Ethiop. J. Agric. Sci. 34(3) 120-134 (2024)

Replacement of Fishmeal with Black Soldier Fly (*Hermetia illucens* L.) Larvae (BSFL) Enhances the Growth Performance of Nile Tilapia (*Oreochromis niloticus* L.) Fry in Tanks

Aschalew Lakew[1]*, Abelneh Yimer[1] and Fekede Feyissa[2]
[1]*Ethiopian Institute of Agricultural Research, National Fishery and Aquatic Life Research Center, P.O.B. 64 Sebeta;* [2]*Ethiopian Institute of Agricultural Research, P.O.B. 2003, Addis Ababa*
**Corresponding author email: aschalewlakewl@gmail.com*

Abstract

Due to the rising cost and limited availability of fish meal (FM), researchers have focused on exploring alternative animal feed sources such as black soldier fly larvae (BSFL) in aquafeed industry. This study investigated the effects of replacing FM with full-fat BSFL on the growth of Nile tilapia fry at inclusion levels of 0%, 25%, 50%, 75% and 100%, hereafter designated as BSFL0%, BSFL25%, BSFL50%, BSFL75% and BSFL100% respectively. A total of 500 healthy Nile tilapia fry (mean weight =2.7±1.1 g) were randomly stocked into 10 plastic tanks (50 fry per tank; two replicates per treatment) and fed for 150 days. Fish were fed three times daily and weighted biweekly to monitor growth performance and adjust the feed offered for the fish. Water quality parameters including temperature, pH and dissolved oxygen were monitored using a real-time IoT device known as SynWater which is SYNELIXIS innovative solutions. Nile tilapia fry fed on BSFL100% showed significantly higher fish weight (74.52±1.32) compared with BSFL25% and BSFL50% ($p < 0.05$), but no significance difference was obtained among BSFL100%, BSFL75% (65.98±1.54) and BSFL0% (61.2±2.08). Regardless of BSFL inclusion levels, all measured water quality parameters remained within acceptable ranges for optimum Nile tilapia fry growth. A simple economic analysis showed that the BSFL100% diet significantly reduced the feed cost and increased the profit index by 52% compared with the FM control diet (BSFL0%). This study demonstrated that BSFL can fully replace FM without adversely affecting the growth of Nile tilapia or the water quality parameters. Future research should focus on optimizing BSFL production techniques in order to promote low-cost insect-based protein diets for livestock and fish production in Ethiopia.

Keywords: Black solder fly, fishmeal, growth performance, Nile tilapia, profit index, water quality

Introduction

It is a global challenge to supply protein-rich food for a rapidly growing population in the presence of climate change and economic uncertainty. Aquaculture plays a crucial role in global food security, providing a rich source of animal protein, essential micronutrients, and fatty acids particularly in low-income countries (Beveridge *et al*., 2013). According to FAO (2024), aquaculture production accounted 50.9% of the total annual fish production globally in 2022.

However, the rapid development of aquaculture has been constrained by the rising costs and limited availability of fish feeds, particularly protein sources (Muin *et al*., 2017). Feed costs, especially protein ingredients make up more than 50% of the total aquaculture production costs, depending on the intensity of the culture system (Limbu *et al*., 2020). Due to its high nutritional content and well-balanced amino acid profile, fishmeal (FM) is widely used as a protein source in aquaculture feeds (Hardy, 2010, Xiao *et al*., 2018; Abdel-Tawwab *et al*., 2020). However, FM is becoming increasingly expensive and scarce due to overfishing, competition with human consumption, and other uses worldwide (FAO, 2022). This indicates that FM is no longer a sustainable option for aquaculture feed sources in both economic and ecological perspectives (Tacon and Metian, 2008). In response, researchers have sought alternative protein sources to replace FM and support the sustainable growth of aquaculture. Over time, plant-based proteins like soybean meal have been increasingly used as partial replacements for FM (de Francesco *et al*., 2004). Nevertheless, plant-based proteins also present limitations, such as imbalanced amino acid profiles, the presence of anti-nutritional factors, and high carbohydrate content (Henry *et al*., 2015). Additionally, the use of crops like soybean in fish feed exacerbates the issue of food-feed competition, as the crops are essentially for feeding the growing human population (Obirikorang *et al*., 2020).

In response to the pressure on both FM and plant-based protein sources, there has been growing interest in finding sustainable, eco-friendly and cost-effective alternatives. Insects are part of the natural diet of many fish species and possess the necessary nutritional qualities for optimal growth and survival (Barroso *et al*., 2014; Henry *et al*., 2015). Insects, particularly black solder fly larvae (BSFL), have shown significant potential as nutrient-rich, low-cost protein sources which can replace FM in aquaculture feeds (Caimi *et al*., 2020; Limbu *et al*., 2022). BSFL production is well-developed, both at small and large scales, and can be efficiently processed and incorporated as fish feed ingredients (Gougbedji *et al*., 2021). High protein content (40-50%) and balanced amino acid profile in BSFL meal , has been successfully used to replace FM in the diets of various fish species, including rainbow trout (*Oncorhynchus mykiss*) (Renna *et al*., 2017), Atlantic salmon (*Salmo salar*) (Belghit *et al*., 2019), European sea bass (*Dicentrarchus labrax*) (Magalhaes *et al*., 2017), Siberian sturgeon (*Acipenser baerii*) (Caimi *et al*., 2020), and Nile tilapia (*Oreochromis niloticus*) (Devic *et al*., 2018; Munguti *et al*., 2024). Nile tilapia is the third most economically important farmed finfish globally, following carp and catfish (FAO, 2024), and this is attributed to its rapid growth, disease resistance, and ability to thrive in diverse culture systems (Munguti, 2024). Moreover, BSFL can be used to recycle organic wastes into high-quality protein and organic fertilizer, contributing to sustainable farming practices (Schiavone *et al*., 2017; FAO, 2024).

Despite the global success of using BSFL in replacing fishmeal in aquafeeds, there has been limited research and experience on utilization of insect-based animal feed in Ethiopia. Additionally, there is a lack of information on the potential use of BSFL to convert organic wastes into high-quality fish feed protein. Therefore, this study investigated the growth performance of Nile tilapia fry fed with increasing levels of BSFL meal as a substitute for FM in Ethiopia. We hypothesized that locally produced BSFL meal can replace FM in Nile tilapia diets, contributing to more sustainable aquaculture practices in the country.

Materials and Methods

Study site

The study was conducted at the National Fishery and Aquatic Life Research Center (NFALRC) under controlled greenhouse conditions from February to July 2024. The NFALRC is located 24 km southwest of Addis Ababa, Ethiopia, at an altitude of 2240 meters above sea level (8°55.076'N; 38°38.161'E). The site experiences atmospheric temperature ranged from 14^{o}C to 24.5^{o}C, with an average of 19.6 ^{o}C. However, the greenhouse condition maintained an average temperature of 25.2^{o}C throughout the study period. The greenhouse structure has a sufficient roof height of approximately 5 meters and perforated sidewalls, allowing efficient air exchange to prevent heat buildup during warmer months, particularly in May and June. This design ensured consistent and optimal environmental conditions for the experiment. Experimental tanks were set up inside the greenhouse as shown in Figure 1, and arranged to facilitate proper airflow and light exposure while minimizing external temperature fluctuations. The tanks were positioned to optimize space utilization and ensure uniform treatment conditions.

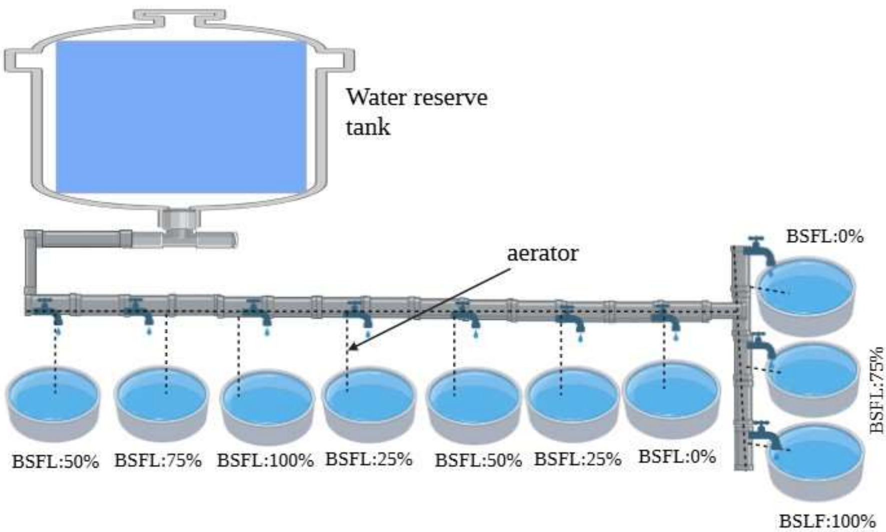

Figure 1. Experimental setup of fish tanks showing different level of black soldier fly larvae (BSFL) inclusions.

Sources and production of black soldier fly larvae (BSFL)

The black solder fly rearing and larvae production facilities were established at NFALRC pilot site. Black soldier fly prepupae were initially obtained from Addis Ababa University and Debre Zeit Agricultural Research Center as starter stock and reared at pilot site. To attract adult black soldier fly (BSF) and induce egg-laying and hatching, a substrate composed of wheat bran, maize, and fruit waste was prepared. The larvae were fed with a mixture of grain-based by-products and fruit - vegetable wastes. The temperature and relative humidity at the pilot site were maintained between 25°C and 30°C, and 45% to 65% respectively. Daily routine practices were done regularly to ensure continuous larvae production. The BSFL were harvested every 13-18 days and processed according to the method described by Caruso *et al*. (2013). The larvae were dried under sunlight until it reached a constant weight, after which it was ground into a fine powder using a laboratory mill. The resulting BSFL meal was stored in airtight containers at room temperature until it was ready for use in diet formulations.

Formulation of experimental diets

Experimental feed ingredients were formulated using feed formulation software, ensuring each experimental diet contained 35% isonitrogenous crude protein. The ingredients were finely ground using a mill, weighed according to their specified proportions, thoroughly mixed, and then pelleted using an extruder with mesh sizes of 1 mm and 1.5 mm. The pellets were sun-dried and stored in a plastic bag to prevent fungal contamination during the experimental period. Five experimental diets were prepared by replacing fishmeal (FM) with BSFL meal at replacement levels of 0% (control diet), 25%, 50%, 75%, and 100%.

Proximate analysis of each feed was conducted following the procedures outlined by the AOAC (2005). Dry matter (DM) content was determined by drying a 5-gram sample at 110 ^{o}C in the oven for 24 hours. Crude protein (CP) was determined using the micro-Kjeldahl nitrogen method, where the distilled ammonia was trapped in a 2% boric acid solution and titrated with 0.1N HCl. The CP content was then calculated by multiplying the nitrogen content by a factor of 6.25. Crude fat was assessed by extracting 3-gram samples in a Soxhlet extractor for four hours using petroleum ether (boiling point 40-60°C). After extraction, the flask and extract were oven-dried at 100°C, cooled in a desiccator for one hour, and weighed. The percentage of ether extract was calculated by expressing the weight difference relative to the original sample weight. Ash content was determined by burning a 5-gram sample at 550°C in a muffle furnace overnight, with the ash representing the residual weight.

Table 1. The proximate composition and cost of ingredients used to formulate the experimental diets

Ingredient composition (g/kg)	DM	CP	CL	CF	Ash	NfE	Cost (USD/kg)
Barley whole seed	956.7	110	14	131	28.4	673.3	0.45
Wheat whole seed	959.5	134	12.5	59	16.6	737.4	0.58
Noug seed cake	928	331	83	83	53	378	0.49
Fish meal	892	574	96	6	83	133	1.29
BSFL	883	466	136	103	106	72	0.73

DM=Dry matter, CP=Crude protein, CL=Crude lipid, CF=Crude fiber, NfE= Nitrogen-free Extract, USD=112 ETB

Table 2. Composition and proportion of ingredients, and cost of the experimental diets.

Ingredient (g/kg)	Experimental feeds				
	BSFL0%	BSFL25%	BSFL50%	BSFL75%	BSFL100%
Barley whole seed	142.9	146.2	123.3	105.5	61.9
Wheat whole seed	155.9	155.2	135.4	119.5	90.2
Noug seed cake	262.7	228.9	234.4	234.6	322.4
Fish meal	394.5	319.8	231.45	124.1	0
BSFL meal	0	105.9	231.45	372.3	481.5
Premix	20	20	20	20	20
Methionine	15	15	15	15	15
Lysine	9	9	9	9	9
Proximate composition (g/kg)					
Dry matter	925.1	923.1	919.3	915.9	913.2
Crude protein	350	350	350	350	350
Crude lipid	63.6	68.1	76.6	85	89.8
Crude fiber	52.1	60.1	68.8	79.4	89.8
Ash	53.3	56.6	61.9	67.2	71.4
Nitrogen-free Extract	362.9	349.6	318.9	291.1	264.7
Cost (USD/kg)	0.89	0.86	0.82	0.76	0.69

Note: Exchange rate was calculated at 1 USD=112 ETB

Source of Nile tilapia fry and experimental setup

Nile tilapia fries were collected from the NFALRC hatchery and reared in hapas installed in fishponds for two months. During this period, the fish were fed on commercial feed until the feeding trial was commenced. The fish fries were then acclimatized for 12 days in experimental tanks, and their initial weight was recorded. For the experiment, 10 circular plastic tanks, each with a water holding capacity of 2 cubic meters water (depth= 1m, radius = 0.8 m) were used. The tanks were filled with water to 80% of their total capacity to prevent the fish from escaping. A total of 500 healthy Nile tilapia fingerlings, with an initial weight of 2.7 ± 1.1 g and a length of 5.0 ± 0.7 cm, were visually inspected and randomly distributed into the 10 tanks (50 fish per tank), with duplicates for each experimental diet (Figure 1).

The fish were fed three times daily (8:30, 12:30, and 16:30 hour) at a feeding rate of 8 % of their body weight for the first one month and then 5% for the remaining 4 months. Every two weeks, 50% of the fish in each tank were sampled using a hand net and weighted to the nearest 0.1g. The feed amount was adjusted every two weeks based on the average weight gain of the sampled fish. Fresh water was supplied daily for 30 minutes, and approximately 75% of the water in each tank was replaced every two weeks to remove waste and uneaten feed. The tanks were connected to a continuous aeration system to maintain adequate oxygen levels, and other physicochemical parameters were kept optimal for Nile tilapia growth under culture conditions.

Determination of growth performance

The efficiency of BSFL based formulated feed was assessed by evaluating fish growth performance, which was calculated using standard equations as described by Adebayo *et al*., (2004).

$$\text{Weight gain} = \text{Final weight (g)} - \text{Initial weight (g)}$$

$$\text{Daily Growth Rate (DGR) (g day}^{-1}) = \frac{\text{Final weight (g)} - \text{Initial weight (g}}{\text{Culturing period}}$$

$$\text{Specific growth rate (SGR) (\% day}^{-1}) = \frac{(\ell\text{n Final weight} - \ell\text{n Initial weight})}{\text{Time (days)}} \times 100$$

$$\text{Feed Conversion Ratio (FCR)} = \frac{\text{Total weight of dry diet fed (g)}}{\text{Total wet weight gain of the fish (g)}}$$

$$\text{Survival rate (SR) (\%)} = \frac{\text{Final number of fish harveted}}{\text{Intial number of fish stocked}} \times 100$$

Determination of water quality parameters

The physico-chemical parameters mainly pH, conductivity, temperature, and dissolved oxygen were rigorously monitored and recorded at two-hour intervals throughout the experimental period using real-time-IoT devices known as SynField- SynWater which was received from SYNELIXIS in Greece. Water samples were collected biweekly in 0.5-liter plastic bottles prior to fish sampling for the analysis of ammonia, nitrite, nitrate, reactive phosphorus, and total phosphorus. These samples were then transported to the NFALRC laboratory and analyzed according to standard methods outlined in APHA (1995).

Economic analysis

A simple partial economic analysis was conducted to evaluate the cost-effectiveness of BSFL diets used as a replacement for FM in the production of Nile tilapia reared in fish tanks. The cost of experimental diets was calculated based on the market prices of the ingredients used (Table 1). The cost of fish feed processing such as milling and pelleting were also considered in the calculation. Since BSFL is not available in the local market, its cost was estimated based on the inputs required and labor costs for the production. The fish prices were determined based on local market values and converted to USD (1 USD = 112 ETB). The costs of the fish-rearing tanks, equipment like aerators and expenses related to daily monitoring and data collection were assumed to remain constant.

The cost-effectiveness and profitability of BSFL based diets were evaluated using the methods described by El-Dakar *et al*. (2007) and Limbu *et al.* (2022).

$$\text{Incidence Cost} = \frac{\text{Cost of feed used}}{\text{Weight of fish produced}}$$

$$\text{Profit Index} = \frac{\text{Value of fish produced}}{\text{Cost of feed used}}$$

Statistical Analysis

The growth performance and condition indices of Nile tilapia fry fed on the experimental diets were analyzed using a one-way ANOVA. Prior to analysis, all data were subjected to a normality test. When significant differences were detected, Tukey's post hoc test was used to compare means between treatments. A significance level of $p < 0.05$ was applied for all analyses. Statistical analyses were conducted using SPSS (version 26) for Windows.

Results and Discussion

Proximate analysis of ingredients and experimental diets

The two main protein sources, fish meal (FM) and black soldier fly larvae (BSFL), exhibited distinct nutritional compositions (Table 1). BSFL contained higher levels of crude lipid, crude fiber, ash and nitrogen-free extract (NfE) compared to FM. In contrast, FM had a higher CP content and DM than BSFL. We obtained a crude protein content of 466 g/kg, which is higher than the 416.4g/kg reported by Devic *et al*. (2018) but lower than the 508 g/kg reported by Limbu *et al*. (2022). Similarly, the lipid content of 136 g/kg obtained in this study was higher than the 118 g/kg reported by Kroeckel *et al*. (2012) and lower than 232.4 g/kg reported by Devic *et al*. (2018). These variations in the nutritional composition of BSFL meal can be attributed to factors such as the insect's life stage, feeding substrate, and processing methods, as noted by Aniebo and Owen (2010) and van Huis *et al*. (2020). Previous studies, including El-Sayed and Teshima (1992) and Jauncey (1998) showed that lower fat content (below 120g/kg) is preferred for warm water omnivorous fish such as Nile tilapia. In the present study, the crude lipid content ranged between 63.6 g/kg and 89.8 g/kg across all treatments (Table 2), although there is a trend showing that increasing BSFL inclusion levels results in higher fat content. Several studies, like Kroeckel *et al.* (2012) and Sheppard (2008) indicated that BSFL is a suitable nutrient source for fish feed and can replace conventional ingredients like FM. However, the inclusion level must be carefully adjusted in feed formulations by considering the variability in the nutritional composition of BSFL.

Growth performance of Nile tilapia fry

The present study demonstrated that Nile tilapia fry fed on diets containing 75% and 100% BSFL exhibited significantly higher growth performance, as measured by final weight and weight gain, compared to those fed diets with 25% and 50% BSFL inclusions (Table 3). However, the growth performance observed in the 75% and 100% BSFL diets were comparable or exceeded the diet formulated with 100% conventional FM (BSFL0%) (Figure 2). This could be attributed to the protein and lipid content of BSFL meal, which is comparable to that of fish meal, both of which are essential for muscle development, metabolic processes and overall fish health (Kroeckel *et al.*, 2012; Spranghers *et al.*, 2017; FAO, 2024; Goda *et al.*, 2024). While this study did not analyze essential amino acids and micronutrients, the improved growth performance observed in the 75% and 100% BSFL can be attributed to the rich nutritional profile of BSFL which supports optimal fish growth (Tacon and Metian, 2008; Makkar *et al.*, 2014; Limbu *et al.*, 2022). Additionally, BSFL's high protein digestibility ensures efficient nutrient absorption and feed conversion into biomass (Kroeckel *et al.*, 2012; Limbu *et al.*, 2022; Goda *et al.*, 2024). These nutritional advantages likely explain why growth metrics in the BSFL diets were comparable to or exceeded those of FM-based diets.

Table 3. Growth performances of Nile tilapia fry fed on varying proportions of black soldier fly larvae meal.

Parameters	Experimental diets				
	BSFL0%	**BSFL25%**	**BSFL50%**	**BSFL75%**	**BSFL100%**
Initial weight (g)	2.75±1.1[a]	2.69±1.11[a]	2.71±0.8[a]	2.69±1.2[a]	2.72±1.11[a]
Initial length (cm)	5.24±0.7[a]	4.75±0.8[a]	4.98±0.6[a]	5.16±0.8[a]	5.18±0.8[a]
Final weight (g)	61.2±2.08[a]	47.34±0.79[b]	56.14±0.92[b]	65.98±1.54[a]	74.52±1.32[a]
Final length (cm)	14.86±0.17[a]	13.93±0.9[b]	14.93±0.11[b]	15.62±0.12[a]	16.18±0.11[a]
Weight gain (g)	58.45±1,72[a]	44.67±1.20[b]	53.46±1.83[b]	63.29±1.77[a]	71.80±2.45[a]
DGR (g day^{-1})	0.41	0.30	0.36	0.42	0.48
SGR (% day^{-1})	2.55	2.51	2.64	2.67	2.73
FCR	1.64	1.64	1.63	1.63	1.66
SR (%)	98.73	98.51	98.63	99.20	98.65

Note: DGR = Daily growth rate, SGR = Specific growth rate, FCR = Food conversion ratio, SR = Survival rate

No significant differences ($p > 0.05$) were observed in FCR between the experimental diets with varying BSFL proportions (Table 3). The FCR remained consistent across all treatments, suggesting that BSFL inclusion did not negatively impact feed efficiency. The recorded FCR values were within the range reported for Nile tilapia production, typically 1.5 to 2.5 in pond culture and 1.0 to 1.71 in cage environment (Rana and Hassan, 2013). This finding aligns with previous studies that also reported no significant differences in FCR with varying levels of FM replacement by BSFL in Nile tilapia diets (Muin *et al.*, 2017; Devic *et al.*, 2018; Nairuti *et al.*, 2021), although Kroeckel *et al.* (2012) observed significant differences in FCR across dietary treatments.

The results of this study suggest that replacing FM up to 100% with BSFL meal in Nile tilapia diets has showed no negative effect on the growth performance and agreed well with previous reports (Limbu *et al*., 2022). Survival rates were high across all experimental groups, with no significant differences between BSFL-inclusive diets and the control (BSFL0%). This is consistent with the findings of Henry *et al.* (2015), Devic *et al*. (2018), and Limbu *et al*. (2022), who reported BSFL-based diets do not compromise survival rates compared to conventional FM diets. The high survival rates observed in this study may also be attributed to the nutritional adequacy of BSFL-based diets and optimum water quality parameters maintained during the experimental period.

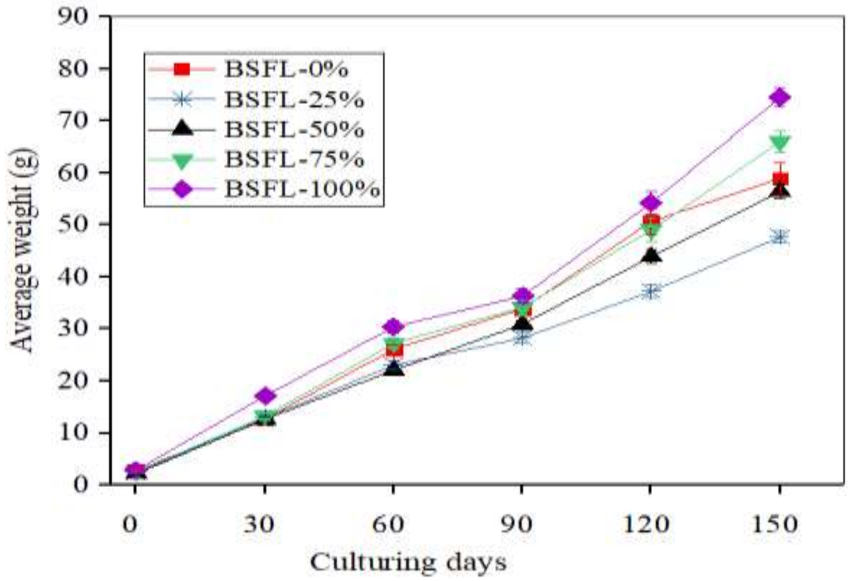

Figure 2. Growth curves for Nile tilapia fry fed with varying levels of BSFL diets for 150 days

Physico-chemical water parameters

The growth of the fish is influenced by both physical and chemical parameters of the water. At the same time, the fish can degrade water quality due to excretion from metabolic activities and the decomposition of uneaten feeds. In this study, all measured water quality parameters remained within acceptable ranges for Nile tilapia fry growth, regardless of the BSFL inclusion level (Table 4).

Table 4. Some physico-chemical water parameters (mean ± SD) recorded during the experimental period

Parameters	Fish tanks with different experimental diet				
	BSFL0%	**BSFL25%**	**BSFL50%**	**BSFL75%**	**BSFL100%**
Temperature (^oC)	25.63±1.52	26.81±2.14	27.57±1.50	26.34±0.92	26.45±2.06
DO (mgL^{-1})	5.42±1.07	5.65±1.46	6.34±2.05	5.73±0.99	5.47±2.08
Conductivity ($\mu S\ cm^{-1}$)	378±11.04	362.7±37.11	363.7±56.23	371.3±23.64	370.12±19.81
pH	7.13±0.25	7.04±0.48	6.95±0.98	7.15±0.24	7.13±0.35
TAN (mgL^{-1})	0.094±0.08	0.049±0.04	0.035±0.02	0.062±0.05	0.100±0.04
NO_2 (mgL^{-1})	0.040±0.02	0.027±0.02	0.026±0.02	0.036±0.02	0.039±0.02
NO_3 (mgL^{-1})	0.057±0.04	0.040±0.02	0.043±0.04	0.039±0.02	0.044±0.01
PO_4 (mgL^{-1})	0.005±0.01	0.007±0.01	0.008±0.01	0.007±0.01	0.007±0.01
TP (mgL^{-1})	0.011±0.01	0.014±0.01	0.013±0.01	0.014±0.01	0.014±0.01

Note: DO = Dissolved oxygen, TAN = Total Ammonia- Nitrogen, NO_2 = Nitrites, NO_3 = Nitrate, PO_4 = Phosphate, TP= Total phosphorus

Continuous aeration was maintained in all tanks to prevent depletion of dissolved oxygen (DO) particularly in the early morning, ensuring DO levels remained above 5 mg/L throughout the study period. Previous study showed that low DO content negatively impacts feed intake and reduces digestibility (Tran-Duy *et al.*, 2012), which in turn affects fish growth.

Our study highlighted the importance of real-time water quality monitoring device for making immediate adjustments when DO levels drop, particularly during aeration system failures caused by power interruptions. Factors that contribute to DO depletion, such as algal load, decomposition of feed waste, and fish excretion, were effectively managed to maintain adequate oxygen availability for optimal Nile tilapia growth (Popma and Masser, 1989). The ideal temperature for tilapia growth ranges from 23^{o}C to 32^{o}C, with the highest growth rate observed at 28^{o}C, although no significant difference was noted at 26 ^{o}C (El-Sayed and Kawanna, 2008). Throughout this study, the average temperature of all treatment tanks was kept above 25 ^{o}C, which is important for stimulating appetite, increasing food consumption, and accelerating digestion (Brett and Groves 1979). In addition to good feed acceptance by the fish, we recorded a high survival rate (above 98%), likely due to the careful regulation of important water quality parameters, including pH and total ammonia nitrogen (TAN) within the recommended ranges for Nile tilapia growth (Popma and Masser, 1989). TAN exists in two forms: ionized ammonia nitrogen (NH4-N) and unionized ammonia nitrogen (NH3-N), with varied ratio depending on water pH and temperature. In this study, TAN levels remained well below the safety threshold (Randall and Tsui, 2002). The observed pH and temperature values favored the formation of non-toxic NH4-N over the toxic NH3-N, regardless of the BSFL inclusion levels.

Incidence cost and profit index

The inclusion of varying levels of BSFL in the diet of Nile tilapia fry significantly influenced the incidence cost and profit index (Table 5).

Table 5: Cost-benefit analysis of Nile tilapia fry fed on different level of black soldier fly larvae-based diets.

Parameter	Experimental diet				
	BSFL0%	BSFL25%	BSFL50%	BSFL75%	BSFL100%
Amount of meal used (kg)	15.21	13.47	13.21	15.34	15.98
Price of meal (USD)	13.57	11.55	10.78	11.71	11.01
Processing cost of meal (USD)	0.90	0.88	0.88	0.88	0.90
Total cost of meal used (USD)	14.47	12.43	11.66	12.59	11.91
Weight of fish produced (kg)	6.01	4.69	5.53	6.47	7.25
Values of fish produced (USD)	16.10	12.55	14.82	17.33	19.42
Incidence cost (USD)	2.41[a]	2.65[a]	2.11[a]	1.95[b]	1.64[b]
Profit index	1.11[a]	1.01[a]	1.27[a]	1.38[b]	1.63[b]

Note: BSFL: black soldier fly larvae, 1 USD= 112 ETB, Different letters indicate significance difference

In a modern aquaculture, economic returns are a fundamental consideration for profitability and sustainability, especially as feed accounts for over 50% of production cost (Liti *et al*.,2005; Limbu, 2020). In the present study, the complete replacement of FM with BSFL meal significantly reduced the incidence cost and increased the profit index by 52%. Furthermore, as the inclusion levels of BSFL increased from 25% to 100%, incidence costs consistently decreased while the profit index simultaneously improved. This finding is supported by Wachira *et al*. (2021), who reported that Nile tilapia fingerlings fed a BSFL100% meal achieved a higher gross profit margin compared to other FM substitution levels. Similarly, Limbu *et al*. (2022) observed the lowest incidence cost and highest profit index in diets with BSFL 75% inclusion, though these values were not significantly different from those at BSFL 100%. The lower incidence cost and the higher profit index for Nile tilapia fry fed diets with high BSFL inclusion levels (e.g., 75% and 100%) can be attributed to the lower cost of BSFL meal, which offers a nutrient-rich and affordable alternative to FM. Given the high market price and limited availability of FM, utilizing BSFL would significantly reduce the cost of formulated feeds for Nile tilapia production in Ethiopia.

Conclusion and Recommendations

The present study demonstrated that BSFL meal can completely replace FM in the diet of Nile tilapia without negatively affecting the growth performance, survival rate and the water quality parameters. The cost of FM was approximately twice that of BSFL meal, and FM is often limited in availability and subjected to ecological restrictions. Thus, replacing FM with BSFL meal significantly reduced the cost of fish feed while maintaining the necessary nutrient composition for optimal Nile tilapia growth in tank culture system. The present study has elevated our understanding of BSFL not only as a valuable alternative ingredient to fishmeal for sustainable fish (tilapia) production but also for promoting a healthy environment by converting organic waste into high quality animal feed and frass (organic fertilizer). Currently the importance of utilizing non-conventional diets such as BSFL for livestock and fish production is poorly known in Ethiopia. Therefore, it is necessary to conduct further research in order to optimize BSFL production and processing techniques by considering diverse organic waste sources, and promote its utilization by different stakeholders to increase their profitability.

Acknowledgements

This study was financed by NESTLER project (Project: 101060762 — NESTLER — HORIZON-CL6-2021-FARM2FORK-01) and real time water monitoring device (SynField-SynWater) was obtained from NESTLER technological partner in Greece. The authors would like to thank Dr. Yitbarek W/Hawariat for his guidance on BSF rearing and providing pre-pupae to start BSFL production at NFALRC pilot site. The authors would also like to thank Dr. Etalem Tesfaye for her unreserved advice on the BSF management and valuable editorial comments given to improve the manuscript. We also thank Mr. Mengistu G/Tsadik for preparing organic waste and ensuring continuous BSFL production, and Ms. Tsige Admekew for her help during water and feed analysis in the laboratory.

References

Abdel-Tawwab, M., R. H. Khalil, A. A. Metwally, M. S. Shakweer, M. A. Khallaf, & H. M. R. Abdel-Latif. 2020. Effects of black soldier fly (*Hermetia illucens* L.) larvae meal on growth performance, organs-somatic indices, body composition, and hemato-biochemical variables of European sea bass, *Dicentrarchus labrax*. Aquaculture, 522, 735136. https://doi.org/10.1016/j.aquaculture.2020.735136

Adebayo, O.T., O.A. Fagbenro, & T. Jegede. 2004. Evaluation of Cassia fistula meal as a replacement of soyabean meal in practical diets of Oreochromis niloticus fingerlings. Aquac. Nutr. 9: 99–104.

Aniebo, A. O., & O. J. Owen. 2010. Effects of age and method of drying on the proximate composition of housefly larvae (*Musca domestica* Linnaeus) meal (HFLM). Pakistan Journal of Nutrition. 9, 485–487.

AOAC. 2005. Official methods of analysis of AOAC International. AOAC International.

APHA. 1995. Standard methods for the examination of water and wastewater. 19th ed., APHA, Washington D.C., USA.

Barroso, F. G., de Haro, C., Sánchez-Muros, M.-J., Venegas, E., Martínez- Sánchez, A., & C. Pérez-Bañón. 2014. The potential of various insect species for use as food for fish. Aquaculture, 423,193–201.

Belghit, I., Liland, N. S., Gjesdal, P., Biancarosa, I., Menchetti, E., Li, Y., Waagbø, R., Krogdahl, Å., &, E. J .Lock. 2019. Black soldier fly larvae meal can replace fish meal in diets of sea-water phase Atlantic salmon *(Salmo salar*). Aquaculture, 503, 609–619. https://doi.org/10.1016/j.aquaculture.2018.12.032

Beveridge, M. C. M., Thilsted, S. H., Phillips, M. J., Metian, M., Troell, M., & S. J Hall. 2013. Meeting the food and nutrition needs of the poor: The role of fish and the opportunities and challenges emerging from the rise of aquaculture. Journal of Fish Biology, 83, 1067–1084.

Brett, J.R & T.D. Groves. 1979. Physiological energetics. In: Hoar WS, Randall DJ, Brett JR (eds) Academic Press, London, UK. 8, 280–344.

Caimi, C., Renna, M., Lussiana, C., Bonaldo, A., Gariglio, M., Meneguz, M., Dabbou, S., Schiavone, A., Gai, F., Elia, A. C., Prearo, M., & L. Gasco. 2020. First insights on Black Soldier Fly (*Hermetia illucens* L.) larvae meal dietary administration in Siberian sturgeon (*Acipenser baerii* Brandt) juveniles. Aquaculture, 515(734539) https://doi.org/10.1016/j.aquaculture.2019.734539

Caruso, D., Devic, E. Subamia, I, Talamond,P. & E. Baras. 2013. Technical handbook of domestication and production of diptera Black Soldier Fly (BSF) *Hermetia illucens*, Stratiomyidae. ISBN: 978-979-493-610-8

de Francesco, M., Parisi, G., M´edale, F., Lupi, P., Kaushik, S.J.& B.M. Poli. 2004. Effect of long-term feeding with a plant protein mixture-based diet on growth and body/fillet quality traits of large rainbow trout (*Oncorhynchus mykiss*). Aquaculture 236, 413–429. https://doi.org/10.1016/j.aquaculture.2004.01.006.

Devic, E., Leschen, W., Murray, F., & D. C. Little. 2018. Growth performance, feed utilization and body composition of advanced nursing Nile tilapia (*Oreochromis niloticus*) fed diets containing Black Soldier Fly (*Hermetia illucens*) larvae meal. Aquaculture Nutrition, 24(1), 416–423. https://doi.org/10.1111/anu.12573

El-Dakar, A. Y., Shalaby, S. M., & I. P. Saoud. 2007. Assessing the use of a dietary probiotic/prebiotic as an enhancer of spinefoot rabbit fish (*Siganus rivulatus*) survival and growth. Aquaculture Nutrition, 13, 407–412. https://doi.org/10.1111/j.1365-2095.2007.00491.x

El-Sayed, A.F.M & M. Kawanna. 2008. Optimum water temperature boosts the growth performance of Nile tilapia (*Oreochromis niloticus*) fry reared in a recycling system. Aquaculture Research, 39, 670-672

El-Sayed, A.F.M. & S. Teshima. 1992. Protein and energy requirements of Nile tilapia, *Oreochromis niloticus*, fry. Aquaculture 103(1): 55–63.

FAO. 2024. The State of World Fisheries and Aquaculture. In The State of World Fisheries and Aquaculture 2024. FAO. https://doi.org/10.4060/cd0683en

FAO. 2022. The State of World Fisheries and Aquaculture. Towards blue transformation. FAO, Rome. https://doi.org/10.4060/cc0461en.

Goda, A. M. A., El-Haroun, E., Nazmi, H., Van Doan, H., Aboseif, A. M., Taha, M. K. S., & N. M. Abou Shabana. 2024. Black soldier fly oil-based diets enriched in lauric acid enhance growth, hematological indices, and fatty acid profiles of Nile tilapia, *Oreochromis niloticus* fry. Aquaculture Reports, 37. https://doi.org/10.1016/j.aqrep.2024.102269

Gougbedji, A., P. Agbohessou, A. Philippe A. Francis F. & R.C. Megido. 2021. Technical basis for the small-scale production of black soldier fly, *Hermetia illucens* (L. 1758), meal as fish feed in Benin. Journal of Agriculture and Food Research 4 (100153). https://doi.org/10.1016/j.jafr.2021.100153

Hardy, R. W. 2010. Utilization of plant proteins in fish diets: Effects of global demand and supplies of fishmeal. In Aquaculture Research. 41(5), 770–776). https://doi.org/10.1111/j.1365-2109.2009.02349.x

Henry, M., Gasco, L., Piccolo, G., & Fountoulaki, E. 2015. Review on the use of insects in the diet of farmed fish: past and future. Animal Feed Science and Technology, 203, 1-22. https://doi.org/10.1016/j.anifeedsci.2015.03.001

Jauncey, K. 1998. Tilapia Feeds and Feeding. Stirling, UK: Pisces Press Ltd.

Kroeckel, S., Harjes, A. G. E., Roth, I., Katz, H., Wuertz, S., Susenbeth, A., & C. Schulz. 2012. When a turbot catches a fly: Evaluation of a pre-pupae meal of the Black Soldier Fly (*Hermetia illucens*) as fish meal substitute - Growth performance and chitin degradation in juvenile turbot (Psetta maxima). Aquaculture, 365, 345–352. https://doi.org/10.1016/j.aquaculture.2012.08.041

Limbu, S.M. 2020. The effects of on-farm produced feeds on growth, survival, yield and feed cost of juvenile African sharp tooth catfish (*Clarias gariepinus*). Aquaculture and Fisheries, 5, 58–64. https://doi.org/10.1016/ j.aaf.2019.07.002

Limbu, S. M., Shoko, A. P., Ulotu, E. E., Luvanga, S. A., Munyi, F. M., John, J. O., & M. A. Opiyo. 2022. Black soldier fly (*Hermetia illucens*,) larvae meal improves growth performance, feed efficiency and economic returns of Nile tilapia (*Oreochromis niloticus*, L.) fry. Aquaculture, Fish and Fisheries, 2(3), 167–178. https://doi.org/10.1002/aff2.48

Liti, D., Cherop, L., Munguti, J., & L. Chhorn. 2005. Growth and economic performance of Nile tilapia (*Oreochromis niloticus*) fed on two formulated diets and two locally a available feeds in fertilized ponds. Aquaculture Research, 36, 746–752. https://doi. org/10.1111/j.1365-2109.2005.01265. x.

Magalhaes, R., Sánchez-López, A., Leal, R. S., Martínez-Llorens, S., Oliva-Teles, A., & H. Peres. 2017. Black soldier fly (*Hermetia illucens*) pre-pupae meal as a fish meal replacement in diets for European seabass (*Dicentrarchus labrax*). Aquaculture, 476, 79–85. https://doi.org/10.1016/j.aquaculture.2017.04.021

Makkar, H. P. S., Tran, G., Heuzé, V., & P.Ankers. 2014. State-of-the-art on use of insects as animal feed. Animal Feed Science and Technology, 197, 1–33. https://doi.org/10.1016/j.anifeedsci.2014.07.008

Muin, H.; Taufek, N.M.; Kamarudin, M.S.; & S.A. Razak. 2017. Growth performance, feed utilization and body composition of Nile tilapia, *Oreochromis niloticus* (Linnaeus, 1758) fed with different levels of black soldier fly, *Hermetia illucens* (Linnaeus, 1758) maggot meal diet. Iranian Journal of Fisheries Science, 16, 567–577.

Munguti, J.,Wekesa F., Osuga I., Kariuki M., Yossa R.,Mungai D., Kyule D., et al. 2024. Utilization of Black Soldier Fly (*Hermetia illucens*) Larvae as a Potential Substitute for Fish Meal in the Production of Nile Tilapia (*Oreochromis niloticus* L.). Sustainable Agriculture Research; 13 (1), 40-49.

Nairuti, R.N., Jonathan.M. M., Herwig,W., & Z. Werner. 2021. Growth Performance and Survival Rates of Nile tilapia (*Oreochromis niloticus* L.) reared on diets containing Black Soldier Fly (*Hermetia Illucens* L.). Journal of Land Management, Food and Environment,72(1),9-19. https://doi.org/10.2478/boku-2021-0002

Obirikorang, K. A., Gyamfi, S., Goode, M. E., Amisah, S., Edziyie, R. E., & K. Quagrainie. 2020. Effect of soybean meal diets on the growth performance, ammonia excretion rates, gut histology and feed cost of Nile tilapia (*Oreochromis niloticus*) fry. Aquaculture Research 51, 3520–3532.

Popma, T. & M. Masser. 1989. Tilapia life history and biology. Southern Regional Aquaculture Center, SRAC Publication No. 283.

Rana K.J. & M.R. Hasen. 2013. On-farm feeding and feed management practices for sustainable aquaculture production: An analysis of case studies from selected Asian and African countries. In: On-farm feeding and feed management in aquaculture. Hasan M.R., New M.B. eds. FAO Fisheries and Aquaculture Technical Paper No. 583. Rome: FAO. p. 21–69.

Randall, D.J. & T.K.N. Tsui. 2002. Ammonia toxicity in fish. Marine Pollution Bulletin, 45, 17–23. https://doi.org/10.1016/S0025-326X(02)00227-8

Renna, M., Schiavone, A., Gai, F., Dabbou, S., Lussiana, C., Malfatto, V., Prearo, M., Capucchio, M. T., Biasato, I., Biasibetti, E., De Marco, M., Brugiapaglia, A., Zoccarato, I., & L. Gasco, 2017. Evaluation of the suitability of a partially defatted black soldier fly (*Hermetia illucens* L.) larvae meal as ingredient for rainbow trout (*Oncorhynchus mykiss*, Walbaum) diets. Journal of Animal Science and Biotechnology, 8(1), 1–13. https://doi.org/10.1186/s40104-017-0191-3

Schiavone, A., De Marco, M., Martínez, S., Dabbou, S., Renna, M., Madrid, J., Hernandez, F., Rotolo, L., Costa, P., Gai, F., &, L. Gasco. 2017. Nutritional value of a partially defatted and a highly defatted black soldier fly larvae (*Hermetia illucens* L.) meal for broiler chickens:

Apparent nutrient digestibility, apparent metabolizable energy and apparent ileal amino acid digestibility. Journal of Animal Science and Biotechnology, 8(1). https://doi.org/10.1186/s40104-017-0181-5

Sheppard, C.J. 2008. Black soldier fly and others for value added manure management. University of Georgia. Department of Entomology and Animal Science, Athens, GA.

Spranghers, T., Ottoboni, M., Klootwijk, C., Ovyn, A., Deboosere, S., De Meulenaer, B., Michiels, J., Eeckhout, M., De Clercq, P., & S. De Smet. 2017. Nutritional composition of black soldier fly (*Hermetia illucens*) prepupae reared on different organic waste substrates. Journal of the Science of Food and Agriculture, 97(8), 2594–2600. https://doi.org/10.1002/jsfa.8081

Tacon, A. G. J., & M. Metian. 2008. Global overview on the use of fish meal and fish oil in industrially compounded aquafeeds: Trends and future prospects. Aquaculture, 285, 146–158.

Tran-Duy, A., van Dam, A.A. & J.W. Schrama. 2012. Feed intake, growth and metabolism of Nile tilapia (*Oreochromis niloticus*) in relation to dissolved oxygen concentration. Aquaculture Research, 43, 730-744.

van Huis, A. 2020. Insects as food and feed, a new emerging agricultural sector: A review. In Journal of Insects as Food and Feed. 6: 27–44. https://doi.org/10.3920/JIFF2019.0017

Wachira, M.N., Osuga, I.M., Munguti, J.M., Ambula, M.K., Subramanian, S. & C.M. Tanga, 2021. Efficiency and improved profitability of insect-based aquafeeds for farming Nile tilapia fish (*Oreochromis niloticus* L.). Animals, 11 (2599). https://doi.org/10.3390/ani11092599

Xiao, X., Jin, P., Zheng, L., Cai, M., Yu, Z., Yu, J. & J. Zhang. 2018. Effects of black soldier fly (*Hermetia illucen*s) larvae meal protein as a fishmeal replacement on the growth and immune index of yellow catfish (*Pelteobagrus fulvidraco*). Aquaculture Research, 49, 1569-1577. https://doi.org/10.1111/are.13611