

# Black soldier fly larvae (*Hermetia illucens*) meal as a sustainable fishmeal replacement: growth, water quality, and economic profitability in tilapia (*Oreochromis* sp.) fingerling culture

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**ABSTRACT.** The present study evaluated the suitability of black soldier fly (*Hermetia illucens*) larvae (BSFL) as a fishmeal substitute in the diets of tilapia fingerlings (*Oreochromis* sp.) reared in a recirculating aquaculture system, with particular emphasis on growth performance, water quality, and economic profitability. Three isoproteic diets were formulated by replacing fishmeal at levels of 0, 50, and 75% (D0, D50, and D75, respectively). Growth parameters, feed utilisation efficiency, and water quality indicators were monitored during a 45-day feeding trial, and the profitability of the diets was assessed. Significant differences in growth and feed conversion were observed between treatments ( $P < 0.05$ ), with comparable performance obtained in fish fed the D0 and D75 diets. Metabolic rate analysis further suggested improved protein utilisation in diets containing insect meal. Moreover, the D50 diet significantly reduced ammonium concentrations in the recirculating water system ( $P < 0.05$ ). From an economic perspective, the inclusion of BSFL meal resulted in higher profitability compared with conventional fishmeal-based feeds. Overall, the results confirm that BSFL meal represents a practical and sustainable alternative to fishmeal in intensive tilapia fingerling production, supporting both production efficiency and environmental sustainability.

## Introduction

The development of aquaculture has resulted in more than half of aquatic products intended for human consumption being obtained from farming systems, exceeding the contribution of capture fisheries (FAO, 2024). Among cultured species, tilapia ranks third worldwide due to its high adaptability, rapid growth rate, tolerance to variable environ-

mental conditions, and substantial economic and social importance (Nunes et al., 2024). Nevertheless, the intensification of aquaculture production poses major sustainability challenges, particularly in feed formulation, where protein represents a critical and costly component (Kou et al., 2022). Fishmeal (FM) has traditionally been the main protein source in aquafeeds due to its high nutritional value and digestibility; however, reliance on wild fish

stocks raises concerns regarding long-term resource sustainability and price volatility (Ghamkhar and Hicks, 2020). Consequently, increasing attention has been directed towards identifying alternative feed ingredients that ensure high nutritional quality, scalability of production, and reduced environmental impact.

In this context, black soldier fly larvae (BSFL) have emerged as a highly promising alternative protein source. They are rich in protein and beneficial fatty acids, while their production contributes to sustainability through the bioconversion of organic waste into valuable biomass (Fantatto et al., 2024). BSFL inclusion has been evaluated in the diets of various cultured species, including tilapia, salmon, and rainbow trout, with most studies reporting improvements in growth, nutrient utilisation, health, and in some cases, even fillet quality (Sangsawang et al., 2024; Meesala et al., 2025; Singha et al., 2025). In addition, BSFL has been recognised as a functional feed ingredient associated with a reduced environmental footprint compared to marine-derived protein sources (Mohan et al., 2022; Fantatto et al., 2024). Despite extensive research, there is still no consensus regarding optimal inclusion levels in aquafeed formulations. Reported replacement rates for fishmeal range widely, from 25% to complete substitution (Kariuki et al., 2024). To date, inclusion levels between 30% and 75% have generally been considered optimal due to BSFL balanced nutrient composition, positive effects on fish growth and development, and favourable cost-benefit ratio (Limbu et al., 2022). Nevertheless, the optimal proportion may vary depending on larval rearing conditions and the developmental stage of the fish (Munguti et al., 2025).

Another key aspect in aquaculture sustainability is water quality management. Protein metabolism results in the production of ammoniacal nitrogen, which becomes toxic at elevated concentrations and is closely linked to protein digestibility and utilisation efficiency (Mes et al., 2023; Félix-Cuencas et al., 2025). This issue is particularly relevant in fingerling culture, when protein requirements (35–45%) and metabolic activity are high, often leading to significant nitrogen excretion that adversely affects production efficiency and environmental sustainability (López-Tejeda et al., 2020). Although BSFL has been extensively investigated as a protein source, relatively few studies have simultaneously assessed their effects on growth, water quality, and economic performance in tilapia fingerlings. Addressing this issue is essential to fully assess the potential of BSFL as a sustainable protein substitute. Therefore, the aim of this study was to evaluate the replacement of

up to 75% of fishmeal with BSFL meal in the diet of Nile tilapia fingerling, focusing on its effects on growth performance, water quality parameters, and feed profitability.

## Material and methods

### Ethical approval

The animal study protocol was approved by the Applied Ethics Committee of the Universidad Autónoma de Querétaro, Facultad de Ingeniería (protocol code CEAIFI-214-2021-TP).

### Feed formulation

Three isoproteic diets (35%) were formulated by partially replacing fishmeal with defatted BSFL meal at 0, 50, and 75%. The diet without BSFL served as a control (Table 1). The BSFL meal was obtained from the Black Soldier Fly Pilot Plant at the Faculty of Engineering, Amazcala Campus, Universidad Autónoma de Querétaro (UAQ). Before diet preparation, the meals were homogenised and manually mixed with water and vegetal oil, then processed using a single-screw extruder at the Carbohydrate Chemistry and Functionality Laboratory, Faculty of Chemistry, UAQ (30 rpm, 130 °C, 2 mm die). The diets were dried at 60 °C for 24 h and subsequently ground into flour for feeding tilapia fingerlings.

### Experimental design

The feeding trial was conducted in a recirculating aquaculture system (RAS) with 15 acrylic tanks (30 cm × 25 cm × 20 cm), each filled to 12 l. The tanks were connected to three water reservoirs (60 l each) and supplied by a pump delivering 10 l of water per min to maintain system operation. Three partial water changes were performed weekly in the reservoirs. Tilapia fingerlings (*Oreochromis* sp.; 0.93 ± 0.02 g) were obtained from the Tilapia Production Unit (Amazcala Campus, UAQ). Prior to the experiment, 150 individuals were randomly selected and acclimated to the RAS conditions. After acclimation, 10 fish were stocked per tank, with five replicates per treatment (50 fish/treatment). Fish were fed *ad libitum* five times daily (10:00–18:00) for 45 day, following the protocol described by Fava et al. (2022).

### Chemical analysis

The proximate composition of the diets and fish carcasses were determined in triplicate following AOAC International (2002) methods: moisture

**Table 1.** *Hermetia illucens* and experimental diets formulation, proximate composition and amino acid profile, dry basis

Ingredient, %	Experimental diet			
	BSFL	D0	D50	D75
Fishmeal		35.00	14.00	11.10
Soybean meal		20.00	20.00	16.80
BSFL	-		29.50	45.10
Corn meal		18.00	16.50	9.00
Wheat bran		16.00	10.00	10.00
Soybean oil		10.00	9.00	7.00
Celite		1.00	1.00	1.00
Chemical composition, %				
moisture	1.93	6.10	4.02	5.66
ash	20.98	10.64	12.22	13.31
lipids	12.85	13.20	11.33	11.42
crude protein	40.55	35.69	35.30	35.56
crude fiber	3.19	2.10	3.06	4.61
nitrogen-free extract	23.69	34.38	37.11	33.58
Amino acids, %				
glycine	2.07	1.90	2.10	2.65
alanine	2.11	2.70	3.28	5.20
serine	1.55	1.70	1.92	2.57
proline	1.72	2.73	3.41	5.65
valine	1.83	2.44	2.96	4.67
threonine	1.48	1.54	1.74	2.34
cysteine	0.43	0.4	0.4	<1.21
isoleucine	1.57	1.97	2.35	3.55
Leucine	2.76	3.5	4.16	6.30
aspartic acid	3.49	3.49	3.83	4.69
lysine	2.53	2.08	2.18	2.31
glutamic acid	5.46	5.23	5.57	6.16
methionine	0.87	0.77	0.85	<1.49
histidine	0.93	1.16	1.37	2.04
phenylalanine	1.57	1.98	2.34	3.45
arginine	2.47	2.48	2.75	3.45
tyrosine	1.19	1.85	2.32	3.86
tryptophane	0.42	0.29	0.27	0.12

BSFL – black soldier fly larvae, D0 – 0% of black soldier fly, D50 – 50% of black soldier fly, D75 – 75% of black soldier fly

(934.01) by oven-drying at 100 °C, ash (942.05) by incineration at 550 °C, crude protein by the Kjeldahl method (HACH 8075; N × 6.25), and lipids by Soxhlet extraction assisted by microwave digestion (EPA 3546, acetone/hexane). Nitrogen-free extract was quantified using the anthrone colorimetric method at 620 nm. The amino acid profile was determined based on reference values for each ingredient included in the formulation of the experimental diets.

### Water quality

Water quality was monitored three times per week using a portable multiparameter meter (HQ40d, HACH) to measure pH, temperature, and dissolved oxygen. Nitrite and nitrate were quantified weekly

following HACH method 8507, while ammonium was measured using the Nessler method (HACH 8038) with a UV-Vis spectrophotometer (HACH DR6000).

### Growth performance and feed utilisation

Total length and weight were measured to calculate fish performance and feed utilisation. Fish were collected from each tank and anaesthetised before handling (tricaine methane sulphonate 20 mg/l). The recorded data were applied using the following formulas:

$$\text{survival rate (\%)} = \left( \frac{\text{final fish stocked}}{\text{initial fish stocked}} \right) \times 100, \quad (1)$$

$$\text{daily weight gain} \left( \frac{\text{gfish}}{\text{day}} \right) = \frac{(Wf - Wi)}{\text{days}}, \quad (2)$$

$$\text{weight gain (\%)} = \left( \frac{(Wf - Wi)}{Wi} \right) \times 100, \quad (3)$$

$$\begin{aligned} \text{specific growth rate (SGR)} \left( \frac{\%}{\text{day}} \right) &= \quad (4) \\ &= \left( \frac{\ln Wf - \ln Wi}{\text{days}} \right) \times 100, \end{aligned}$$

$$\text{feed conversion ratio (FCR)} = \frac{\text{feed consumed}}{(Wf - Wi)}, \quad (5)$$

$$\text{protein efficiency ratio (PER)} = \frac{\text{weight gain}}{\text{protein intake}}, \quad (6)$$

$$\text{condition factor (CF)} = \frac{Wf}{FL^3} \times 100. \quad (7)$$

where: Wf – final live weight, Wi – the initial live weight in grams, and FL – fish length in cm.

### Metabolic rate

At the end of the trial, five fish per treatment were randomly selected for basal metabolic rate determination using individual semi-closed respirometry chambers. Each chamber contained a known water volume at the same temperature as the RAS to minimise stress. One fish was placed in each chamber for 24 h to quantify oxygen consumption and ammonia excretion. Dissolved oxygen was measured every 4 h using a portable multiparameter meter (HACH HQ40d), while water samples were collected for ammonium analysis using the Nessler method (HACH 8038). Oxygen consumption was calculated from the difference between initial and final dissolved oxygen concentrations, exposure time, and fish dry weight (O<sub>2</sub> mg/h/g fish). After the metabolic rate measurements, fish from all treatments were euthanised with an overdose of tricaine methane sulphonate (250 mg/l) to obtain dry weight. Ammonium concentration data were used to calculate the O:N ratio (oxygen consump-

tion to nitrogen excretion), oxygen consumption, and ammonia excretion rate following the method of Cao and Wang (2014). Three chambers without fish were used as blanks to account for background oxygen consumption.

### Feed profitability

The cost-to-benefit ratio of the feed was determined using partial cost analysis according to Limbu et al. (2022). Ingredient purchase prices and diet preparation expenses were considered, while operating and rearing costs were assumed to be constant and therefore excluded from the comparisons. The incidence cost represented the proportion of feed cost relative to total production, whereas the profit index reflected the economic return from fish sales in relation to feed expenses. Costs were converted to US dollars at the time of analysis (1 USD = 18.8 MXN).

$$\text{incidence cost} = \frac{\text{amount of meal used} \times \text{total cost of meal}}{\text{total fish weight}}, \quad (8)$$

$$\text{profit index} = \frac{\text{total fish weight} \times \text{fish price}}{\text{amount of meal used} \times \text{total cost of meal}}. \quad (9)$$

### Statistical analysis

The data were analysed using STATGRAPHICS software (Stat Point Inc. 2006). Homogeneity of variance was assessed using Levene's test ( $P = 0.05$ ). Growth and feed utilisation parameters, as well as water quality, metabolic rate, and profitability results, were analysed by analysis of variance (ANOVA), followed by Tukey's post hoc test ( $P < 0.05$ ) to identify significant differences between treatments based on mean values. Results in tables are presented as means  $\pm$  standard deviation.

## Results

### Growth performance and feed utilisation

Significant differences in survival were observed between treatments, with the highest values in fish fed the control diet (D0), followed by D50 and D75 (Table 2). The D0 diet resulted in a higher percentage of weight gain (19.9%) and SGR (0.45%/day), with no significant differences compared to D75. The D50 diet showed the highest FCR, followed by D75 and D0, while the highest protein efficiency ratio (PER) was obtained with the diet containing only fishmeal, in contrast to the BSFL-based diets. The condition factor did not differ significantly among diets.

**Table 2.** Comparison of growth performance and feed utilization of tilapia fingerling fed black soldier fly larvae as fish meal replacement at 50 and 75%,  $n = 4$

Indices	Experimental diets		
	D0	D50	D75
Wi, g	0.94 $\pm$ 0.02 <sup>a</sup>	0.93 $\pm$ 0.02 <sup>a</sup>	0.93 $\pm$ 0.02 <sup>a</sup>
Wf, g	1.21 $\pm$ 0.14 <sup>a</sup>	1.14 $\pm$ 0.16 <sup>a</sup>	1.07 $\pm$ 0.05 <sup>a</sup>
SR, %	96 $\pm$ 5.47 <sup>a</sup>	88 $\pm$ 16.40 <sup>ab</sup>	72.5 $\pm$ 5.00 <sup>b</sup>
WG, %	19.91 $\pm$ 1.09 <sup>a</sup>	11.07 $\pm$ 2.45 <sup>b</sup>	17.9 $\pm$ 3.13 <sup>a</sup>
SGR, %/day	0.45 $\pm$ 0.02 <sup>a</sup>	0.26 $\pm$ 0.05 <sup>b</sup>	0.41 $\pm$ 0.07 <sup>a</sup>
FCR	1.94 $\pm$ 0.07 <sup>a</sup>	2.90 $\pm$ 1.04 <sup>a</sup>	1.56 $\pm$ 0.25 <sup>a</sup>
PER	1.61 $\pm$ 0.28 <sup>a</sup>	1.36 $\pm$ 0.66 <sup>a</sup>	1.48 $\pm$ 0.77 <sup>a</sup>
CF	1.38 $\pm$ 0.04 <sup>a</sup>	1.38 $\pm$ 0.07 <sup>a</sup>	1.40 $\pm$ 0.04 <sup>a</sup>

D0 – 0% of black soldier fly, D50 – 50% of black soldier fly, D75 – 75% of black soldier fly. Wi – initial weight; Wf – final weight; SR – survival rate; WG – weight gain; SGR – specific growth rate; FCR – feed conversion rate; PER – protein efficiency rate; CF – condition factor; values are presented as means  $\pm$  standard deviation. <sup>ab</sup> – means within a row with different superscripts are significantly different at  $P < 0.05$

### Water quality

Regarding nitrogenous compounds, significant differences were detected for all three parameters (Table 3). Tanks supplied with the FM diet (D0) showed the highest levels, while diets containing BSFL (D50 and D75) resulted in lower concentrations of ammoniacal N, nitrate and nitrite. Dissolved oxygen and pH remained stable in all diets, without significant variation.

**Table 3.** Comparison of water quality variables of tilapia fingerling recirculation system fed black soldier fly larvae as fish meal replacement at 50 and 75%,  $n = 4$

Indices	Experimental diets		
	D0	D50	D75
NH <sub>4</sub>	0.46 $\pm$ 0.32 <sup>a</sup>	0.23 $\pm$ 0.12 <sup>b</sup>	0.33 $\pm$ 0.13 <sup>ab</sup>
NO <sub>2</sub>	1.20 $\pm$ 0.32 <sup>a</sup>	0.66 $\pm$ 0.18 <sup>b</sup>	0.99 $\pm$ 0.35 <sup>ab</sup>
NO <sub>3</sub>	4.2 $\pm$ 0.64 <sup>a</sup>	3.09 $\pm$ 0.49 <sup>b</sup>	3.43 $\pm$ 0.55 <sup>b</sup>
D.O.	6.43 $\pm$ 0.63 <sup>a</sup>	6.64 $\pm$ 0.51 <sup>a</sup>	6.40 $\pm$ 0.52 <sup>a</sup>
pH	8.73 $\pm$ 0.09 <sup>a</sup>	8.75 $\pm$ 0.10 <sup>a</sup>	8.8 $\pm$ 0.24 <sup>a</sup>

D0 – 0% of black soldier fly, D50 – 50% of black soldier fly, D75 – 75% of black soldier fly; NH<sub>4</sub> – ammoniacal nitrogen, NO<sub>2</sub> – nitrites, NO<sub>3</sub> – nitrates, D.O. – dissolve oxygen. values are presented as means  $\pm$  standard deviation. <sup>ab</sup> – means within a row with different superscripts are significantly different at  $P < 0.05$

### Metabolic rate

Oxygen consumption and ammonium excretion did not differ significantly ( $P > 0.05$ ) between the experimental diets (Table 4). Oxygen consumption and ammonium excretion rates remained unchanged among the BSFL-based feeds and the control diet. The O:N ratio was stable in all treatments, indicating no alterations in the balance between protein and lipid metabolism.

**Table 4.** Oxygen consumption, ammonia excretion and O:N ratio of tilapia fingerling fed black soldier fly larvae as fish meal replacement at 50 and 75%, n = 5

Indices	Experimental diets		
	D0	D50	D75
O <sub>2</sub> consumption, mg/h/g	2.55 ± 0.07	1.80 ± 1.78	1.81 ± 1.77
NH <sub>4</sub> excretion, mg/h/g	0.12 ± 0.03	0.08 ± 0.03	0.1 ± 0.09
O:N ratio	21.58 ± 9.39	26.90 ± 19.8	16.31 ± 11.0

D0 – 0% of black soldier fly, D50 – 50% of black soldier fly, D75 – 75% of black soldier fly; O<sub>2</sub> – oxygen, NH<sub>4</sub> – ammoniacal nitrogen, O:N – oxygen and nitrogen ratio;  $P > 0.05$  (no statistically significant); values are presented as means ± standard deviation.

## Feed profitability

Significant differences were found in incidence cost and profit index, with BSFL diets (D50, D75) showing reduced feed costs and higher profitability compared to the FM control (D0). A clear trend was evident, with increasing levels of FM replacement by BSFL meal resulting in lower production costs and improved economic efficiency (Table 5). This indicates that, in addition to maintaining acceptable growth performance, incorporating insect meal improves the financial sustainability of tilapia fingerling culture.

**Table 5.** Feed cost and cost-benefit analysis of experimental diets formulated with black soldier fly larvae as fish meal replacement, n = 4

	Experimental diets		
	D0	D50	D75
Amount of meal used, kg	0.05	0.04	0.03
Total cost of meal, USD	1.81	1.10	0.99
Total fingerling weight, kg	0.01	0.01	0.007
Tilapia fingerling price, USD/kg	52.94	52.94	52.94
Incidence cost, USD	8.13 ± 0.02 <sup>a</sup>	4.94 ± 0.00 <sup>b</sup>	4.48 ± 0.02 <sup>c</sup>
Profit index	6.50 ± 0.02 <sup>c</sup>	10.71 ± 0.01 <sup>b</sup>	11.79 ± 0.07 <sup>a</sup>

D0 – 0% of black soldier fly, D50 – 50% of black soldier fly, D75 – 75% of black soldier fly; values are presented as means ± standard deviation; <sup>abc</sup> – means within a row with different superscripts are significantly different at  $P < 0.05$

## Discussion

### Experimental diets

The inclusion of BSFL meal as a partial substitute for FM was feasible up to 75% without compromising growth in tilapia fingerling. These results are consistent with previous studies regarding the upper limit for BSFL meal inclusion in tilapia diets (Rapatsa and Moyo, 2022). Moreover, the use of BSFL meal allowed for the formulation of diets that met the protein requirements of tilapia at the fingerling stage. These confirm the findings reported by Kariuki et al. (2024), who propose BSFL as a protein source for developing starter tilapia feed

with a protein content of 35%. Regarding dietary amino acid content of diets, Furuya et al. (2023) have reported that arginine, lysine, and phenylalanine + threonine are the most important amino acids for fry development in tilapia, as they are involved in protein synthesis, immune function, and biomass production. As shown in Table 1, the inclusion of BSFL increased the content of most essential amino acids, particularly phenylalanine, arginine and lysine, compared to the FM-based diet. These results align with the findings published by Munguti et al. (2025) and confirm that BSFL is a viable source of protein and essential amino acids suitable for the earliest stages of tilapia development.

### Growth performance, feed utilisation and metabolic rate

Regarding growth variables, statistically significant differences were observed between the three experimental diets. Weight gain and specific growth rate (SGR) were comparable between the D0 and D75 diets. Muin et al. (2017) reported that up to 75% of FM can be replaced in tilapia fingerling diets without affecting growth. Unlike the present study, their trial involved fish weighing less than 1 g, suggesting that tilapia fingerlings are capable of efficiently accepting and utilising insect meals such as BSFL for biomass growth.

The feed conversion factor (FCR) indicates the amount of feed required for organism growth, specifically the feed needed to produce one gram of biomass. Lower FCR values indicate greater feed efficiency for fish. Although the D75 diet showed a lower FCR value compared to the fishmeal-based diets, no significant differences were observed between treatments. These results are consistent with those reported by Tippayadara et al. (2021), who obtained FCR values of approximately 2 when replacing up to 100% of fishmeal in tilapia diets.

The values obtained for PER, which reflects protein retention by the organism from the consumed feed, were 1.61 and 1.48 for the D0 and D75 diets, respectively, but without significant differences. This parameter is associated with protein quality and the balance of amino acids provided in the feed. According to Munguti et al. (2025), BSFL meal can meet the essential amino acid requirements of tilapia, mainly histidine, lysine, leucine, and valine, and is considered a viable protein source for their feed and replacement for fish meal. The results summarised in Table 2 show that the experimental diets containing BSFL meal supported adequate growth through protein utilisation, achieving performance comparable to the FM-based diet.

Finally, the condition factor (CF), also known as the Fulton factor, is an indicator of the health status of organisms. In this study, it was calculated to assess the condition of fingerlings in response to the change in dietary protein source. No significant differences were observed between the individual diets, with very similar values across treatments. A CF value greater than 1 indicates that the fish are in good health and growing well (Félix-Cuencas et al., 2021). These results suggest that, despite the experimental conditions and feeding changes, BSFL meal can be included in tilapia fingerling diets in RAS without affecting their homeostasis. Similar findings have been reported by Limbu et al. (2022) and Fayed et al. (2024), who achieved condition factors of up to 1.5 using BSFL as a protein source for tilapia fingerlings.

Changes in fish environmental conditions of development, such as diet, can increase metabolic activity in fish to maintain energy balance, often at the expense of biomass production (Jobling, 2017). This maintenance energy can be estimated by measuring basal metabolism, which represents the state of homeostasis in the organism. Basal oxygen consumption did not differ significantly between treatments (Table 4); however, fish fed BSFL diets tended to show lower oxygen consumption compared with the control, indicating more efficient energy allocation. This energy provided by the experimental diets appears sufficient to support growth, consistent with the observed performance results. Ammonium excretion, on the other hand, is linked to nitrogen metabolism and serves as an indicator of nutrient utilisation, particularly protein, by the organism (Engin et al., 2013). The results did not show significant differences compared to the control diet, although a reduction in ammonium excretion was observed in fish fed the D50 diet. The decrease in ammonium excretion may be related to the protein quality of the experimental diets. The O:N ratio, calculated from the relationship between oxygen consumption and nitrogen excretion, provides an indication of the substrate being metabolised: values below 10 reflect protein metabolism, whereas values above 10 indicate lipid and carbohydrate metabolism (Cao and Wang, 2014). Main energy source of all experimental diets assessed in this study was based on lipid and carbohydrate catabolism, without significant differences between treatments (Table 4). These results suggest that protein was effectively used for synthesis and growth, while lipids and carbohydrates in the feed served as energy sources. The similar responses between treatments confirm that BSFL is a viable protein source for tilapia fingerlings, allowing up to 75% of fishmeal replacement.

### Water quality parameters

The quality and digestibility of dietary protein are directly associated with nitrogen excretion and, consequently, with water quality in aquaculture systems. In this study, significant differences were observed in nitrogen compound concentrations, with the FM-based diet (D0) resulting in the highest levels. Since all the diets were isoproteic, the lower  $\text{NH}_4$  production in D50 and D75 could reflect improved digestibility and utilisation of these diets by tilapia fingerlings. Similar findings have been reported in red hybrid tilapia, where BSFL-based diets improved protein digestibility compared to conventional FM diets (Muin and Taufek, 2022). Ammoniacal nitrogen is the primary nitrogenous waste in fish, generated during amino acid catabolism (Mes et al., 2023). The inclusion of BSFL not only provides high-quality protein for tilapia, as reflected in the amino acid profiles of the D50 and D75 diets, but the chitin content in BSFL has also been reported to improve intestinal function through its prebiotic properties, enhancing feed digestibility (Oviedo-Olvera et al., 2025). This effect promotes nitrogen retention by the organism and reduces its excretion into the farming system (Odhiambo et al., 2023). Elevated  $\text{NH}_4^+$  levels are toxic to fish and pose a significant challenge in intensive recirculating aquaculture systems (RAS). Importantly, BSFL diets (D50 and D75) reduced ammonia accumulation, thereby improving water quality and lowering the risk of nitrogen toxicity. These confirm the assumption that when selecting alternative protein sources for fish feed, not only growth performance but also their ecological impact on the rearing environment should be considered (Limbu et al., 2022). Accordingly, the experimental diets with BSFL meal decreased ammonia production during the experiment, contributing to a healthier aquatic environment of the organisms and reduced water pollution.

In addition,  $\text{NO}_2$  and  $\text{NO}_3$  are produced as a result of ammonium conversion by bacteria present in the system; high concentrations of these compounds tend to affect fish physiological processes, such as respiration and cardiovascular functions (Zhang et al., 2023). The inclusion of BSFL in the diet of tilapia fry did not significantly affect  $\text{NO}_2$  and  $\text{NO}_3$  concentrations in the aquaculture system compared to the D0 diet. However, a downward trend was observed for the D50 and D75 diets compared to the control group. This decrease can be attributed to lower  $\text{NH}_4$  excretion by BSFLfed fingerling, limiting substrate availability for nitrification.

## Feed profitability

Reducing production costs is one of the most critical challenges for sustaining aquaculture systems, particularly when profitability is heavily dependent on feed expenses. The results of the present study (Table 5) demonstrate a reduction in incidence costs when using diets formulated with BSFL meal. Similarly, the profit index, which estimates the profitability of a production system, increased with higher inclusion levels of BSFL in the diets, indicating greater economic returns. These findings are consistent with Vodounnou et al. (2025), who reported that including 50–60% BSFL meal in Nile tilapia diets not only enhanced growth but also improved feed efficiency and reduced production costs, as reflected in the economic conversion ratio. This confirms that BSFL meal is a lower-cost protein source compared to fishmeal while providing similar growth benefits, even at the fingerling stage. Favourable outcomes have also been reported in African catfish and sturgeon, where 60–70% inclusion of BSFL meal in feed improved production costs and system profitability. Furthermore, these studies describe BSFL meal as a sustainable input, contributing to a reduced fish in-fish out (FIFO) ratio with increasing levels of BSFL inclusion (Hervé et al., 2025). Thus, the use of BSFL meal in aquafeeds supports aquaculture sustainability and circularity, as it can be produced through the biotransformation of organic waste, enabling nutrient recycling within aquaculture systems and reducing environmental pollution.

## Conclusions

The inclusion of defatted black soldier fly larvae (BSFL) meal as a partial replacement for fish meal in tilapia fingerling diets is feasible. BSFL can be used as a protein source without compromising fish growth or feed utilisation. Furthermore, replacing between 50 and up to 75% of fishmeal with BSFL meal is recommended to reduce ammonium production in recirculating aquaculture systems and ensure efficient protein utilisation. From an economic perspective, incorporating BSFL in feed lowers production costs by increasing profitability, although replacement should not exceed 75% inclusion to avoid negative effects on fish growth.

## Conflict of interest

The authors declare that there is no conflict of interest.

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