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Black Soldier Fly Larvae Meal as a Sustainable Alternative to Fishmeal in Juvenile Swamp Eel Diets: Effects on Growth and Meat Quality

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Abstract: The rising scarcity and cost of fishmeal due to overfishing and environmental challenges demand alternatives. Black soldier fly (*Hermetia illucens*) larvae (BSFL) meal, with its nutritional value, shows promise as a sustainable supplement for aquaculture species. This study evaluated the effects of BSFL meal supplementation on growth performance, survival, feed conversion efficiency, and meat quality in juvenile swamp eels (*Monopterus albus*) initially weighing 4.0 ± 0.5 g. The eels were fed diets with 0% (control), 10%, 30%, and 50% BSFL meal for three months. Growth performance was assessed using the absolute growth rate (AGR) and the specific growth rate (SGR). Feed conversion ratios (FCRs), survival rates, and meat quality metrics, including fillet percentage, crude protein, and moisture content, were analyzed. Statistical differences among groups were evaluated using one-way ANOVA followed by Tukey's post hoc test for pairwise comparisons. The 30% BSFL group exhibited superior performance, achieving the highest AGR and SGR ($p < 0.05$) and the lowest FCR (2.33 ± 0.03). Fillet percentage was highest in this group (27.3% ± 0.7%), with no significant differences in crude protein or moisture content. Survival rates were consistent across treatments (75.2–76.0%, $p > 0.05$). These results confirm that 30% BSFL supplementation optimally enhances productivity and meat quality in swamp eels, highlighting BSFL meal's potential as a sustainable aquafeed alternative.

Keywords: black soldier fly larvae meal; fishmeal supplement; sustainable aquafeed; swamp eel

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1. Introduction

The aquaculture industry faces challenges in meeting the growing demand for sustainable and environmentally friendly protein sources. Fishmeal, the primary protein source in aquatic animal diets, is becoming increasingly scarce and expensive due to overfishing pressures and climate change impacts [1,2]. These constraints necessitate the search for alternative protein sources that are efficient, cost-effective, and environmentally sustainable.

Black soldier fly (*Hermetia illucens*) larvae (BSFL) have been extensively studied as a promising alternative protein source due to their high nutritional value, particularly in terms of protein and lipid content [3–5]. BSFL meal not only reduces dependence on fishmeal but also supports biological waste management, as the larvae can thrive on various organic by-products, contributing to environmental protection and sustainable aquaculture growth [6,7]. Recent studies by our group have further expanded the applications of BSFL. We demonstrated that BSFL supplementation improved meat yield and quality in

Ac chickens [8], as well as its effectiveness in enhancing growth performance and meat quality in loach fish [9]. We also demonstrated the genetic diversity of BSFL populations in Vietnam [10], showing the potential for optimizing their utilization in aqua- and animal feed in a local context.

Studies have shown that BSFL meal can effectively replace fishmeal in diets for aquaculture species such as Atlantic salmon [11], rainbow trout [12], and Nile tilapia [13]. The use of BSFL in aquafeeds also contributes to reducing the environmental footprint of fish farming [14]. Additionally, BSFL meal provides nutritional benefits that enhance growth performance and disease resistance in aquatic species [15,16].

Despite its potential as an alternative protein source, BSFL meal has several anti-nutritional factors (ANFs) that may impact its digestibility and nutrient bioavailability. One of the primary concerns is chitin, a structural polysaccharide in the exoskeleton that can reduce protein digestibility and interfere with nutrient absorption, particularly in species with limited chitinase activity [17]. Additionally, BSFL meal has an imbalanced amino acid profile, with relatively low methionine and lysine levels compared to fishmeal, which could limit growth performance in fish [5]. Excessive saturated fatty acids may also influence lipid metabolism and energy utilization [18]. To mitigate these limitations, various processing methods have been explored to enhance BSFL meal's nutritional quality. Defatting can increase protein content and improve digestibility [19], while fermentation and enzymatic hydrolysis have shown promise in breaking down chitin and improving amino acid bioavailability [20]. In the present study, BSFL was processed by drying at 80 °C for four hours before being ground into powder, ensuring a consistent and stable ingredient for formulation. Oven-drying is a widely used method that preserves nutrients while reducing moisture content, thereby improving shelf life and pellet stability [21]. However, further optimization, such as partial defatting or enzymatic treatment, may enhance digestibility and protein utilization in future studies.

Given the observed decline in growth performance at higher BSFL inclusion levels, future research should explore supplementary strategies, such as amino acid fortification, enzyme supplementation, and modified processing methods, to counteract potential nutrient imbalances and improve feed efficiency.

The swamp eel (*Monopterus albus*) holds significant cultural and economic importance across various Asian countries, including China, Vietnam, Thailand, and Japan. In these regions, it is esteemed for its high protein content and distinctive taste, making it a delicacy in local cuisine. The swamp eel is also utilized in traditional medicine practices. The demand for swamp eel has led to its extensive farming, with China reporting an annual production exceeding 300,000 tons [22]. However, the aquaculture of *M. albus* faces notable challenges, particularly concerning feed. Traditionally, the diet of farmed swamp eels relies heavily on wild-caught fry and trash fish, leading to high mortality rates and inconsistent feeding initiation among juveniles. Studies have indicated that incorporating feeds such as earthworms and yellow mealworms can enhance survival rates and promote better growth performance in juvenile swamp eels [23]. Swamp eels require specialized nutrition during their juvenile stage to ensure optimal growth and health [24,25]. Incorporating BSFL meal into juvenile eel diets offers multiple benefits, including reduced feed costs and environmental impacts [3,16]. While BSFL meal has been extensively studied as a potential fishmeal alternative in aquaculture, research on its application in swamp eel (*Monopterus albus*) diets remains limited. Most previous studies focused on commonly farmed species, such as Nile tilapia (*Oreochromis niloticus*), rainbow trout (*Oncorhynchus mykiss*), and Japanese eel (*Anguilla japonica*) [17,19,26]. However, swamp eel exhibits unique feeding behavior, digestive physiology, and dietary protein–lipid requirements, which may influence the efficiency of BSFL as a protein source. Additionally, while concerns regarding

chitin content, amino acid balance, and lipid composition have been raised in studies on other fish species, no study has specifically evaluated how these factors impact swamp eel growth performance, feed utilization, and overall health. Furthermore, processing methods such as defatting and enzymatic hydrolysis have been shown to improve BSFL meal digestibility in some species [18], but their effects on swamp eels remain unexplored. This study aimed to fill this research gap by evaluating the optimal BSFL inclusion level in swamp eel diets, assessing its effectiveness as a partial fishmeal replacement. It focused on growth performance, feed conversion, and meat quality in juvenile swamp eels, providing insights into its potential as a sustainable alternative. The findings aim to support the development of more sustainable aquafeeds globally.

2. Materials and Methods

The experimental diets consisted of four formulations, prepared according to Cargill's recommendations [26], with varying proportions of BSFL meal replacing fishmeal (Table 1). The diets were designed to evaluate BSFL's potential as a sustainable alternative protein source, aligning with previous studies that demonstrated its effectiveness in other aquaculture species [27].

Table 1. Composition of experimental diets with varying levels of BSFL meal supplementation.

Ingredient (%)	0% BSFL (Control)	10% BSFL	30% BSFL	50% BSFL
Fishmeal	40	36	28	20
BSFL meal	0	4	12	20
Soybean flour	28.4	28.4	28.4	28.4
Rice bran	12	12	12	12
Premix vitamins—minerals	3	3	3	3
Soybean oil	3	3	3	3
Adhesive	3	3	3	3
Ground corn flour	10.6	10.6	10.6	10.6
Total	100	100	100	100

The feed utilized in this study was manufactured through a mechanical pelletizing process, as previously described [9]. In summary, the feed formulation comprised fishmeal, BSFL powder, soybean meal, rice bran, and cornmeal, supplemented with a premix of vitamins and minerals. These included vitamin C, vitamin E, various B-complex vitamins, and essential trace elements such as zinc and selenium, aimed at promoting fish health and growth. To improve pellet stability and minimize disintegration in water, binders like carboxymethyl cellulose (CMC) were incorporated. The BSFL was cultivated in the Animal Biotechnology Laboratory at VNUA using a standardized method [9]. Briefly, the larvae were fed a diet of processed beans and vegetables sourced from a local market. Upon reaching the fifth instar, they were thoroughly washed with clean water and subsequently dried in a heater set at 80 °C for approximately four hours until they attained a crispy texture. The dried larvae were then ground into powder and securely stored in sealed plastic bags [21]. The amino acid composition of both fishmeal and BSFL was monitored to ensure consistency for experimental purposes.

The eel fry were purchased from a commercial farm; the weight at the time of purchase was about 4 g/eel. Then, the eels were raised to acclimatize for 10 days before the experiment began.

The experiment was conducted in 12 plastic tanks (1.32 m × 0.95 m × 0.66 m), with each tank containing a stocking density of 40 eels/m^2. The eels were divided into four treatment groups, each with three replicates, corresponding to the different feed formulations. Black nylon bundles (0.5 kg/tank) were added to provide hiding spaces for the eels. The

tanks were partially cleaned daily by replacing 50% of the water, maintaining the remaining 50% before refilling. Temperature, pH, and dissolved oxygen (DO) were monitored twice daily (at 8:00 a.m. and 3:00 p.m.) using calibrated instruments (a TFA Dostmann Digital Thermometer, TFA Dostmann GmbH & Co. KG, Wertheim-Reicholzheim, Germany; and Hanna HI98107, Hanna Instruments, Woonsocket, Rhode Island, USA; and AZ8403 meters, AZ Instrument Corp., Taiwan; respectively). The eels were fed once daily at 5 p.m., with feed amounts adjusted to 5% of their total body weight.

Weight and length measurements were taken weekly from 10 randomly selected eels per tank. Growth rates were calculated as follows:

Absolute growth rate (AGR) for weight:

$$\mathrm{AGRw(g/individual/day)} = \frac{\mathrm{Wt} - \mathrm{W0}}{\mathrm{t}}$$

Absolute growth rate ($\mathrm{AGR_L}$) for length:

$$\mathrm{AGR_L(cm/individual/day)} = \frac{\mathrm{Lt} - \mathrm{L0}}{\mathrm{t}}$$

where

Wt: weight of an eel at the end of the experiment (g/individual);
W0: weight of an eel at the beginning of the experiment (g/individual);
Lt: length of an eel at the end of the experiment (cm/individual);
L0: length of an eel at the beginning of the experiment (cm/individual);
t: experimental period (days).

Specific growth rate (SGR):

$$\mathrm{SGR_W(\%/day)} = \frac{\mathrm{lnWt} - \mathrm{lnW0}}{\mathrm{t}} \times 100$$

Specific growth rate for length:

$$\mathrm{SGR_L(\%/day)} = \frac{\mathrm{lnLt} - \mathrm{lnL0}}{\mathrm{t}} \times 100$$

Survival rate (SR):

$$\mathrm{SR(\%)} = \frac{\text{Number of surviving eels}}{\text{Initial number of eels}} \times 100$$

Feed conversion ratio (FCR):

$$\mathrm{FCR} = \frac{\mathrm{Wtf}}{(\mathrm{Wtt} - \mathrm{Wt0} + \mathrm{Wtd})}$$

where

Wtf: total mass of food provided (g), calculated on a dry matter basis;
Wt0: total initial weight of eels (g);
Wtt: total weight of the eels at the end of the experiment (g);
Wtd: total weight of dead eels (g).

Meat quality: Fillet ratios, crude protein contents, and moisture levels were assessed. Meat color was evaluated using a colorimeter.

$$\text{Fillet ratio } (\%) = \frac{\text{Fillet weight (g)}}{\text{Weight of eels before filleting (g)}} \times 100$$

Crude protein content was calculated by the Kjeldahl method [28].

Moisture content was calculated by weighing 100 g of eel meat (sampled evenly from all positions) from each experimental batch. The samples were dried at 60 °C until a

constant mass was achieved. After drying, the total mass of the meat was weighed, and the water content was calculated as follows:

$$\text{Water Weight (g)} = \text{Initial Weight (g)} - \text{Weight After Drying (g)}$$

$$\%\ \text{moisture} = \frac{\text{Water Weight (g)}}{\text{Initial Weight (g)}} \times 100$$

Meat color was assessed using a colorimeter.

Data entry and management were performed using Excel software. Statistical analyses were conducted using Minitab Statistical Software (version 21), applying a one-way ANOVA with a 95% confidence level, followed by Tukey's post hoc test for pairwise comparisons. In the tables, values within the same column that are labeled with different letters indicate statistically significant differences ($p < 0.05$).

3. Results

3.1. Growth Rate for Weight

The growth rates for the weight and length of the eels across the experimental groups are presented in Table 2.

Table 2. Absolute growth rates and specific growth rates for weight and length of eels.

Growth Rate	0% BSFL (Control)	10% BSFL	30% BSFL	50% BSFL
AGR_W (g/individual/day)	$0.08^{a} \pm 0.004$	$0.08^{a} \pm 0.003$	$0.09^{b} \pm 0.004$	$0.07^{c} \pm 0.002$
SGR_W (%/day)	$1.42^{a} \pm 0.05$	$1.41^{a} \pm 0.04$	$1.47^{b} \pm 0.05$	$1.37^{c} \pm 0.06$
AGR_L (cm/individual/day)	$0.14^{a} \pm 0.005$	$0.15^{a} \pm 0.006$	$0.19^{b} \pm 0.008$	$0.12^{c} \pm 0.004$
SGR_L (%/day)	$0.63^{a} \pm 0.02$	$0.66^{a} \pm 0.03$	$0.70^{b} \pm 0.04$	$0.60^{c} \pm 0.03$

Values in the same column with different letters are statistically different ($p < 0.05$).

When BSFL meal was supplemented at 10%, the absolute growth rate (AGR_W) was 0.08 g/individual/day, which was not significantly different from the control group (0.08 g/individual/day). Increasing the BSFL meal level to 30% resulted in a significantly higher AGR_W of 0.09 g/individual/day compared to the control. Supplementation at 50% BSFL meal led to a decrease in AGRw to 0.07 g/individual/day, which was significantly lower than the control group.

The SGR_L values of the control group (0.63%/day) and the group supplemented with 10% BSFL meal (0.66%/day) showed no statistical difference. When the supplementation level was increased to 30% BSFL meal, the relative growth rate in length rose to 0.70%/day, which was significantly higher than in the other groups ($p < 0.05$). Increasing the supplementation level to 50% BSFL meal resulted in a relative growth rate in length of 0.60%/day, significantly lower than in the other groups.

3.2. Survival Rate

The survival rates of eels across the experimental treatments are shown in Table 3.

Table 3. Survival rates across treatments.

	0% BSFL (Control)	10% BSFL	30% BSFL	50% BSFL
SR (%)	$75.8^{a} \pm 1.2$	$76.0^{a} \pm 1.1$	$75.5^{a} \pm 1.3$	$75.2^{a} \pm 1.0$

Values in the same column with different letters are statistically different ($p < 0.05$).

The survival rates of eels in the treatments ranged from 75.2% to 76.0%, with no statistically significant differences between groups ($p > 0.05$). This indicates that the addition of BSFL meal to the diet, at levels of 10%, 30%, or 50%, did not negatively affect eel survival.

3.3. Feed Conversion Ratio

The FCRs of the eels in the experimental treatments are presented in Table 4.

Table 4. Feed conversion ratios across treatments.

	0% BSFL (Control)	10% BSFL	30% BSFL	50% BSFL
FCR	$2.41^{a} \pm 0.02$	$2.37^{a} \pm 0.04$	$2.33^{b} \pm 0.03$	$2.48^{c} \pm 0.05$

Values in the same column with different letters are statistically different ($p < 0.05$).

The FCR value for the 30% BSFL meal group (2.33) was significantly lower ($p < 0.05$) than those of the other groups. The 50% BSFL meal group had the highest FCR (2.48, $p < 0.05$) compared to the other groups, while the control group (2.41) and the 10% BSFL meal group (2.37) showed no significant difference ($p > 0.05$). As a lower FCR indicates more efficient feed conversion, these results suggest that feed conversion efficiency is not improved with 10% BSFL supplementation but is optimized with 30% BSFL. However, efficiency declines with 50% BSFL inclusion.

3.4. Meat Quality

The results of the meat quality assessment of the four treatments are shown in Table 5.

Table 5. Meat quality of eels across treatments.

	0% BSFL (Control)	10% BSFL	30% BSFL	50% BSFL
Fillet ratio (%)	$25.7^{a} \pm 0.3$	$25.5^{a} \pm 0.6$	$27.3^{b} \pm 0.7$	$24.6^{c} \pm 0.5$
Crude protein content (%)	$16.5^{a} \pm 0.4$	$16.2^{a} \pm 0.5$	$16.3^{a} \pm 0.4$	$1\,6.3^{a} \pm 0.3$
Moisture (%)	$79.5^{a} \pm 0.5$	$79.3^{a} \pm 0.6$	$79.6^{a} \pm 0.5$	$79.2^{a} \pm 0.4$
Meat color (L*)	$50.0^{a} \pm 0.8$	$51.2^{b} \pm 0.7$	$52.0^{c} \pm 0.6$	$53.0^{d} \pm 0.5$
Meat color (a*)	$7.2^{a} \pm 0.4$	$7.5^{b} \pm 0.3$	$7.8^{c} \pm 0.4$	$8.0^{c} \pm 0.3$

Values in the same column with different letters are statistically different ($p < 0.05$). L*: lightness (0 = black, 100 = white). a*: represents the red–green axis (positive = red, negative = green) in the CIE Lab color space.

The 30% BSFL meal group exhibited the highest fillet ratio (27.3%), which was significantly higher than in both the control group (25.7%) and the 50% BSFL meal group (24.6%). This suggests that 30% BSFL meal supplementation not only promotes growth but also enhances the proportion of usable meat. The 10% BSFL meal group showed no statistical difference in fillet ratio compared to the control group.

There was no significant difference in crude protein content across all groups, with values ranging from 16.2% to 16.5%. Moisture content was similarly consistent, varying between 79.2% and 79.6%. These results indicate that BSFL meal supplementation does not negatively affect the protein or moisture composition of eel meat.

The color of the meat showed a notable trend, with both brightness (L) and redness (a) values increasing proportionally with the BSFL meal content in the diet. The highest values for brightness (53.0) and redness (8.0) were observed in the 50% BSFL meal group. While the 50% supplementation level did not enhance growth performance, it positively influenced meat color, which could be a desirable attribute for certain markets.

4. Discussion

The results showed that the 10% BSFL meal level did not provide sufficient nutritional impact to influence growth in both weight and length. Increasing the BSFL meal level to

30% resulted in a higher growth rate compared to the control and 10% BSFL meal groups, but further increasing to 50% BSFL meal led to a growth decline. These results indicated that 30% BSFL supplementation was optimal for promoting growth, likely providing adequate nutrients without causing imbalances or deficiencies, thereby supporting growth. Previous studies have also demonstrated the positive effect of BSFL supplementation on the growth rate in many aqua species, including sea bass (*Lates calcarifer*) [29,30] and red tilapia (*Oreochromis* sp.) [31]. These studies reinforce the conclusion that BSFL meal can serve as an effective alternative to fishmeal in aquafeeds. Our findings about 30% BSFL meal as the optimal inclusion level aligned with a previous report demonstrating that replacing 30% of fishmeal and fish oil with BSFL protein and oil did not compromise growth performance in sea bass (*Lates calcarifer*) [30]. Another study investigated the effects of BSFL meal supplementation in the diet of Pacific white shrimp (*Litopenaeus vannamei*) [15]. The authors found that BSFL meal improved growth performance, weight gain, and survival rates. Additionally, BSFL meal enhanced gut health, balanced intestinal microflora, and increased resistance to pathogens like *Vibrio parahaemolyticus*, a common aquaculture disease agent. These benefits affirm the potential of BSFL meal as a sustainable and health-promoting alternative protein source in aquafeeds.

The consistently high survival rates across all treatments (above 75%) reflect favorable rearing conditions, including appropriate water quality, stocking density, and effective management practices. These findings align with those reported in similar studies. A study [32] demonstrated that BSFL meal supplementation in the diet of ornamental Koi (*Cyprinus carpio var. Koi*) enhanced immune responses. Genes related to immunity, such as TNF-α, IL1, IL10, and hsp70, were upregulated in fish fed BSFL meal, especially at higher inclusion levels, suggesting that BSFL meal positively influences fish health and immunity. Another study [13] examined the effects of BSFL meal as a replacement for fishmeal in the diet of Nile tilapia (*Oreochromis niloticus*). This study showed that partial replacement of fishmeal with BSFL meal not only supported survival and growth rates but also improved hematological parameters, including red blood cell count and hemoglobin levels. BSFL meal also enhanced fish immunity by improving skin mucus quality, which plays a crucial role in disease resistance. The findings of these studies support the results of the current study, demonstrating that BSFL meal can replace fishmeal without adversely affecting survival rates. Furthermore, its potential to enhance immunity provides additional benefits, making BSFL meal a promising alternative protein source in aquafeeds.

Supplementation at 50% BSFL meal led to a decrease in growth rate in both weight and length, suggesting that excessive inclusion of BSFL meal may create dietary imbalances, possibly due to the high chitin content or other anti-nutritional factors that disrupt dietary balance, impair nutrient absorption, or cause digestive disturbances. The high chitin content in BSFL meal is likely a contributing factor, as it can impair digestibility and reduce overall feed efficiency. Chitin, a structural component in the exoskeletons of insects, has been shown to influence nutrient digestibility in fish. Studies have demonstrated that while species like Nile tilapia (*Oreochromis niloticus*) and rainbow trout (*Oncorhynchus mykiss*) can digest chitin, its digestibility decreases with higher dietary inclusion levels, potentially acting as an anti-nutrient and impairing nutrient absorption [33]. To mitigate the adverse effects of chitin in BSFL meal, various processing methods have been explored. Enzymatic hydrolysis, involving the use of chitinase enzymes, has been effective in breaking down chitin, thereby enhancing protein digestibility and nutrient utilization in fish. Additionally, defatting methods, such as mechanical pressing and supercritical fluid extraction, have been employed to reduce the lipid content of BSFL meal. These defatting processes not only decrease the fat content but also improve the oxidative stability of the meal, making it a more suitable ingredient in aquafeeds [34]. Implementing these processing strategies can enhance

the nutritional value of BSFL meal, improving its digestibility and making it a more viable protein source in aquaculture diets. In some study conditions with up to 50% substitution in the diets of rainbow trout (*Oncorhynchus mykiss*), BSF protein hydrolysates (BPHs) exhibit cytoprotective effects, reducing inflammation and oxidative stress in LPS-challenged cells in gut microbiota [35]. Our findings are consistent with those of a previous study [36] on the effects of replacing fishmeal with BSFL meal in the diet of lamprey (*Cynoglossus semilaevis*). This research showed that BSFL meal improved growth performance, digestive function, and muscle quality at moderate replacement levels, but at very high replacement levels (above 50%) adverse effects were observed, including changes in intestinal structure and biochemical indices, suggesting potential limitations of high BSFL inclusion.

The optimal performance observed with 30% BSFL meal supplementation highlighted its potential as a sustainable and nutritionally balanced feed ingredient for enhancing eel growth. The FCR data from the current study further emphasize the effectiveness of 30% BSFL meal as an optimal supplementation level, balancing nutritional benefits while avoiding the adverse effects associated with higher replacement levels. These findings underscore the potential of BSFL meal as a sustainable protein source in aquafeeds when used at appropriate levels. However, further investigations are needed to refine the inclusion levels and address potential limitations associated with higher supplementation.

Regarding meat quality, the 3-month period is a favorable time to detect differences in meat quality across treatments because this is the period when eels grow strongly and can clearly reflect the impact of nutritional factors. This is also the period when eels begin to enter a stable stage [24,25]. Our findings suggested that supplementation at 30% balanced growth and meat quality, maximizing growth and fillet yield while maintaining acceptable levels of meat quality attributes. These results align with those of a previous study which demonstrated that BSFL meal supplementation improved protein and fat composition in hybrid red tilapia [37]. Similarly, another study [36] showed that replacing fishmeal with defatted BSFL meal in the diet of lamprey (*Cynoglossus semilaevis*) positively impacted growth performance, digestive function, and muscle quality. The use of BSFL meal also enhanced the water-holding capacity and antioxidant properties of fish meat, contributing to improved overall quality.

A comparative discussion on the effects of BSFL meal in other anguilliform species would provide valuable context. In an 8-week feeding trial, researchers investigated the effects of replacing fishmeal with defatted BSFL meal in the diets of Japanese eel (*Anguilla japonica)*. The study formulated six isoproteic and isolipidic diets with fishmeal replacement levels ranging from 0% to 75%. The results indicated that at up to a 45% replacement level there were no significant adverse effects on growth performance, fillet texture, serum biochemical parameters, or intestinal histomorphology. However, higher inclusion levels led to reduced growth performance and alterations in intestinal morphology, suggesting that excessive BSFL meal might affect nutrient absorption and overall health [38]. While specific studies on the inclusion of BSFL meal in the diets of European eels (*Anguilla anguilla*) are currently limited, research on other fish species provides some insights. For instance, studies on Betta splendens have evaluated growth performance, feed stability, blood biochemistry, and liver and gut morphology, using BSFL as an alternative to fishmeal. These studies suggest that while BSFL meal can serve as a viable protein source, optimal inclusion levels must be carefully determined to avoid potential negative impacts on growth and health [39]. These findings underscore the importance of species-specific evaluations when considering BSFL meal as a dietary component. Factors such as digestibility, amino acid profile, and chitin content play crucial roles in determining the suitability and optimal inclusion levels of BSFL meal in aquafeeds. We have incorporated these insights into

the revised manuscript to provide a more comprehensive understanding of BSFL meal's potential across different anguilliform species.

The current study did not investigate sensory characteristics such as taste, texture, and overall consumer acceptability, which are important factors in evaluating the practical application of BSFL meal in swamp eel diets [40]. While BSFL meal at 30% inclusion improved fillet yield without affecting proximate composition, we recognize that flavor and consumer perception are also key considerations for commercial adoption. To address this, we have included a discussion highlighting the need for future research on sensory attributes and consumer acceptance of eels fed with BSFL-based diets.

Several limitations should be acknowledged. First, the study focused primarily on growth performance, feed conversion efficiency, and meat quality, without assessing potential impacts on gut health, immune response, and long-term physiological effects. Given the chitin content and lipid profile of BSFL meal, future research should investigate intestinal histology, microbiota composition, and immune-related gene expression to better understand its broader implications for eel health. Feeding at a fixed 5% body weight may have led to variations in actual feed intake among groups and therefore bias. We will consider alternative feeding strategies (ad libitum feeding with controlled satiation or dynamic feeding rate adjustments) in future studies to further refine FCR comparisons. Next, fiber analysis was not included, which would have provided further insights into the digestibility challenges. The study was conducted over a three-month period, which may not have been sufficient to fully capture the long-term effects of BSFL on swamp eels. Extended feeding trials are needed to evaluate these aspects. Lastly, the economic feasibility and scalability of BSFL meal production for commercial swamp eel farming require further assessment, including cost–benefit analysis and environmental impact evaluation. Addressing these limitations in future studies will enhance our understanding of BSFL meal as a sustainable aquafeed ingredient and support its broader adoption in aquaculture.

5. Conclusions

In conclusion, the 30% BSFL meal supplementation level not only supports optimal growth and feed efficiency but also yields high fillet ratios while maintaining meat quality. This supplementation level offers a promising approach for integrating BSFL meal into aquaculture diets as a sustainable alternative protein source. However, future research should consider more variety in experimental conditions and evaluate the impacts of BSFL meal on health, immunity, and reproductive performance in eels. This will help refine its inclusion levels and pave the way for broader commercialization of BSFL-based feeds in aquaculture, contributing to sustainable industry practices globally.

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(VietGAP)" standards (TCVN 13528-1:2022), ensuring safe and hygienic products, disease reduction, ecological environmental protection, and social responsibility.

Data Availability Statement: The data supporting the findings of this study can be made available upon reasonable request by contacting the authors. The data are not publicly available due to privacy concerns.

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