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Original Article

# Early fry performance of swamp eel (*Monopterus albus*) fed diets containing black soldier fly (*Hermetia illucens*) pupa meal

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**Abstract:** The swamp eel (*Monopterus albus*) is an economically important freshwater species in Asia. However, its early life stage is constrained by high mortality and strong dependence on high-quality diets in intensive farming. This study evaluated the effects of dietary black soldier fly (*Hermetia illucens*) pupa meal (DBSFPM) on the growth performance, feed utilization, and survival of swamp eel fry during a 45-day rearing period. Five diets were formulated with graded DBSFPM levels (0, 5, 10, 15, and 20 g kg$^{-1}$), and 675 fry were reared in a completely randomized design with triplicate treatments. Growth performance improved significantly with increasing DBSFPM supplementation during the rearing period ($P \leq 0.05$). At day 45, weight-related parameters exhibited a threshold response, with no significant difference between 0 and 5 g kg$^{-1}$ ($P \geq 0.05$), whereas higher supplementation levels (10-20 g kg$^{-1}$) significantly enhanced growth ($P \leq 0.05$). In contrast, length-related parameters responded at lower supplementation levels, with all supplemented groups outperforming the control ($P \leq 0.05$). The feed conversion ratio was significantly improved at 15-20 g kg$^{-1}$ ($P \leq 0.05$). Survival rates remained high (>93%) in all treatments. Although survival did not differ between supplemental groups and the control ($P \geq 0.05$), the 20 g kg$^{-1}$ group showed a significantly higher survival rate than lower supplemental treatments (5-15 g kg$^{-1}$) ($P \leq 0.05$). There was no significant difference in size uniformity among treatments ($P \geq 0.05$). Overall, DBSFPM supplementation enhanced growth performance and feed efficiency, with optimal results observed at 15-20 g kg$^{-1}$. These findings support the use of DBSFPM as a functional dietary ingredient for improving early-stage aquaculture performance in swamp eels.

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## Introduction

Worldwide aquaculture production continues to rely heavily on fishmeal and fish oil as primary dietary components. However, increasing costs, limited availability, and environmental concerns associated with these marine resources have intensified the search for sustainable alternative protein sources (Tacon and Metian, 2015; Hua, 2021). In this regard, insect-derived ingredients have emerged as promising candidates due to their high efficiency in converting organic waste into nutrient-rich biomass and their relatively low ecological footprint (van Huis et al., 2013; Makkar et al., 2014; Mohan et al., 2022).

Among these, the black soldier fly (*Hermetia illucens*) has gained considerable attention as a sustainable feed ingredient in aquaculture. Its larvae and pupae contain high levels of crude protein (30-58%) and possess a well-balanced amino acid profile comparable to fishmeal (Barragan-Fonseca et al., 2017; Spranghers et al., 2017). In addition to their nutritional value, black soldier fly (BSF)-derived products have been reported to enhance growth performance, improve digestive enzyme activity, and modulate gut microbiota in aquatic animals (Li et al., 2017; Rimoldi et al., 2019; Wang et al., 2019; Gasco et al., 2020; Hu et al., 2020). These beneficial effects are partly attributed to bioactive compounds such as medium-chain fatty acids, particularly lauric acid, as well as chitin and antimicrobial peptides, which may contribute to improved nutrient utilization, immune

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function, and disease resistance (St-Hilaire et al., 2007; Li et al., 2016; Abdel-Latif et al., 2021; Chen et al., 2021; Kumar et al., 2021). Consequently, the use of BSF in aquafeeds has increased significantly in recent years (Camperio et al., 2026; Shirly-Lim et al., 2025).

Previous studies have demonstrated that the effects of BSF ingredient inclusion vary depending on species, life stage, and dietary formulation. When used as a replacement for fishmeal, high inclusion levels of BSF larvae (ranging from 10 to 60% or more) have been reported to show no adverse effects in several species, such as Atlantic salmon (*Salmo salar*) and African catfish (*Clarias gariepinus*) (Belghit et al., 2019; Fawole et al., 2020). In contrast, when applied as a functional dietary supplement, lower inclusion levels (approximately 10-20%) are often sufficient to improve growth and feed utilization, whereas excessive inclusion may impair performance (Makkar et al., 2014; Hua, 2021; Kariuki et al., 2024). Despite extensive research in many teleost species, studies on eel species remain limited. Available evidence indicates that BSF-derived ingredients can improve growth performance, digestive enzyme activity, and physiological responses in juvenile swamp eel (*M. albus*) and Japanese eel (*Anguilla japonica*) (Hu et al., 2020; Kuo et al., 2022). However, the optimal inclusion level and dose–response relationship of BSF in early developmental stages are not yet well established.

The swamp eel (*M. albus*) is an economically important freshwater species widely cultured in Asia due to its high market value and adaptability to diverse environmental conditions (Hii et al., 2007; Mao et al., 2022; Pintar et al., 2024; Zhang et al., 2025; Zhao et al., 2025). Nevertheless, its aquaculture production is constrained by slow growth, high mortality, and sensitivity to environmental stress, particularly during early life stages (Tok et al., 2009; Ayah et al., 2018). During this period, underdeveloped digestive and immune systems increase dependence on high-quality diets, making nutrition a critical factor influencing survival and growth (Cahu and Zambonino-Infante, 2001; Hamre et al., 2013; Bojarski et al., 2025). Therefore, the development of effective dietary strategies is essential to improve early-stage performance in this species.

Although ingredients derived from BSF have significant potential, their nutritional and functional effects can vary based on developmental stage and level of inclusion. This variability highlights the necessity for species-specific evaluations (Meneguz et al., 2018; Tschirner and Simon, 2015). In particular, information on the application of black soldier fly pupa meal as a functional dietary supplement during the early ontogeny of swamp eel remains scarce.

Therefore, the present study aimed to evaluate the effects of graded levels of DBSFPM on the growth performance, feed utilization, and survival of *M. albus* fry during a 45-day rearing period. The results are expected to contribute to the development of sustainable feeding strategies for improving early-stage aquaculture performance in this species.

## Materials and Methods

**Experimental materials:** Swamp eel fry at the onset of exogenous feeding (initial weight of 0.019±0.002 g and length of 2.9±0.18 cm) were obtained from a commercial hatchery and transported to the Aquaculture Experimental Hatchery of Tra Vinh University (Vietnam) using a closed aerated system (Erikson et al., 2022). The eels were acclimated for 7 days before the experiment. Freshwater was prepared from tap water after it was filtered through an RO (reverse osmosis) filtration system. The aerated plastic trays (262.5 cm²; 35 cm length × 7.5 cm width × 25 cm height) maintained a water depth of 4 cm and were used as rearing devices. Nylon fiber substrates were provided in each tray to serve as shelter. This study was conducted in accordance with the guidelines of the U.S. National Research Council for the care and use of experimental animals (Directive 86/609/EEC).

**Diet preparation:** A commercial pellet diet containing 42% crude protein (Grobest Joint Stock Company, Vietnam) was used as the basal feed. The proximate composition of basal feed is presented in Table 1. BSF pupae were dried at 70°C for 8 hours before processing. Both the basal feed and dried BSF

Table 1. Proximate nutritional components of basal feed used in experiments.

| | |
|---|---|
| Protein (%) | 42 |
| Lipid (%) | 4 |
| Fiber (%) | 4 |
| Moisture content (%) | 11 |
| Phosphorus (%) | 0.9 |
| Lysine (%) | 1.6 |
| Ethoxyquin (ppm) | 100 |

Values are based on the manufacturer's specifications for commercial pellets containing 42% crude protein (Grobest Joint Stock Company, Vietnam).

pupae were ground into fine meals. Five experimental diets were prepared by supplementing the basal diet with graded levels of DBSFPM at 0 (control), 5, 10, 15, and 20 g $kg^{-1}$. All ingredients were thoroughly homogenized using a laboratory mixer to ensure uniform distribution. The experimental diets were stored in a refrigerator at 4°C until use.

**Experimental procedure:** This study was conducted from September to December 2024 at the Aquaculture Experimental Hatchery of Tra Vinh University in southern Vietnam. It aimed to assess the performance of swamp eel fry at the onset of exogenous feeding, using five experimental diets with varying DBSFPM levels. The completely randomized design in three replications was carried out in the aerated plastic trays (262.5 $cm^2$) and lasted 45 days. The experimental details are described as follows:

A total of 675 uniform healthy fry were randomly distributed into 15 trays at a stocking density of 45 individuals per tray. Eels were hand-fed twice daily (08:00 and 18:00) at 5-7% of their body weight. Before feeding, the trial diets were sufficiently weighed to the required ration of each treatment and made into a paste with 0.5-1.0 mL of water. The resulting slurry was formed into flat cakes (~2 cm in diameter) and placed on the rearing trays. Feeding rates were adjusted daily based on feed intake. Uneaten feed was collected approximately 2 h after feeding to estimate consumption. Tanks were siphoned daily to remove waste and residual feed, and water was completely renewed twice daily.

**Data collection and calculation:** Initial measurements were recorded before stocking. Sampling was conducted at 15-day intervals (days 15, 30, and 45). At each sampling point, five fish were randomly collected from each replicate (n = 15 per treatment). Fish were gently blotted dry before measurement. Body weight was recorded using an electronic balance (±0.01 g), and total length was measured to the nearest 0.1 cm. At the end of the experiment, growth performance indices, survival rate, feed conversion ratio (FCR), and coefficient of variation (CV) were calculated. The monitored parameters were calculated using standard formulas (Stickney, 2000; Hieu et al., 2022).

Mean weight (MW, g) = total weight of 15 fish / 15

Mean length (ML, cm) = total length of 15 fish / 15

Weight gain (WG, g) = final weight – initial weight

Length gain (LG, cm) = final length – initial length

Daily weight gain (DWG, g $day^{-1}$) = (final weight – initial weight) / days

Daily length gain (DLG, cm $day^{-1}$) = (final length – initial length) / days

Specific growth rate in weight (SGRW, % $day^{-1}$) = [(ln final weight – ln initial weight) / days] × 100

Specific growth rate in length (SGRL, % $day^{-1}$) = [(ln final length – ln initial length) / days] × 100

Survival rate (%) = (final number / initial number) × 100

Feed conversion ratio (FCR) = feed intake (g) / weight gain (g)

Coefficient of variation (CV, %) = (standard deviation / mean) × 100

**Water quality monitoring:** During the experiment, temperature and pH were measured twice daily (07:00 and 14:00) using a HANNA meter (Model HI98103, Romania). Total ammonia nitrogen (TAN) and nitrite ($NO_2^-$) were measured every three days using commercial test kits (Sera, Germany).

**Analyzing data:** Data were analyzed using one-way

Table 2. Water quality during the 45 days of rearing under various dietary black soldier fly pupa meal levels.

| | Test Time | Dietary black soldier fly pupa meal levels (g $kg^{-1}$) | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 5 | 10 | 15 | 20 |
| Temperature (°C) | 7:00 | 27.20±1.03 | 26.00±0.69 | 26.03±1.33 | 26.16±1.14 | 26.25±1.04 |
| | 14:00 | 27.73±0.96 | 27.55±1.06 | 27.74±0.98 | 27.66±1.06 | 27.61±1.05 |
| pH | 7:00 | 7.65±0.12 | 7.89±0.07 | 7.90±0.05 | 8.01±0.05 | 8.06±0.32 |
| | 14:00 | 7.90±0.02 | 7.91±0.12 | 8.00±0.11 | 8.04±0.31 | 8.07±0.26 |
| TAN (mg $L^{-1}$) | | 0.19±0.05 | 0.26±0.07 | 0.20±0.05 | 0.24±0.07 | 0.22±0.06 |
| $NO_2^-$ (mg $L^{-1}$) | | 0.08±0.02 | 0.13±0.05 | 0.18±0.06 | 0.17±0.06 | 0.16±0.04 |

Values are presented as mean±SD.

Table 3. Initial mean weight (IMW), mean weight (MW), weight gain (WG), daily weight gain (DWG), and specific growth rate in weight (SGRw) of swamp eel fry during the 45 days of rearing under various dietary black soldier fly pupa meal levels.

| Parameters | Dietary black soldier fly pupa meal levels (g $kg^{-1}$) | | | | |
|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | 20 |
| IMW (g $ind^{-1}$) | 0.019±0.002 | 0.019±0.002 | 0.019±0.002 | 0.019±0.002 | 0.019±0.002 |
| $MW_{15}$ (g $ind^{-1}$) | 0.021±0.004$^a$ | 0.033±0.007$^b$ | 0.046±0.009$^c$ | 0.049±0.009$^c$ | 0.067±0.013$^d$ |
| $MW_{30}$ (g $ind^{-1}$) | 0.072±0.020$^a$ | 0.113±0.026$^b$ | 0.113±0.029$^b$ | 0.154±0.046$^c$ | 0.215±0.037$^d$ |
| $MW_{45}$ (g $ind^{-1}$) | 0.172±0.057$^a$ | 0.204±0.049$^a$ | 0.294±0.074$^b$ | 0.449±0.135$^c$ | 0.607±0.170$^d$ |
| WG (g $ind^{-1}$) | 0.154±0.058$^a$ | 0.185±0.049$^a$ | 0.275±0.074$^b$ | 0.429±0.135$^c$ | 0.588±0.170$^d$ |
| DWG (g $ind^{-1}$) | 0.003±0.001$^a$ | 0.004±0.001$^a$ | 0.007±0.003$^b$ | 0.009±0.003$^c$ | 0.013±0.004$^d$ |
| $SGR_W$ (% $day^{-1}$) | 4.804±0.779$^a$ | 5.240±0.521$^a$ | 6.039±0.598$^b$ | 6.950±0.700$^c$ | 7.650±0.575$^d$ |

Values are presented as mean±SD. Values with different letters (a, b, c, d) in the same row show a significant difference ($P≤0.05$).

Table 4. Initial mean length (IML), mean length (ML), length gain (LG), daily length gain (DLG), and specific growth rate in length ($SGR_L$) of swamp eel fry during the 45 days of rearing under various dietary black soldier fly pupa meal levels.

| Parameters | Dietary black soldier fly pupa meal levels (g $kg^{-1}$) | | | | |
|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | 20 |
| IML (cm $ind^{-1}$) | 2.9±0.18 | 2.9±0.18 | 2.9±0.18 | 2.9±0.18 | 2.9±0.18 |
| $ML_{15}$ (cm $ind^{-1}$) | 3.12±0.17$^a$ | 3.46±0.25$^b$ | 3.95±0.24$^c$ | 4.04±0.23$^c$ | 4.54±0.29$^d$ |
| $ML_{30}$ (cm $ind^{-1}$) | 4.88±0.52$^a$ | 5.19±0.47$^a$ | 5.25±0.46$^a$ | 5.95±0.67$^b$ | 6.53±0.44$^c$ |
| $ML_{45}$ (cm $ind^{-1}$) | 5.70±0.51$^a$ | 6.37±0.56$^b$ | 7.23±0.63$^c$ | 8.33±0.82$^d$ | 9.09±0.92$^e$ |
| LG (cm $ind^{-1}$) | 2.80±0.51$^a$ | 3.47±0.56$^b$ | 4.33±0.64$^c$ | 5.43±0.82$^d$ | 6.19±0.92$^e$ |
| DLG (cm $ind^{-1}$) | 0.06±0.01$^a$ | 0.08±0.01$^b$ | 0.09±0.01$^c$ | 0.12±0.02$^d$ | 0.14±0.02$^e$ |
| $SGR_L$ (% $day^{-1}$) | 1.49±0.19$^a$ | 1.73±0.20$^b$ | 2.02±0.19$^c$ | 2.33±0.22$^d$ | 2.53±0.22$^e$ |

Values are presented as mean±SD. Values with different letters (a, b, c, d) in the same row show a significant difference ($P≤0.05$).

analysis of variance (ANOVA). Duncan's multiple range test was applied for pairwise comparisons at P = 0.05. Normality and homogeneity of variance were verified using Shapiro–Wilk and Levene's tests, respectively. Percentage data were arcsine-transformed when necessary. All analyses were performed using SPSS software (Version 20.0).

## Results

**Water quality parameters:** The monitored water quality remained stable during the 45-day rearing period, with minimal variation among treatments. Temperature ranged from 26.00±0.69 to 27.74±0.98°C, while pH values varied between 7.65±0.12 and 8.07±0.26. TAN and $NO_2^-$ concentrations remained low and showed minimal variation among treatments, ranging from 0.19±0.05 to 0.26±0.07 mg $L^{-1}$ and 0.08±0.02 to 0.18±0.06 mg $L^{-1}$, respectively (Table 2).

**Rearing performance:** Growth responses showed clear dose- and time-dependent patterns. At day 15, both mean weight ($MW_{15}$) and mean length ($ML_{15}$) increased progressively with DBSFPM levels, with all supplemented groups outperforming the control ($P≤0.05$, Tables 3, 4), and the highest values were observed at 20 g $kg^{-1}$. By day 30, eels fed 15 and 20 g $kg^{-1}$ diets showed significantly higher $MW_{30}$ and $ML_{30}$ than those fed 0-10 g $kg^{-1}$ ($P≤0.05$, Tables 3, 4), while no differences were detected among the lower inclusion levels ($P≥0.05$, Tables 3, 4).

At day 45, weight-related parameters (MW, WG, DWG, and $SGR_W$) showed a threshold response.

Table 5. Coefficient of variation in weight ($CV_W$) and length ($CV_L$) of swamp eel fry after the 45 days of rearing under various dietary black soldier fly pupa meal levels.

| Parameters | Dietary black soldier fly pupa meal levels (g kg$^{-1}$) | | | | |
|---|---|---|---|---|---|
| | 0 | 5 | 10 | 15 | 20 |
| $CV_W$ (%) | 34.67±16.50[a] | 24.33±6.03[a] | 26.67±6.03[a] | 32.33±6.66[a] | 24.00±6.56[a] |
| $CV_L$ (%) | 9.33±3.06[a] | 8.33±5.13[a] | 9.67±1.58[a] | 10.33±1.53[a] | 10.00±4.36[a] |

Values are presented as mean±SD. Values sharing the same letter (a) indicate no significant difference ($P \leq 0.05$).

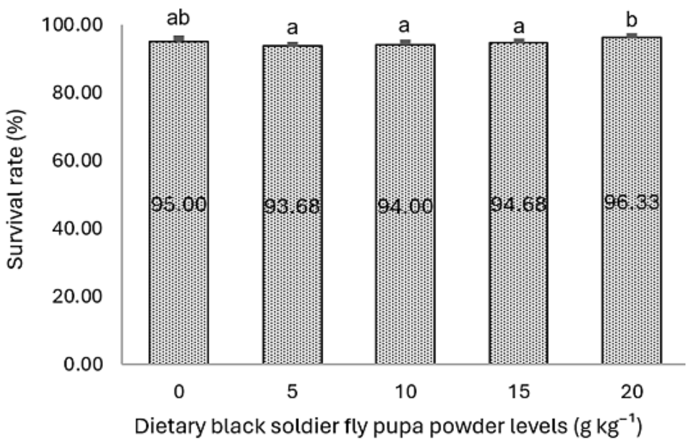


Figure 1. Survival rate of swamp eel fry after the 45 days of rearing under various dietary black soldier fly pupa meal levels. The bars with different letters (a, b) indicate a significant difference ($P \leq 0.05$).

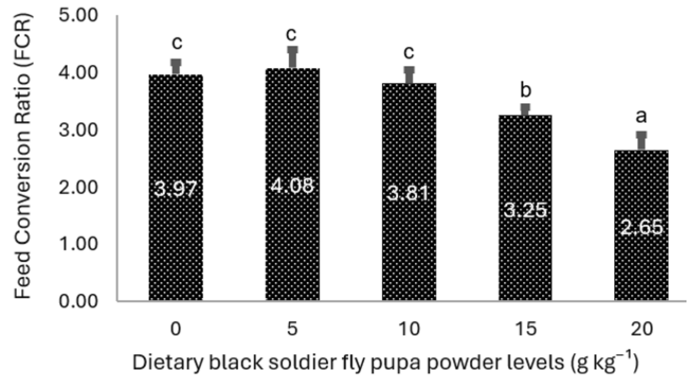


Figure 2. Feed conversion ratio (FCR) of swamp eel fry after the 45 days of rearing under various dietary black soldier fly pupa meal levels. Values are presented as mean±SD. The bars with different letters (a, b, c) indicate a significant difference ($P \leq 0.05$).

These parameters did not show significant differences between 0 and 5 g kg$^{-1}$ ($P \geq 0.05$, Table 3), whereas higher supplementation levels (10-20 g kg$^{-1}$) exhibited progressively greater increases with higher DBSFPM levels ($P \leq 0.05$, Table 3). Compared with the control, $MW_{45}$ increased by approximately 71, 161, and 253% at 10, 15, and 20 g kg$^{-1}$, respectively (Table 3). In contrast, length-related parameters (ML, LG, DLG, and $SGR_L$) responded in a graded manner, with all supplemented groups (≥5 g kg$^{-1}$) exceeding the control ($P \leq 0.05$, Table 4). The highest $ML_{45}$ (9.09±0.92 cm) was recorded at 20 g kg$^{-1}$ (Table 4).

The survival rate in the supplement groups did not differ significantly from the control ($P \geq 0.05$, Fig. 1), while the 20 g kg$^{-1}$ group showed higher survival than lower supplementation levels (5-15 g kg$^{-1}$) ($P \leq 0.05$, Fig. 1). Feed conversion ratio (FCR) was significantly improved at 15 and 20 g kg$^{-1}$ compared with 0-10 g kg$^{-1}$ ($P \leq 0.05$, Fig. 2), with no differences among the lower supplementation levels ($P \geq 0.05$, Fig. 2). Both coefficients of variation in weight ($CV_W$) and length ($CV_L$) did not differ significantly among treatments ($P \geq 0.05$, Table 5).

## Discussions

The present study indicates that DBSFPM supplementation resulted in a clear improvement in growth performance across supplementation levels and rearing time. This positive effect was observed consistently across both weight- and length-related parameters (MW, WG, DWG, and $SGR_W$; ML, LG, DLG, and $SGR_L$), with significant and progressive improvements in growth achieved at supplementation levels of 10-20 g kg$^{-1}$.

The significant increase in ML and MW with increasing DBSFPM levels, observable as early as day 15, indicates that DBSFPM supplementation plays a critical role during the initial ontogeny period of *M. albus* fry, when digestive capacity and nutrient assimilation efficiency are not yet fully developed (Cahu and Zambonino-Infante, 2001; Hamre et al., 2013). However, by the end of the experiment, the absence of significant differences in weight-related parameters between the control and 5 g $kg^{-1}$ groups suggests that low supplementation levels are insufficient to elicit measurable physiological benefits, thereby showing a threshold-dependent response during ontogenetic development, with the need for higher levels of DBSFPM for weight gain in older eels. Similar threshold effects have been reported in other fish species, where insect-derived ingredients require a minimum supplementation level to effectively modulate digestive and metabolic processes (Fawole et al., 2020; Hua, 2021; Kariuki et al., 2024).

The consistently significant improvement in both length and weight observed at ≥10 g $kg^{-1}$, culminating in the highest performance at 20 g $kg^{-1}$, together with the progressive reduction in FCR within the 15-20 g $kg^{-1}$ range, suggests that DBSFPM functions not only as a protein source but also as a functional feed ingredient. While the high-quality protein and well-balanced amino acid profile of *H. illucens* contribute directly to somatic growth (Makkar et al., 2014; Barragan-Fonseca et al., 2017), the improved FCR indicates enhanced feed utilization efficiency. This effect may be associated with the presence of medium-chain fatty acids, particularly lauric acid, which are rapidly oxidized and can support mitochondrial energy metabolism (Li et al., 2016). In addition, bioactive components such as chitin and antimicrobial peptides may contribute to improved gut health and nutrient absorption, potentially by modulating the intestinal microbiota and mucosal immunity (Gasco et al., 2020; Kumar et al., 2021). Furthermore, previous studies have shown that insect-based diets can upregulate digestive enzyme activity and the expression of genes involved in nutrient transport and immune regulation (Li et al., 2017; Rimoldi et al., 2019; Hu et al., 2020).

Survival remained high (>93%) in all treatments, indicating that DBSFPM was well tolerated at the tested levels. Survival in the basal diet was comparable to, or marginally higher than, that observed in the low DBSFPM supplementation groups (<15 g $kg^{-1}$), suggesting that suboptimal supplement levels did not confer additional survival benefits. Remarkably, the significantly higher survival rate at 20 g $kg^{-1}$ may suggest improved physiological resilience at higher supplementation levels. This effect may be related to the reported functional properties of BSF-derived ingredients, which have been reported to support immune function, antioxidant capacity, and disease resistance in fish and crustaceans (Abdel-Latif et al., 2021; Chen et al., 2021; Wang et al., 2025). Recent studies highlighted their role in strengthening mucosal immunity and systemic defense responses (Islam et al., 2024; Xiao et al., 2024). These findings suggest that DBSFPM may provide both nutritional and functional benefits.

The CV is used to evaluate size uniformity in farmed fish populations. Lower CV values indicate more uniform body sizes, which benefit feeding efficiency, growth performance, and synchronized harvesting, whereas higher values reflect greater size heterogeneity, which may reduce production efficiency and market value (Gomez and Gomez, 1984; Santos and Dias, 2021). In the present study, $CV_W$ and $CV_L$ did not differ significantly among treatments, with values (24.00-34.67% and 8.33-10.33%, respectively) falling within the typical range reported for cultured fish species (Gjedrem, 1997). These findings indicate that DBSFPM improves growth, survival, and FCR without increasing size variability, which is advantageous in early-stage eel aquaculture by limiting size-dependent competition and supporting overall production efficiency.

Key water quality parameters were stably maintained within optimal ranges for swamp eels throughout the rearing period, including a temperature of 26.00-27.74°C, pH of 7.65-8.07, TAN at 0.19-0.26 mg $L^{-1}$, and nitrite-nitrogen ($NO_2^-$) at 0.08-0.18 mg $L^{-1}$ (Boyd, 1990; Pedersen et al., 2012; Portalia et al., 2019; Yuan et al., 2024), indicating that they did not contribute to the observed main effects. From an applied perspective, the use of DBSFPM at low supplementation levels (5 g $kg^{-1}$) during the initial rearing period of swamp eel fry may support basic growth. However, higher supplementation levels are required at later stages to achieve optimal rearing performance. The highest supplementation level tested in this study (20 g $kg^{-1}$) effectively enhanced early-stage performance without any observable adverse effects. Further studies at higher supplementation levels are needed to determine the optimum for maximizing aquaculture performance.

## Conclusions

DBSFPM supplementation improved the rearing performance of *M. albus* fry, with evident effects observed above a threshold level of supplementation. Dietary supplementation at 10-20 g $kg^{-1}$ enhanced both weight and length growth, while higher levels (15-20 g $kg^{-1}$) further improved feed conversion efficiency. The highest level tested (20 g $kg^{-1}$) produced the best overall performance without adverse effects on survival or size uniformity. These results indicate that DBSFPM is an effective dietary supplement for early-stage swamp eel culture. However, the study was limited to a short-term feeding period and did not assess underlying physiological mechanisms. Future research should evaluate higher supplementation levels, long-term effects, and mechanisms to optimize its application in aquaculture.

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