meal supplementation in the formulation of mealworms boosts the innate immunity of shrimp. Furthermore, studies have revealed enhanced activity of other enzymes involved in immunity, such as SOD, phenoloxidase, acid phosphatase, and alkaline phosphatase. These diets resulted in an increase in CMD-marker genes, such as BGBP, proPO, and crustin, which are signs of improved defense against pathogen invasion. In fact, some experimental diets containing mealworm larvae had positive effects on the immunological response to White Spot Syndrome Virus (WSSV) infection. The difference in the post-WSSV challenge survival of shrimp fed on 25% mealworm and the control group that was fed on fishmeal was compared as follows: shrimp fed on a 25% mealworm diet had 40% survival at 8 days post-WSSV challenge, whereas all the shrimp in the control group fed on fishmeal died within 3 days after the challenge. In addition, a significant increase in the total hemolymph count (THC) supported the notion that mealworm-based feed could bolster white-leg shrimp immunity.

It is also suggested in the study of [23] that there are various changes in shrimp serum biochemistry on fishmeal substitution with mealworms. The effect of different levels of mealworm replacement on serum biochemical indices, such as cholesterol, triglycerides, and glucose, is presented here. The highest relative mass of Cho and TG was detected in the control group T0, while the minimum values of these indicators were revealed in the T100 group, where 100% fishmeal was replaced by soybean meal. Of the tested shrimp, those fed a diet with 60% replacement of fishmeal (T60) displayed a marked elevation in protein values in the hemolymph. This means that incorporating mealworms into the diet instead of fishmeal influences the shrimp serum biochemical profile, particularly cholesterol, triglyceride, glucose, and protein [23].

An increase in antioxidant activity was revealed in the hepatopancreatic tissues of white-leg shrimp, presumably due to higher antioxidant enzyme activity [23]. Furthermore, the endogenous enzyme activity in the intestine of the shrimp was observed to have been affected by the replacement, as protease and lipase enzymes showed an upward trend with the amount of mealworm inclusion. In conclusion, it may be recommended that focal mealworm levels can be a potential substitute for fishmeal in the diet of Pacific white shrimp, although without harming the result [23].

It has been observed that the feeding of mealworm meal protein has a considerable impact on the immunology of prawns, namely giant freshwater prawns [7]. From the findings of this study, it was established that as the concentration of mealworm meal in the diet of the prawn increased, certain immunological alterations were observed. Such changes necessitated a significant increase in THC, SCs, GCs, and HC richness. Furthermore, muskmelon proteins incorporated in mealworm meal increased the activities of SOD, PO, LZ, and ALP. In addition, restaurants for quantification of mRNA levels of prophenoloxidase (proPO), lipopolysaccharide- and β-1,3-glucan-binding protein (LGBP), peroxinectin (PE), and α2-macroglobulin (α2-M) in giant freshwater prawn raised with protein levels of mealworm. These findings suggest that replacing fish meal with mealworm proteins affects the immunological aspects of Macrobrachium rosenbergii by enhancing immune responses. Hence, the perceived amount of bacterial infection in prawns [7].

5.4.2. Growth Performance and Feed Utilization

Concerning growth performance, according to the study done by [23], it was clear that replacement of fish meal with mealworm was significantly enhanced. An increase in the body weight gain, feed efficiency, and hepatopancreas index of the shrimp was observed up to a drastic level of replacement of 30 percent. Balancing the nutritional value of the diet is important, and although using over 30% fishmeal replacement may have a negative impact on the growth parameters, increasing the replacement level may even improve the growth rate of *Litopenaeus vannamei* [23]. Their research revealed that obtaining 50% of the fish meal and replacing it with mealworm significantly increased shrimp growth performance by approximately 35% more than shrimp fed with only fish alone. They further established that with the amino acids, mealworms can also offer amino acids that are considered vital in supporting optimal growth among shrimp. However, based on a previous study [6], it was shown that despite the fact that mealworms could be used as a source of protein in feeding white-leg shrimp juveniles, methionine supplementation may need to be included.

Recently, [7] conducted a study was conducted to evaluate the effect of dietary mealworm meal protein (MMP) on the growth, feed utilization, body composition, and immunological response of *M. rosenbergii* fed five diets containing different concentrations of mealworm meal to prawns over a 10-week period. The highest protein content of mealworms (12%) had the most effective effects on growth performance, as evidenced by weight gain, specific growth rate, and protein efficiency ratio. Furthermore, the body was more on protein and less on lipid as mealworm meal protein levels rose in proximate composition of carcass and muscle [7].

5.5. What Is Chitin and Its Relationship in Mealworm Feed-Based?

Chitin, a component that can be derived from the insect cuticles, is formed with a straight-chain homopolymer β(1-4) of N-acetylglucosamine and it was previously thought that ingestion of chitin from marine fish diets would cause growth reduction due to problems in digestion [9]. In carnivorous and omnivorous fish, chitin digestion involves the activity of three enzymes: chitinase, chitobiase, and lysozyme, all of which are present in their digestive systems. Chitinase, found in the fish stomach, aids in the disintegration of chitinous exoskeletons, whereas chitobiase, found in the fish intestine, facilitates nutrient absorption. These enzymes have been observed in freshwater and marine fishes [17]. It has also been established that certain fish species, particularly marine carnivorous teleosts, may have chitinase activity in their digestive tract, indicating their capability to degrade chitin.

A widely held belief is that monogastric animals, such as fish and crustaceans, generally face challenges in chitin digestion. Many growth experiments involving the incorporation of insects into fish diets, which resulted in decreased fish growth and reduced digestibility of proteins and lipids, have frequently attributed these effects to chitin, without substantial evidence. In contrast, it has been recommended that maintaining minimal levels of dietary chitin or incorporating feed ingredients rich in chitin can enhance the host's digestive capabilities and, in turn, lead to improved nutrient utilisation by positively influencing the composition or activity of beneficial gut microbiota [33]. This was supported by [19] in their study, who found that 10% chitin supplementation could improve the growth performance of red seabream. [19] also stated that the immunostimulatory activity of mealworms, possibly in the presence of chitin or unknown polysaccharides, may play a role in improving disease resistance.

Nevertheless, their elevated incorporation levels have been linked to impaired digestion or absorption of various dietary nutrients, particularly lipids. [14] stated that it is reasonable to infer that the poor nutrient digestibility observed with high dietary inclusion of mealworm meal in olive flounder could be a contributing factor to the decline in feed formulation efficiency, resulting in impaired growth performance. Conversely, a higher feed utilization efficiency is observed if the inclusion level of the mealworm is at a low level, according to [14].

Chitin is elaborated by simple alkaline extraction from insect meal for incorporation into animal feed [34]. Dietary association with chitinolytic bacteria or the source of the fungal enzyme itself in the diet can even result in higher digestibility than when feeding purified bacterial enzymes [9]. Another possible approach is to degrade chitin chemically or enzymatically and then incorporate the end products (chitooligosaccharides), acetylglucosamine, and/or chitosan into fish diets. Such processes may significantly increase the cost of insect meal production [17].

In general, we can conclude that inclusion and supplementation with insect-derived chitin does not necessarily inhibit the growth of crustaceans and fish at the same time. According to [17], some fish that consume crustaceans, insects, or benthic invertebrates naturally have high digests of prawn and crab meals. However, it is critical to accurately determine the optimal levels of chitin in diet plans.

6. Conclusion

This review discusses the potential of mealworms as a viable alternative to traditional fishmeal in aquaculture. Mealworms contain high-quality protein and necessary fatty acids, which aid in the growth and health of farmed fish and crustaceans. Researchers have found that including mealworms in aquafeeds increases growth performance, feed conversion ratios, and overall health in farmed species such as crustaceans and fishes. This study also highlights the role of mealworm feeding substrates and fat content in shaping their nutritional profiles. These review findings are consistent with earlier research, which found that employing insect meal as a fishmeal replacement has beneficial benefits. Mealworms have specific benefits in terms of their amino acid content and palatability. Furthermore, the sustainability component of mealworm production, which requires less land and water, is consistent with the wider move towards sustainable aquaculture feeds. These findings show that mealworms could be a feasible alternative to overfishing in wild populations of fishmeal and fish oil. This adjustment may substantially decrease the environmental impact of aquaculture, thereby making it more sustainable. Furthermore, the study suggests that optimizing mealworm raising and feeding procedures could make them more suitable for a wider range of farmed species.

While the inclusion of mealworms in aquaculture feeds is obvious, future studies should focus on long-term feeding trials to determine their effects on growth, reproduction, and product quality in various aquaculture species. Furthermore, research on increasing mealworm production and determining their economic viability of including them in commercial feeds is critical. Further research should examine the impact of different substrates on mealworm nutritional profiles as well as how this affects the health and market value of farmed species.

Declarations

Author Contributions

Conceptualization, A.E. and N.E.A.; methodology, A.E.; software, S.M.; validation, N.E.A., C.F.F., S.M. and A.E.; formal analysis, A.E.; investigation, A.E. and N.E.A.; resources, C.F.F.; data curation, A.E; writing—original draft preparation, S.M.; writing—review and editing, A.E.; visualization, C.F.F.; supervision, A.E.; project administration, N.E.A. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Conflicts of Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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