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Black Soldier Fly Larval Meal as a Cost-Effective Protein Source for Enhancing Tilapia (*Oreochromis noloticus*) Growth

TF Safrana[1], MNM Fouzi[1*], Muneeb M Musthafa[2], Faiz MMT Marikar[3]

[1]Department of Farm Animal Production and Health, Faculty of Veterinary Medicine and Animal Science, University of Peradeniya, Peradeniya, Sri Lanka
[2]Department of Biosystems Technology, Faculty of Technology, South Eastern University of Sri Lanka, Oluvil, Sri Lanka
[3]General Sir John Kotelawala Defence University, Ratmalana, Sri Lanka
***Corresponding Author: mnmf@vet.pdn.ac.lk**

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ABSTRACT

Tilapia is an important freshwater species in global aquaculture, but rising commercial feed costs have reduced its economic viability. Black soldier fly larval (BSFL) meal offers a cost-effective, protein-rich alternative that can lower feed expenses and increase the profit by utilizing food waste for production. The objective of the present study is to evaluate BSFL meal as an alternative protein source for tilapia growth and to assess its economic impact in Sri Lanka. A 42-day feeding trial was conducted using a completely randomized design to evaluate the effectiveness of BSFL meal as a protein substitute in tilapia diets. The study included four treatment groups, each conducted in duplicate, a control group fed 100% commercial feed, and three experimental groups fed diets containing 50, 75, and 100% BSFL based feed, respectively. Each tank was stocked with 10 tilapia fries of uniform size, with a mean initial body weight of 27 ± 2 g and a mean initial total length of 9.5 ± 0.5 cm. Fish growth performance was assessed through measurements of length, weight gain, and feed conversion ratio (FCR), while feed cost was analyzed to determine economic viability. The final average length (cm) of tilapia was recorded as 11.28±0.37, 11.40±0.59, 11.12±0.38, 11.01±0.50 in control, treatment 1, treatment 2 and treatment 3, respectively. In terms of final average weight (g) the results were 52.55±5.93, 51.20±3.68, 49.15±3.26, 45.56±2.24 in control, treatment 1, treatment 2 and treatment 3, respectively. Fish weight and length differed significantly among the feeding groups (P< 0.05), as determined by ANOVA. However, Tukey's HSD post-hoc test revealed a statistically significant difference in weight (P< 0.05) only between the control group and the 100% BSFL group (Treatment 3). The average FCR for the control, treatment 1, treatment 2, and treatment 3 groups was 1.20 ± 0.21, 1.27 ± 0.22, 1.36 ± 0.29, and 1.46 ± 0.14, respectively. There were no statistically significant differences in FCR between the ccontrol group and any of the treatment groups. Increasing the inclusion level of BSFL meal reduced the feed cost to two-thirds of the original cost. This study concludes that BSFL meal can replace up to 75% of commercial feed, without negatively impacting growth performance or feed efficiency. No significant differences were observed in key growth parameters, and feed costs were substantially reduced. Thus, BSFL meal can be used a viable, cost-effective alternative protein source in tilapia feed.

INTRODUCTION

Aquaculture is one of the fastest-growing sectors in global food production, with tilapia (*Oreochromis* spp.) recognized as a key freshwater species due to its adaptability, rapid growth, and high market demand. Fish serve as a primary source of high-quality animal protein for much of the global population and provide essential nutrients, including amino acids, vitamins, minerals, and omega-3 fatty acids **(Badoni *et al.*, 2021)**. The rising global demand for fish, driven by population growth and increased consumption, has placed significant pressure on aquaculture systems. The growing demand for sustainable and cost-effective protein sources in aquaculture has driven research into alternative protein ingredients to reduce reliance on conventional feed components. BSFL meal is currently a leading alternative feed ingredient in aquaculture due to its high protein content, rapid production cycle, and cost-effective cultivation, which utilizes organic waste materials as a substrate **(Eide *et al.*, 2024)**.

Fish products meet a huge percentage of the needs of the world population and account for 15% of all animal protein consumed globally **(Aisyah *et al.*, 2022)**. The per capita consumption of fish in the Southeast Asian region is approximately three times that of the global average. Moreover, the global consumption index of fish improved from 53.1kg in 2011 to 61.1kg by 2020 and is expected to rise in the future due to the alarming growth in the population **(Aisyah *et al.*, 2022)**. As global population increases, the reliance on aquatic food sources continues to rise, requiring the development of sustainable and economically viable aquaculture practices.

Among farmed species, tilapia, particularly the genetically improved farmed tilapia (GIFT) strain, has gained recognition due to its fast growth, efficient feed conversion, adaptability to varying environmental conditions, and broad consumer acceptance **(Momin *et al.*, 2024)**. GIFT represents a major advancement in tilapia farming, indicating superior performance in terms of survival rates, disease resistance, and overall yield. Its contribution to sustainable fish farming practices aligns with the wide-ranging goal of improving global food security and supporting economic growth in developing nations **(Perera & Marikar, 2013; Arumugam *et al.*, 2023)**.

A fundamental determinant of success in tilapia farming is the cost-effectiveness and nutritional quality of feed, which constitutes up to 70–80% of total operational expenses in aquaculture **(Arumugam *et al.*, 2023; Rodríguez-Hernández *et al.*, 2025)**. Conventional aqua feeds depend heavily on fishmeal and soybean meal as primary protein sources, both of which are becoming increasingly expensive and environmentally unsustainable due to overfishing and competition from other agricultural industries **(Vázquez-Rowe, 2020)**. The search for alternative protein sources has strengthened as the industry contends with increasing feed costs, falling fishmeal availability, and environmental concerns associated with large-scale soy production. A promising alternative to traditional protein sources is BSFL (*Hermetia illucens*), which has demonstrated high nutritional value, a favorable amino acid profile and sustainability as an aqua feed ingredient **(Mohan *et al.*, 2022)**.

BSFL meal is a rich source of protein, lipids, and essential micronutrients, making it a viable substitute for fishmeal in aquaculture diets. One of its key advantages is its capability to be cultured on organic waste, converting low-value substrates into high-quality biomass **(Maroušek *et al.*, 2023)**. This capacity not only reduces the environmental footprint of fish farming but also addresses waste management challenges. Additionally, BSFL can be produced in various conditions using locally available agricultural by-products, making it a cost-effective feed option for fish farmers in developing regions such as Sri Lanka. The increasing global focus on circular economy practices further highlights the importance of insect-based proteins in sustainable agriculture and aquaculture systems **(Priyadarshana *et al.*, 2021)**.

Despite the numerous benefits of BSFL as a feed ingredient, challenges remain in optimizing its use in tilapia diets. One major concern is the high lipid content in BSFL meal, which, if not appropriately balanced, can lead to excessive fat deposition in fish tissues, affecting meat quality **(English *et al.*, 2021)**. Additionally, BSFL contains chitin, is a fibrous component that in excessive amounts can reduce digestibility and nutrient absorption in fish **(Moraes & de Almeida 2020)**. Processing methods such as defatting and enzyme treatment have been explored to improve the digestibility and nutritional profile of BSFL meal **(Indriawati & Rahardja, 2021)**. Another challenge is the scale of BSFL production and its cost relative to traditional feed ingredients which used rearing the BSFL. Although BSFL meal is generally 30–40% cheaper than conventional fishmeal, large-scale production requires infrastructure investment and efficient substrate sourcing to maintain consistent supply, quality and price **(Batool *et al.*, 2024)**.

From an environmental perspective, the use of BSFL in aquaculture aligns with global sustainability goals by mitigating overfishing, reducing waste accumulation, and lowering the carbon footprint of feed production **(Ordoñez *et al.*, 2022)**. Traditional fishmeal production is associated with habitat destruction, by catch and depletion of wild fish stocks, raising concerns about the long-term sustainability of marine-derived proteins **(Mohan *et al.*, 2022)**. In contrast, BSFL farming utilizes food and agricultural waste streams, transforming them into a valuable protein source while simultaneously addressing waste management challenges **(Ravi *et al.*, 2020)**. The potential of BSFL to be integrated into circular economy models strengthens its role as a sustainable aqua feed ingredient.

This study investigates the effectiveness of BSFL meal as an alternative for traditional commercial fish feed in growth performance of a selected population of GIFT fish. By evaluating different inclusion level of BSFL meal, the research aims to identify optimal that not only enhances the fish growth but also improve the economic viability of aquaculture operations in Sri Lanka.

MATERIALS AND METHODS

Experimental setup

The research was conducted at the Centre for Aquatic Animal Diseases Diagnosis and Research (CAADDR) using 1,000-liter fiberglass tanks for fish rearing. The commercial feed was procured from a local aquaculture supply store, while the BSFL meal was produced on-site from BSFL eggs cultivated under controlled farm conditions. Thus, the eggs were initially placed in hen mash to facilitate hatching. After hatching, the larvae remained in the same substrate until they reached five days of age, allowing for easier handling and improved survival during their early development. Once the larvae were five days old, they were transferred to the substrates of canteen waste and were allowed to grow until 12 days of age under room temperature, and then larvae were inactivated using hot water then were left to dry under sunlight. Proximate analysis was conducted on both the commercial feed and the BSFL-based feed to determine their nutritional composition, specifically assessing crude protein, crude fat, and ash content. To conduct the proximate analysis, dried BSFL and commercial feeds were taken and ground into a fine powder using mortar and pestle, then 1g of each sample was obtained for crude fat, crude protein and crude ash analysis using soxlet apparatus, kjeldahl apparatus and muffle furnace, respectively. GIFTs were obtained from the National Aquaculture Development Authority (NAQDA), Dambulla. Prior to the experiment, the fries were graded to ensure size uniformity, with a mean initial body weight of 27 ± 2 g and a mean initial total length of 9.5 ± 0.5 cm. The fish fries were acclimated to a temperature of 26°C ± 1°C for two weeks before the experiment. A total of eight 1,000-liter tanks were used in the study, with each tank stocked with 10 tilapia fish.

Feeding trial design and experimental procedure

Following a period of acclimatization, 80 GIFT tilapia of uniform size were randomly assigned to four dietary treatment groups, each with two replicates, resulting in a total of eight experimental units. The study was conducted using a completely randomized design (CRD) to ensure statistical robustness. The dietary treatments consisted of: Control group with 100% commercial feed; Treatment 1 with 50% commercial feed and 50% BSFL meal; Treatment 2 with 25% commercial feed and 75% BSFL meal; and Treatment 3 with 100% BSFL meal. Each 1,000-liter tank was stocked with 10 tilapia fries and filled to 50% of its volume with dechlorinated freshwater. Fish were fed twice daily, in the morning and evening, at a rate of 4% of the total biomass per tank, with feed amounts adjusted weekly based on batch weight measurements. Feed intake and fish growth were monitored weekly, with individual fish in each tank weighed and their body length and weight recorded on days 0, 7, 14, 21, 28, 35, and 42. Survival rates were determined by counting the remaining fish per tank at the end of the experiment. Water quality parameters were maintained within optimal ranges throughout the 42-day trial, with dissolved oxygen and pH levels recorded weekly and maintained at

5.04 ± 0.64 mg/L and 7.9 ± 0.2, respectively. Approximately 50% of the water in each tank was replaced twice weekly to preserve water quality, and uneaten feed along with faecal matter were removed daily by siphoning the tank bottoms.

Dosage used in this study

The selection of BSFL replacement levels in the current study was informed by extensive literature precedent and preliminary experimental observations. Previous investigations incorporating similar BSFL inclusion levels in tilapia diets have provided valuable baseline data for formulation strategies **(Priyadarshana *et al.*, 2021; Aisyah *et al.*, 2022)**, demonstrating the feasibility of substantial protein source substitution in this species. Furthermore, research conducted on related fish species has consistently identified the 50-75% replacement range as optimal for maintaining growth performance while maximizing the economic and sustainability benefits of BSFL incorporation **(Mohan *et al.*, 2022; Eide *et al.*, 2024)**. These findings established a critical framework suggesting that moderate to high replacement levels could be achieved without compromising nutritional adequacy or growth outcomes.

Measurements of growth rate and statistical analysis

Statistical analysis of weight and length data was performed using analysis of variance (ANOVA) in MINITAB 17 statistical software. To assess differences among individual treatment means, Tukey's honestly significant difference (HSD) post-hoc test was applied **(Abdi & Williams, 2010)**. The FCR was calculated based on total feed intake and corresponding weight gain, and differences in FCR among treatments were also analyzed using one-way ANOVA.

Formulas used

Weight Gain (g) = Final weight - Initial weight
Length Gain (cm) = Final length - Initial length
Specific Growth Rate (SGR, %/day) = [(ln final weight - ln initial weight) / 42 days] × 100
Daily Weight Gain (DWG, g/day) = (Final weight - Initial weight) / 42 days
Feed Conversion Ratio (FCR) = Total feed intake (g) / Total weight gain (g)
Protein Efficiency Ratio (PER) = Weight gain (g) / Protein intake (g)
Lipid Efficiency Ratio (LER) = Weight gain (g) / Lipid intake (g)
Condition Factor (K) = [Weight (g) / Length^3 (cm)] × 100

Water quality parameters

Water quality parameters remained stable across all treatments, with dissolved oxygen maintained at 5.04 ± 0.64 mg/L and pH at 7.9 ± 0.2, both within the optimal range for tilapia culture. These observations suggest that BSFL meal is a safe and nondetrimental dietary component for the Nile tilapia, supporting its suitability for sustainable aquaculture operations.

Assessments of growth performance and feed utilization

Growth performance was assessed based on weight gain, length increment, and feed utilization efficiency. Initial body weights of the fish were recorded at the start of the experiment using a precision electronic balance, and fish were weighed weekly thereafter to monitor growth. Similarly, the total length of each fish was measured weekly using a standard measuring scale. Daily feed intake was recorded by quantifying the total amount of dry feed administered to each tank. Weekly wet weight gain was measured for each treatment group, and FCR was calculated as the ratio of total feed intake to total weight gain to evaluate feed efficiency.

Feed cost analysis

The cost-effectiveness of each dietary treatment was evaluated by comparing the feed costs of commercial fish feed with BSFL feed. The total feed cost for each treatment was determined based on the quantity of feed consumed and its respective market price. Growth performance was assessed using specific calculations, including weight gain, determined as the final weight minus the initial weight per week; length growth, calculated as the final length minus the initial length per week; and feed conversion ratio (FCR), computed as the total dry feed intake (g) divided by the total wet weight gain (g).

RESULTS

Nutritional composition of experimental feeds

Proximate composition analysis was performed on both the black soldier fly larvae (BSFL)-based feed and the commercial fish feed to quantify their nutritional constituents. The analytical results, summarized in Table (1), indicate that the BSFL-based feed exhibited substantially higher crude protein, crude fat, and ash contents compared to the commercial counterpart. Specifically, the BSFL feed contained 45.52% crude protein, 22.67% crude fat, and 12.42% crude ash, whereas the commercial feed contained 34.68% crude protein, 4.50% crude fat, and 10.66% crude ash.

Table 1. Proximate composition of commercial and BSFL-based feeds (% dry matter basis)

Component	Commercial (%)	BSFL (%)
Crude ash	10.66	12.42
Crude fat	4.5	22.67
Crude Protein	34.68	45.52

Economic analysis of feed costs

The cost evaluation was conducted for four dietary treatments formulated with increasing levels of black soldier fly larvae (BSFL) meal substituting commercial fish feed. The unit cost of commercial fish feed was LKR 600/kg (USD 2.00/kg), whereas BSFL meal production cost was LKR 400/kg (USD 1.33/kg). Incremental inclusion of BSFL meal produced proportional reductions in feed cost. A 50% substitution lowered feed cost by LKR 100/kg (USD 0.33/kg), while 75% substitution achieved a reduction of LKR 150/kg (USD 0.50/kg). Complete replacement (100% BSFL meal) resulted in the highest cost saving of LKR 200/kg (~USD 0.67/kg). These results indicate that BSFL meal incorporation substantially reduces feed costs, thereby enhancing the economic sustainability of tilapia aquaculture (Table 2).

Table 2. Effect of BSFL meal inclusion on feed cost per kilogram

BSFL Inclusion Level (%)	Feed Cost (LKR/kg)	Feed Cost (USD/kg)	Cost Reduction (LKR/kg)	Cost Reduction (USD/kg)
0 (Control)	600	2.00	0	0.00
50	500	1.67	100	0.33
75	450	1.50	150	0.50
100	400	1.33	200	0.67

Growth performance analysis

At the conclusion of the 42-day feeding trial, the mean final body weight and body length, along with their respective standard deviations (SD), were determined for all dietary treatments (Table 2). The control group (100% commercial feed), Treatment 1 (50% commercial feed + 50% BSFL meal), and Treatment 2 (25% commercial feed +

75% BSFL meal) exhibited comparable mean body weights and lengths. In contrast, Treatment 3 (100% BSFL meal) recorded the lowest mean values for both growth parameters. Among all treatments, the control group achieved the highest final mean body weight (52.55 ± 5.93 g), whereas Treatment 1 exhibited the highest mean body length (11.40 ± 0.59 cm). These results suggest that partial replacement of commercial feed with BSFL meal (up to 75%) can maintain growth performance comparable to a fully commercial diet; however, complete substitution may result in reduced weight gain and body length (Table 3).

Table 3. Mean final body weight and length (± SD) of tilapia after 42 days of feeding

Treatment	**Diet Composition**	**Final Body Weight (g)**	**Final Body Length (cm)**
Control	100%commercial feed	52.55 ± 5.93	11.28 ± 0.37
T1	50% commercial + 50% BSFL meal	51.20 ± 3.68	11.40 ± 0.59
T2	25% commercial + 75% BSFL meal	49.15 ± 3.26	11.12 ± 0.38
T3	100% BSFL meal	45.56 ± 2.24	11.01 ± 0.50

Statistical analysis of growth parameters

Analysis of variance (ANOVA) revealed significant differences in both final body weight and body length among the dietary treatment groups ($P < 0.05$). Post-hoc comparisons using Tukey’s HSD test indicated no significant differences ($P > 0.05$) in body weight or length between the control, Treatment 1 (50% BSFL meal), and Treatment 2 (75% BSFL meal). A significant reduction in final body weight ($P < 0.05$) was observed only in Treatment 3 (100% BSFL meal) when compared to the control group. For body length, Tukey’s HSD test showed no significant differences ($P > 0.05$) between the control and any of the treatment groups. However, Treatment 1 recorded a significantly greater mean length ($P < 0.05$) compared to Treatment 3. These results suggest that partial substitution of commercial feed with BSFL meal (≤ 75%) does not adversely affect growth performance, whereas complete replacement may reduce final body weight and, to a lesser extent, body length.

Table 4. Comprehensive growth performance metrics of tilapia fed different BSFL inclusion levels growth and efficiency parameters (Mean ± SD)

Parameter	Control (0% BSFL)	T1 (50% BSFL)	T2 (75% BSFL)	T3 (100% BSFL)	*P*-value
Initial Weight (g)	27.00 ± 2.00	27.00 ± 2.00	27.00 ± 2.00	27.00 ± 2.00	NS
Final Weight (g)	52.55 ± 5.93[a]	51.20 ± 3.68[a]	49.15 ± 3.26[ab]	45.56 ± 2.24[b]	<0.05
Weight Gain (g)	25.55 ± 5.93[a]	24.20 ± 3.68[a]	22.15 ± 3.26[ab]	18.56 ± 2.24[b]	<0.05
Initial Length (cm)	9.50 ± 0.50	9.50 ± 0.50	9.50 ± 0.50	9.50 ± 0.50	NS
Final Length (cm)	11.28 ± 0.37[ab]	11.40 ± 0.59[a]	11.12 ± 0.38[ab]	11.01 ± 0.50[b]	<0.05
Length Gain (cm)	1.78 ± 0.37[ab]	1.90 ± 0.59[a]	1.62 ± 0.38[ab]	1.51 ± 0.50[b]	<0.05
SGR (%/day)	1.61 ± 0.28[a]	1.56 ± 0.19[a]	1.47 ± 0.21[ab]	1.28 ± 0.15[b]	<0.05
DWG (g/day)	0.608 ± 0.141[a]	0.576 ± 0.088[a]	0.527 ± 0.078[ab]	0.442 ± 0.053[b]	<0.05
FCR	1.20 ± 0.21[a]	1.27 ± 0.22[a]	1.36 ± 0.29[a]	1.46 ± 0.14[a]	>0.05
PER	2.42 ± 0.42[a]	2.21 ± 0.38[ab]	2.02 ± 0.43[bc]	1.79 ± 0.17[c]	<0.05
LER	5.67 ± 0.99[a]	3.78 ± 0.65[b]	2.69 ± 0.58[c]	1.95 ± 0.19[d]	<0.001
Condition Factor (K)	3.65 ± 0.31[a]	3.42 ± 0.28[a]	3.58 ± 0.25[a]	3.39 ± 0.22[a]	>0.05
Survival Rate (%)	100.0	100.0	100.0	100.0	NS

The growth performance parameters revealed distinct patterns across dietary treatments. Final weight and total length showed significant reductions only in the 100% BSFL group compared to the control ($P < 0.05$), while intermediate replacement levels maintained comparable measurements. Both specific growth rate (SGR) and daily weight gain (DWG) exhibited a progressive decline with increasing BSFL inclusion, with statistically significant reductions observed exclusively at the 100% replacement level. Feed conversion ratio (FCR) showed no significant differences among treatments despite numerical increases at higher BSFL inclusion rates, suggesting relatively consistent feed utilization efficiency. Protein efficiency ratio (PER) demonstrated a gradual decline with BSFL incorporation, reaching statistical significance only between the control and 100% BSFL treatments, indicating that protein utilization remained reasonably effective even at elevated replacement levels.

Lipid efficiency ratio (LER) presented the most dramatic response, with highly significant differences ($P < 0.001$) observed across all treatment groups. This pronounced effect was directly attributable to the high lipid content of BSFL meal (22.67%), which substantially altered the dietary lipid-to-protein balance and consequently impacted lipid utilization efficiency. Condition factor values remained statistically comparable across all treatments, demonstrating that fish maintained similar body condition regardless of BSFL inclusion level. Notably, survival rates reached 100% across all dietary treatments throughout the experimental period, providing clear evidence that BSFL meal poses no adverse health effects and is well-tolerated by the fish.

Overall, these results indicate that BSFL meal can effectively replace up to 75% of commercial feed while maintaining growth performance comparable to the control diet. However, complete replacement at 100% BSFL resulted in significantly compromised growth metrics, suggesting that some proportion of conventional feed remains beneficial for optimal fish performance.

General observations during the experimental period

No mortality was recorded in any treatment group throughout the 42-day experimental period. Furthermore, no adverse health effects or behavioral abnormalities were observed in fish fed diets containing varying proportions of black soldier fly larvae (BSFL) meal, including the 100% replacement group.

Feed conversion ratio (FCR) analysis

The mean feed conversion ratio (FCR) and standard deviation for each treatment group were calculated as follows: Control (1.20 ± 0.20), Treatment 1 (1.27 ± 0.22), Treatment 2 (1.36 ± 0.29), and Treatment 3 (1.46 ± 0.14). An increasing trend in FCR was observed with higher inclusion levels of black soldier fly larvae (BSFL) meal, with the highest value recorded in Treatment 3 (100% BSFL meal) and the lowest in the control group (100% commercial feed) (Fig. 5). One-way ANOVA revealed no statistically significant differences among treatment groups in terms of FCR ($P > 0.05$). This indicates that the replacement of commercial feed with BSFL meal, even at 100% inclusion, does not significantly impair feed utilization efficiency, supporting its potential as a viable alternative protein source in tilapia aquaculture (Fig. 1).

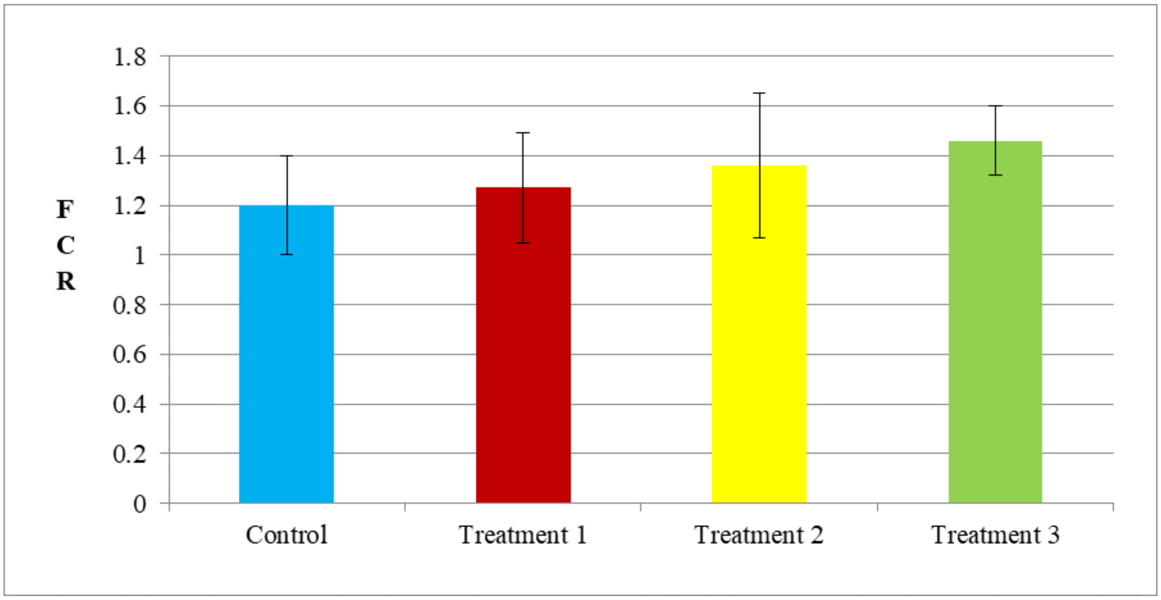

Fig. 1. Average FCR for different treatments

DISCUSSION

The escalating cost of conventional fish feed, primarily driven by the limited availability of high-quality raw materials, has intensified the search for alternative protein sources in aquaculture. In countries such as Sri Lanka, where aquafeed production heavily depends on imported ingredients, this reliance poses significant economic and logistical constraints. Consequently, sustainable and cost-effective alternatives have gained increasing research attention, with insect-based meals particularly black soldier fly larvae (BSFL) meal emerging as promising candidates due to their high nutritional value and relatively low production costs **(Boyd *et al.*, 2020)**.

BSFL production offers dual benefits: providing a nutrient-dense protein source and facilitating organic waste management by converting biodegradable materials from households, agro-industries, and municipal waste streams into valuable biomass **(Ordoñez *et al.*, 2022)**. This circular bioeconomy approach aligns closely with the principles of sustainable aquaculture development.

Fish growth performance is conventionally assessed by measuring changes in body weight and length over time **(Aisyah *et al.*, 2022)**. Optimal growth in aquaculture species such as the Nile tilapia (Genetically improved farmed tilapia, GIFT) requires nutritionally balanced diets rich in high-quality proteins, lipids, essential amino acids, fatty acids, minerals, and vitamins. In this context, insect meals like BSFL have garnered interest due to their favorable macronutrient profiles, notably high protein and fat contents **(Aisyah *et al.*, 2022)**.

The present study evaluated the efficacy of BSFL meal as a partial or complete replacement for conventional fishmeal in diets formulated for GIFT tilapia. Findings indicate that BSFL meal can replace up to 75% of commercial fishmeal without detrimental effects on growth performance or feed conversion efficiency. However, diets containing 100% BSFL meal resulted in significantly reduced growth, suggesting limitations associated with full substitution.

Several factors may account for the diminished growth observed with complete BSFL replacement despite its high crude protein content. Notably, BSFL contains chitin, a structural polysaccharide constituting the insect exoskeleton, which is largely indigestible to many fish species due to the absence of endogenous chitinase enzymes **(Hasan *et al.*, 2023)**. Elevated dietary chitin levels have been associated with impaired nutrient digestibility and reduced feed efficiency **(Eggink *et al.*, 2025)**, potentially explaining the observed decline in growth metrics at 100% BSFL inclusion.

Secondly, although BSFL meal possesses a high crude protein content, its amino acid profile may be inferior to that of conventional fishmeal. Essential amino acids, particularly methionine and lysine, are frequently found at suboptimal concentrations in BSFL, potentially limiting protein synthesis and growth performance when BSFL is used as the sole protein source **(Seyedalmoosavi *et al.*, 2022)**.

Thirdly, the lipid fraction of BSFL is characterized by elevated levels of saturated fatty acids and comparatively low concentrations of long-chain polyunsaturated fatty acids (LC-PUFAs), such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), which are critical for optimal fish health, development, and physiological function **(Lutfi *et al.*, 2022)**. This imbalance in fatty acid composition may contribute to the observed reduction in growth rates at higher BSFL inclusion levels.

Palatability also represents a significant factor influencing feed intake. Complete replacement of fishmeal with BSFL meal may result in reduced palatability, thereby decreasing voluntary feed consumption and negatively affecting growth **(Ashfaq *et al.*, 2020)**. This phenomenon was evident in the present study, where Treatment 3 (100% BSFL) exhibited lower feed intake relative to other experimental groups, likely attributable to diminished palatability.

Moreover, suboptimal processing methods of BSFL, such as insufficient defatting or inadequate thermal treatment, may result in the retention of anti-nutritional factors (ANFs), which can impair gut integrity and nutrient assimilation **(Gasco *et al.*, 2018)**. These processing shortcomings may partially explain the elevated feed conversion ratio (FCR) observed in the 100% BSFL treatment group.

From an economic standpoint, the inclusion of BSFL meal significantly reduces feed costs. Our cost analysis demonstrated a clear inverse relationship between BSFL inclusion level and feed price, with potential savings of up to LKR 200 per kilogram at complete replacement. The capability to locally produce BSFL from organic waste not only lowers production expenses but also diminishes reliance on imported feed ingredients, thereby enhancing the economic sustainability of aquaculture operations in Sri Lanka.

Furthermore, BSFL production aligns with environmentally sustainable aquaculture practices by valorizing organic waste streams into high-quality protein, thereby mitigating environmental impacts associated with waste disposal and reducing pressure on wild fish stocks exploited for fishmeal production. Additionally, emerging evidence suggests that BSFL contains bioactive compounds, including antimicrobial peptides and beneficial lipids, which may enhance fish immune responses and reduce antibiotic usage in aquaculture systems **(Ordoñez *et al.*, 2022)**.

While these findings are encouraging, several challenges must be addressed before widespread adoption of BSFL meal in aquafeeds. Further research is warranted to optimize BSFL processing methods to enhance nutrient bioavailability and digestibility. Additionally, efforts are required to overcome consumer perception barriers and to navigate the evolving regulatory frameworks governing the use of insect-derived ingredients in aquaculture. Moreover, long-term feeding trials are essential to comprehensively assess the impacts of sustained BSFL inclusion on fish health, flesh quality, and market acceptance.

CONCLUSION

In conclusion, although black soldier fly larvae (BSFL) meal exhibits a high crude protein content, several nutritional and physiological constraints limit its efficacy as a complete fishmeal substitute. These limitations include the presence of indigestible chitin, an imbalanced essential amino acid profile, suboptimal lipid composition, reduced palatability, and the potential presence of anti-nutritional factors. Consequently, partial replacement of fishmeal with BSFL meal at inclusion levels up to 75% provides an optimal compromise, achieving cost reduction without compromising growth performance. Complete substitution (100%) necessitates further refinement, potentially through enhanced processing techniques, targeted amino acid fortification, or formulation strategies involving ingredient blending to mitigate these inherent challenges.

Ethical approval

All procedures involving animals in this study were conducted in accordance with established ethical standards for the use of animals in research. Ethical approval was obtained from the Undergraduate Animal Ethics Committee of the Faculty of Veterinary Medicine and Animal Science, University of Peradeniya, Sri Lanka ensuring adherence to institutional guidelines on animal welfare, humane handling, and sample collection. Prior to sample collection, informed consent was also obtained from all participating farm owners.

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