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Enhancing Growth and Feed Efficiency in the Nile Tilapia (*Oreochromis niloticus* L.) Using Black Soldier Larvae Meal (*Hermetia illucens* L.) as a Sustainable Aquafeed Source

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ABSTRACT

This study evaluated the effects of incorporating black soldier fly larvae meal (BSFLM) at 0, 15, 30, and 45% of total ration (D1–D4) on growth performance, feed utilization, body composition, and energy retention of the Nile tilapia (*Oreochromis niloticus*) fingerlings. A total of 120 fingerlings, with an initial average weight of 365 ± 0.685g, were acclimated and randomly assigned to 12 aquariums (10 fish per aquarium). BSFLM analysis revealed 35.40% crude protein, 30.00% ether extract, 17.95% ash, and 5511 kcal/kg dry matter gross energy. All experimental diets were formulated to be iso-nitrogenous with minimal differences in caloric content. Results indicated that fish fed diets containing 15, 30, or 45% BSFLM exhibited significant improvements in final weight, total body weight gain, average daily gain, specific growth rate, relative growth rate, feed intake, feed conversion ratio, protein efficiency ratio, and protein productive value. The incorporation of BSFLM also enhanced energy retention, recorded at 16.27, 30.37, 21.36, and 18.75%, and PPV% values of 18.33, 41.25, 31.25, and 38.40% for D1–D4, respectively. Fish body composition was significantly influenced by BSFLM, showing increased CP% and decreased dry matter, EE, ash, and gross energy content, while organic matter remained unaffected. Moreover, inclusion of BSFLM reduced feed costs and improved net economic efficiency. These findings suggest that BSFLM is a promising alternative aquafeed source in the Nile tilapia diets, capable of enhancing growth performance, improving feed utilization, increasing energy retention and protein productivity, and reducing feeding costs. In conclusion, dietary inclusion of BSFLM at different levels positively influenced growth, body composition, energy utilization, and economic efficiency in the Nile tilapia fingerlings, highlighting its potential as a sustainable and cost-effective feed ingredient for aquaculture.

INTRODUCTION

Tilapia (*Oreochromis* spp.) has emerged as one of the most important aquaculture species worldwide, ranking third in global production with nearly 4.5 million tons annually **(FAO, 2022)**. Its popularity is largely attributed to desirable traits such as tolerance to suboptimal water quality, resistance to stress, and relatively low susceptibility to diseases **(Suresh & Lin, 1992; Prabu *et al*., 2019; Sutthi & Van Doan, 2020; Wardani *et al*., 2021)**, rapid growth rates **(El-Sayed, 1999; Lim, 2006; Abdel-Tawwab *et al*., 2006)**, wide acceptance of alternative protein sources **(El-Sayed, 1999; Meric *et al*., 2011; Ng & Romano, 2013)**, and efficient feed conversion **(El-Sayed, 2016; Mengistu *et al*., 2020)**. Nutritionally, tilapia require diets containing 35–45% protein during juvenile stages, which gradually decline to 20–30% in sub-adults **(Siddiqui *et al*., 1988; El-Sayed, 2006)**. Broodstock, however, demand higher protein levels (35–45%) to maintain optimal reproductive performance **(Gunasekera *et al*., 1996a, b; El-Sayed *et al*., 2003)**. Lipid requirements are variable, but 10–15% has been suggested for optimum growth, although farmers frequently apply lower levels of 6–8% **(El-Sayed, 2006)**.

In the search for alternative and sustainable feed ingredients, insect meals have gained growing attention. They are nutrient-dense, rich in essential amino acids, and contain beneficial trace elements **(Kroeckel *et al*., 2012; Barroso *et al*., 2014)**. Additionally, insect farming offers substantial environmental benefits, including reduced greenhouse gas emissions, lower water demand, and the ability to recycle organic waste into valuable protein biomass **(Smetana *et al*., 2016; Wang & Shelomi, 2017)**. Among insect species, the black soldier fly (*Hermetia illucens*; BSF) stands out as particularly promising. It can be reared on agricultural by-products, thereby addressing two major challenges simultaneously: the need for cost-effective feed ingredients and the management of food waste streams **(Diener *et al*., 2009; Nguyen *et al*., 2015)**. Furthermore, BSF production is highly scalable and can be automated to support industrial-level feed production **(Vo, 2019; Zhang *et al*., 2020)**.

Nutritionally, BSF larvae provide 42–58% crude protein and 33–39% lipids **(Newton *et al*., 2005; Kroeckel *et al*., 2012)**, making them suitable for incorporation into livestock and aquaculture diets. Previous studies have confirmed their potential as a feed ingredient in chickens **(Elwert *et al*., 2010; Elangovan *et al*., 2021)**, several fish species, including the African catfish (*Clarias gariepinus*), barramundi (*Lates calcarifer*), rainbow trout (*Oncorhynchus mykiss*), salmon (*Salmo salar*), sea bream (*Sparus aurata*), striped catfish (*Pangasianodon hypophthalmus*), turbot (*Scophthalmus maximus*), tench (*Tinca tinca*), and the Nile tilapia (*O. niloticus*) **(Dietz & Liebert, 2018; Bruni *et al*., 2020; Fabrikov *et al*., 2021)**, pigs **(Yu *et al*., 2019)**, and ruminants **(Fukuda *et al*., 2022)**. In tilapia, BSF meal has successfully replaced more than half of dietary protein without compromising performance when compared with soybean meal-based diets **(Dietz & Liebert, 2018)**.

Given the rising global demand for fish and the escalating cost of conventional protein sources such as fishmeal **(Hardy, 2010; Munguti *et al*., 2021; Tran *et al*., 2022)**, the development of cost-effective and sustainable alternatives is urgent. Therefore, this study was conducted to evaluate the effects of incorporating different levels of black soldier fly larvae meal (BSFLM) in the Nile tilapia fingerling diets on growth performance, feed utilization, body composition, nutrient retention, and economic efficiency.

MATERIALS AND METHODS

The present study was conducted to evaluate the effects of incorporating black soldier fly larvae meal (BSFLM) at different dietary levels on the growth performance, feed utilization, body composition, and economic efficiency of the Nile tilapia (*Oreochromis niloticus*) fingerlings. The experimental work was carried out at the Fish Experimental Laboratory, Animal Production Department, Biological Agriculture Research Institute, National Research Centre (NRC), 33 El-Bohouth Street, P.O. Box 12622, Dokki, Cairo, Egypt, in collaboration with Department of Cell Biology, Biotechnology Research Institute, National Research Centre, Giza, Dokki, Giza, 12622, Egypt.

Experimental unit

A total of 120 the Nile tilapia (*Oreochromis niloticus*) fingerlings were acclimated and then randomly allocated into 12 glass aquaria, each stocked with 10 fish. The aquaria (80 × 40 × 30 cm) were filled with 60L of dechlorinated tap water. Fish had an initial mean weight of 36.5 ± 0.69g per aquarium. The stock was obtained from the Abbassa Fish Hatchery, Sharkia Governorate, Egypt. Prior to the feeding trial, fish were adapted to laboratory conditions and fed a control diet for two weeks.

Experimental designed and diets

Experimental Nile tilapia (*Oreochromis niloticus*) fingerlings were randomly divided into four dietary treatment groups as follows:

D1 (Control): fed a basal diet without black soldier fly larvae meal (BSFLM).

D2: fed a diet containing 15% BSFLM of the total formulation.

D3: fed a diet containing 30% BSFLM of the total formulation.

D4: fed a diet containing 45% BSFLM of the total formulation.

The feeding trial was conducted over a period of 56 days, from the beginning of May to the end of June 2024.

The composition of the different experimental diets is presented in Table (1).

Table 1. Composition of the different experimental diets

Item	Experimental diets				Price of tone LE
	Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM	
	D_1	D_2	D_3	D_4	
Composition of tested diets					
black soldier fly larvae meal	**0**	**15**	**30**	**45**	**25000**
Soybean meal (44%)	**40**	**30**	**9**	**3**	**30000**
Protein concentration (56%)	**17**	**14**	**18**	**12**	**19000**
Ground Yellow corn (8%)	**28**	**26**	**28**	**24**	**11500**
Wheat bran (13%)	**10**	**10**	**10**	**11**	**9100**
Vegetable oil	**3**	**3**	**3**	**3**	**50000**
Vitamin and Minerals mixture*	**2**	**2**	**2**	**2**	**50000**
Price of ton fed (LE)	**21860**	**21810**	**20250**	**20691**	**----**
Price of kg fed (LE)	**21.860**	**21.810**	**20.250**	**20.691**	**----**

*Vitamin and Minerals mixture: contained Vit. A (E672) (IU) 876.19, Vit. D3 (IU) 1141.39, Vit. E 114.30, Vit. K3 7.55, Vit. B1 13.71, Vit. B2 11.44, Vit. B6 15.33, Vit. B12 0.03, Niacin 60.96, Calpan 30.48, Folic Acid 3.04, Biotin 0.37, Vit. C 11.44, Selenium 0.27, Manganese 19.04, Iron 9.15, Iodine 0.77, Zinc 76.19, Copper 3.04, Cobalt 0.37, Choline Chloride 457.14, and Antioxidant 95.23 (Vit. vitamin; IU international unit), Price of tone LE according to 2024, BSFLM: black soldier fly larvae meal

Parameters of growth performance (NRC, 2011)

Body weight gain (BWG) = Final weight - Initial weight.

Survival rate (SR %) = Number of fish at final / Number of fish at start x100.

Specific growth rate (SGR) =

[In final weight (g) - In initial weight (g)] / Experimental days *100

Calculation of feed conversion ratio (FCR)

FCR = total dry matter intake, (TDMI), g / total body weight gain (TBWG), g.

Calculation of crude protein efficiency ratio (CPER)

(PER) = total body weight gain (TBWG), g / total crude protein intake (TCPI), g.

Feed efficiency

Feed efficiency (FE %) = [weight gain (g) / feed intake (g)]

Protein productive value (PPV %) = [PR_1– PR_0 / PI] 100.

Where: PR_1 = is the total fish body protein at the end of the experiment.

PR_0 = is the total fish body protein at the start of the experiment. PI = Protein intake.

Energy retention percentages (ER %)

The energy retention percentage was calculated according the following equation:

Energy retention (ER %) = $E\text{-}E_0 / E_F$ X 100

Where: E= the energy in fish carcass (kcal) at the end of the experiment.

E_0= the energy in fish carcass (kcal) at the start of the experiment.

E_F = the energy (kcal) in feed intake

Energy retention was estamited according to **Blaxter (1968)** and **MacRae and Lobley (2003)**.

The proximate composition of the experimental diets and fish whole-body samples was determined following the standard procedures of the Association of Official Analytical Chemists **(AOAC, 2016)**.

Body composition

At the beginning of the trial, 10 fish were sampled for initial body composition analysis, while at the end of the experiment, 7 fish from each treatment group were randomly selected to determine whole-body composition.

Economic efficiency of diet

The economic efficiency of the experimental diets was evaluated using input–output analysis. Calculations were performed as follows:

Feed cost per kg weight gain = Feed conversion ratio × Cost of 1 kg diet

Profit per kg weight gain = Sale price per kg gain – Feeding cost per kg gain

Economic efficiency (%) = (Profit per kg gain ÷ Feeding cost per kg gain) × 100

Calculated data

The gross energy (GE, kcal/kg DM) of the experimental diets and fish body composition was estimated according to **Blaxter (1968)** and **MacRae and Lobley (2003)**, using the following caloric values: crude protein (CP) = 5.65 kcal/g, ether extract (EE) = 9.40 kcal/g, and crude fiber (CF) and nitrogen-free extract (NFE) = 4.15 kcal/g. Metabolizable energy (ME) was calculated following **NRC (2011)**, applying values of 4.50, 8.15, and 3.49 kcal/g for protein, fat, and carbohydrate, respectively. The protein-to-energy ratio (mg CP/kcal ME) was also determined according to **NRC (2011)**.

Statistical analysis

All collected data were analyzed using one-way analysis of variance (ANOVA) with SPSS software (Version 26.0, IBM, 2020). Significant differences among treatment means were identified using Duncan's Multiple Range Test **(Duncan, 1955)**.

RESULTS

Chemical analysis of experimental diets

As shown in Table (2), black soldier fly larvae meal (BSFLM) contained 35.40% crude protein, 30.00% ether extract, 17.95% ash, 5511 kcal/kg DM gross energy, 432.91 kcal/kg DM metabolizable energy, and a protein-to-energy ratio of 81.77mg CP/kcal ME which was calculated according to **NRC (2011)**.

Table 2. Chemical analysis of different experimental diets

Item	BSFLM	Experimental diets			
		Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM
		D_1	D_2	D_3	D_4
Moisture	**3.66**	**6.24**	**5.96**	**5.35**	**5.33**
Dry matter (DM)	**96.34**	**93.76**	**94.04**	**94.65**	**94.67**
Chemical analysis on DM basis					
Organic matter (OM)	**82.05**	**90.89**	**88.39**	**85.18**	**83.20**
Crude protein (CP)	**35.40**	**29.26**	**29.50**	**29.88**	**29.43**
Crude fiber (CF)	**8.31**	**4.57**	**4.56**	**4.45**	**4.71**
Ether extract (EE)	**30.00**	**3.35**	**5.69**	**8.13**	**10.80**
Nitrogen free extract (NFE)	**8.34**	**53.71**	**48.64**	**42.72**	**38.26**
Ash	**17.95**	**9.11**	**11.61**	**14.82**	**16.80**
Gross energy kcal/ kg DM	**5511**	**4387**	**4409**	**4410**	**4461**
Gross energy cal/ g DM	**5.511**	**4.387**	**4.409**	**4.410**	**4.461**
Metabolizable energy kcal/ kg DM	**432.91**	**346.42**	**348.88**	**349.81**	**353.98**
Protein energy ratio (mg CP/ Kcal ME)	**81.77**	**84.46**	**84.56**	**85.42**	**83.14**

Gross energy (kcal/ kg DM) was calculated according to (**Blaxter1968; MacRae & Lobley 2003**).

Where, each g CP = 5.65 Kcal, g EE = 9.40 kcal and g CF and NFE = 4.15 Kcal.

Metabolizable energy (ME): Calculated according to **NRC (2011)** using values of 4.50, 8.15 and 3.49 Kcal for protein, fat and carbohydrate, respectively. BSFLM: black soldier fly larvae meal.

The proximate composition of the experimental diets revealed crude protein (CP) contents of 29.26, 29.50, 29.88, and 29.43% for D1, D2, D3, and D4, respectively. Crude fiber (CF) levels were similar across treatments (4.56–4.71%). Ether extract (EE) increased progressively with BSFLM inclusion, ranging from 3.35% in D1 to 10.80% in D4. Ash content rose from 9.11% in D1 to 16.80% in D4, while nitrogen-free extract (NFE) decreased from 53.71% to 38.26% with increasing BSFLM levels. Gross energy ranged from 4387 to 4461 kcal/kg DM, metabolizable energy from 346.42 to 353.98 kcal/kg DM, and protein-to-energy ratios from 83.14 to 85.42 mg CP/kcal ME. Overall, BSFLM proved to be a rich source of protein and energy, and the formulated diets were isonitrogenous (29.26–29.88% CP) with only minor differences in caloric values, all of which were within the nutritional requirements of the Nile tilapia fingerlings.

Growth performance and survival

As presented in Table (3), the incorporation of BSFLM at different dietary levels (15, 30, and 45%) significantly ($P<0.05$) improved final weight (FW), total body weight gain (TBWG), average daily gain (ADG), specific growth rate (SGR), and relative growth rate (RGR) compared with the control group. The highest growth performance values were observed in fish fed the diet containing 15% BSFLM (D2), followed by D3 and D4, while the control group (D1) showed the lowest results. Survival rate was 100% across all treatments, with no recorded mortality in any of the experimental groups.

Table 3. Growth performance, specific growth rate and survival ratio of the Nile tilapia fingerlings fed diets containing different levels of black soldier fly larvae meal

Item	Experimental diets				SEM	Sign. *P<0.05*
	Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM		
	G_1	G_2	G_3	G_4		
Number of fish	30	30	30	30	-	-
IW, g	363	367	366	364	0.685	NS
FW, g	472^c	615^a	520^b	516^b	15.780	*
TBWG, g	109^c	248^a	154^b	152^b	15.384	*
Duration trial	56 days				-	-
ADG, g	1.95^c	4.43^a	2.75^b	2.71^b	0.275	*
SGR	0.21^c	0.40^a	0.27^b	0.27^b	0.021	*
RGR	0.30^c	0.68^a	0.42^b	0.42^b	0.042	*
Starter number	30	30	30	30	-	-
End number of	30	30	30	30	-	-
SR %	100	100	100	100	-	-
Dead number	Zero	Zero	Zero	Zero	-	-
Mortality rate %	Zero	Zero	Zero	Zero	-	-

a, b and c: Means in the same row having different superscripts differ significantly (*P<0.05*).
SEM: Standard error of the mean NS: Not significant. *: Significant at (*P<0.05*).
IW: Initial weight, g. FW: Final weight, g. TBWG: Total body weight gain, g.
ADG: Average daily gain, g. SGR: Specific growth rate. RGR: Relative growth rate.
SR: Survival ratio. BSFLM: black soldier fly larvae meal.

Feed utilization of the different experimental groups

As shown in Table (4), feed utilization parameters were positively influenced by the inclusion of BSFLM in the Nile tilapia diets. Feed intake (FI) and crude protein intake (CPI) were significantly higher (*P<0.05*) in groups fed diets containing BSFLM (15%, 30%, and 45%) compared with the control group (D1, 0% BSFLM). The highest FI (1133 g) and CPI (334.24 g) were recorded in fish fed the 15% BSFLM diet (D2).

Feed conversion ratio (FCR) also improved significantly (*P<0.05*) in groups D2, D3, and D4 compared to the control, with the most efficient conversion observed in D2 (4.569), followed by D3 (6.838) and D4 (6.875), whereas the control group exhibited the poorest FCR (9.229).

Similarly, protein efficiency ratio (PER) showed significant (*P<0.05*) improvement in all BSFLM-supplemented groups (D2, D3, and D4), with the highest value in D2.

Table 4. Feed utilization of the Nile tilapia fingerlings fed diets containing different levels of black soldier fly larvae meal

Item	Experimental diets				SEM	Sign. *P<0.05*
	Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM		
	G_1	G_2	G_3	G_4		
TBWG, g	**109^c**	**248^a**	**154^b**	**152^b**	**15.384**	*
FI, g	**1006^c**	**1133^a**	**1053^b**	**1045^b**	**13.961**	*
FCR	**9.229^c**	**4.569^a**	**6.838^b**	**6.875^b**	**0.508**	*
FCP%	**29.26**	**29.50**	**29.88**	**29.43**	-	-
CPI, g	**294.36^d**	**334.24^a**	**314.64^b**	**307.54^c**	**4.359**	*
PER	**0.3703^c**	**0.7420^a**	**0.4894^b**	**0.4942^b**	**0.041**	*

a, b, c and d: Means in the same row having different superscripts differ significantly (*P<0.05*).
SEM: Standard error of the mean, NS: Not significant,*: Significant at (*P<0.05*), BWG: Total body weight gain, FI: Feed intake, FCR: Feed conversion ratio, FCP%: Feed crude protein percentages, CPI: Crude protein intake, PER: Protein efficiency ratio,BSFLM: black soldier fly larvae meal.

Fish body composition of different experimental groups

Data presented in Table (5) indicate that the inclusion of BSFLM at different dietary levels (15, 30, and 45% of the total diet formulation for D2, D3, and D4, respectively) had a significant effect (*P<0.05*) on most parameters of the Nile tilapia whole body composition, except for organic matter (OM) content, when compared with the control group (D1).

Incorporation of BSFLM significantly increased crude protein (CP%) and moisture content, while it significantly reduced dry matter (DM%), ether extract (EE%), ash%, and gross energy (GE; kcal/100 g DM). The highest CP value (62.51%) was recorded in fish from D4, which received the 45% BSFLM diet.

Table 5. Fish body composition of initial and different experimental groups of the Nile tilapia fingerlings fed diets with different levels of black soldier fly larvae meal

Item	Fish body composition of initial fish	Experimental diets				SEM	Sign. *P<0.05*
		Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM		
		G_1	G_2	G_3	G_4		
Moisture	**75.46**	**70.89^d**	**73.37^a**	**72.31^c**	**72.94^b**	**0.287**	*
DM	**24.54**	**29.11^a**	**26.63^d**	**27.69^b**	**27.06^c**	**0.287**	*
Chemical analysis on DM basis		**Chemical analysis on DM basis**				-	-
OM	**83.68**	**85.10**	**85.13**	**86.73**	**86.17**	**0.253**	**NS**
CP	**56.17**	**54.63^d**	**55.94^c**	**58.44^b**	**62.51^a**	**0.906**	*
EE	**27.51**	**30.47^a**	**29.19^b**	**28.29^c**	**23.66^d**	**0.777**	*
Ash	**16.32**	**14.90^a**	**14.87^a**	**13.27^c**	**13.83^b**	**0.211**	*
GE1	**575.95**	**595.08^a**	**590345^b**	**596.11^a**	**575.59^c**	**2.501**	*
GE2	**5.7595**	**5.9508^a**	**5.9045^b**	**5.9611^a**	**5.7559^c**	**0.0251**	*

a, b, c and d: Means in the same row having different superscripts differ significantly (*P<0.05*).

SEM: Standard error of the mean, NS: Not significant, *: Significant at (*P<0.05*), DM: Dry matter

OM: Organic matter, CP: Crude protein, EE: Ether extract, GE1: **Gross energy kcal/ 100g.**

GE2: Gross energy cal/ g DM, BSFLM: black soldier fly larvae meal.

Energy retention and protein productive value percentages

Data illustrated in Table (6) show that energy retention percentage (ER%) and protein productive value percentage (PPV%) were significantly (*P<0.05*) increased in the Nile tilapia fed diets containing BSFLM at 15, 30, and 45% (D2, D3, and D4, respectively) compared with the control group (D1) that received 0% BSFLM.

The corresponding ER% values were 16.27, 30.37, 21.36, and 18.75% for D1, D2, D3, and D4, respectively. Similarly, the PPV% values were 18.33, 41.25, 31.25, and 38.40% for D1, D2, D3, and D4, respectively.

Table 6. Energy retention (ER) and protein productive value (PPV) %of the Nile tilapia fingerlings fed diets containing different levels of black soldier fly larvae meal

Item	Experimental diets				SEM	Sign. *P<0.05*
	Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM		
	G_1	G_2	G_3	G_4		
IW	**363**	**367**	**366**	**364**	**0.685**	**NS**
FW	**472^c**	**615^a**	**520^b**	**516^b**	**15.780**	*
Calculation the energy retention						
ECFBW	**5.9508^a**	**5.9045^b**	**5.9611^a**	**5.7559^c**	**0.025**	*
TEEBF	**2809^d**	**3631^a**	**3100^b**	**2970^c**	**93.275**	*
ECIBF	**5.7595**				-	-
TESBF	**2091**	**2114**	**2108**	**2096**	**3.976**	**NS**
ERBF	**718^d**	**1517^a**	**992^b**	**874^c**	**90.869**	*
EFI	**4.387**	**4.409**	**4.410**	**4.461**	-	-
QFI	**1006^c**	**1133^a**	**1053^b**	**1045^b**	**13.961**	*
TEFI	**4413^c**	**4995^a**	**4644^b**	**4662^b**	**62.758**	*
ER%	**16.27^d**	**30.37^a**	**21.36^b**	**18.75^c**	**1.615**	*
Calculation the protein productive value (PPV) %						
CPFBC%	**54.63^d**	**55.94^c**	**58.44^b**	**62.51^a**	**0.096**	*
PR_1	**257.85^d**	**344.03^a**	**303.89^c**	**322.55^b**	**9.618**	*
CPIBFC%	**56.17**				-	-
PR_2	**203.90**	**206.14**	**205.58**	**204.46**	**0.385**	**NS**
PR_3	**53.95^d**	**137.89^a**	**98.31^c**	**118.09^b**	**9.427**	*
CPFE%	**29.26**	**29.50**	**29.88**	**29.43**	-	-
TPI	**294.36^d**	**334.24^a**	**314.64^b**	**307.54^c**	**4.359**	*
PPV%	**18.33^d**	**41.25^a**	**31.25^c**	**38.40^b**	**2.687**	*

a, b, c and d: Means in the same row having different superscripts differ significantly (*P*<0.05).
SEM: Standard error of the mean, NS: Not significant, *: Significant at (*P*<0.05), IW: Initial weight, g. FW: Final weight, g, ECFBW: Energy content in final body fish (cal / g),TEEBF: Total energy at the end in body fish (E), Energy content in initial body fish (cal / g),TESBF: Total energy at the start in body fish (E0) Energy retained in body fish (E-E0), EFI: Energy of the feed intake (Cal / g feed), QFI: Quantity of feed intake

Economical evaluation of different experimental groups

Data presented in Table (7) show that the incorporation of BSFLM into feed formulation reduced the overall feed cost compared with the control diet. The cost of feed formulation decreased from 21.860 LE/kg feed in the control diet (D1) to 21.810, 20.250, and 20.691 LE/kg feed in diets D2, D3, and D4, respectively.

The net improvement in feeding cost (%) was 0.00, 50.38, 24.00, and 24.14% for D1, D2, D3, and D4, respectively.

Table 7. Economical evaluation of the Nile tilapia fingerlings fed diets containing different levels of black soldier fly larvae meal

Item	Experimental diets			
	Zero BSFLM	15% BSFLM	30% BSFLM	45% BSFLM
	G_1	G_2	G_3	G_4
Costing of kg feed (LE)	**21.860**	**21.810**	**20.250**	**20.691**
Relative to control (%)	**100**	**99.77**	**92.63**	**94.65**
Feed conversion ratio (FCR)	**9.229**	**4.569**	**6.838**	**6.875**
Feeding cost (LE) per (Kg weight gain)	**201.75**	**99.65**	**138.47**	**142.25**
Relative to control (%)	**100**	**49.39**	**68.63**	**70.51**
Net improving in feeding cost (%)	**Zero**	**50.38**	**24.00**	**24.14**

Diet formulation calculated according to the local prices at year 2024, as presented in Table (1).
Feed cost (L.E) FCR×FI. Cost per Kg diet, BSFLM: black soldier fly larvae meal.

DISCUSSION

The proximate composition of black soldier fly larvae meal (BSFLM) in the present study demonstrates its potential as a valuable feed ingredient for aquafeeds. BSFLM contained 35.40% crude protein and 30.00% ether extract, along with considerable ash (17.95%) and high gross and metabolizable energy values (5511 and 432.91 kcal/kg DM, respectively). The calculated protein–energy ratio (81.77 mg CP/kcal ME) further confirms that BSFLM is nutritionally dense and suitable for fish diets. Formulation of the experimental diets showed that all rations were iso-nitrogenous, with crude protein levels ranging from 29.26% to 29.88%, which fall within the recommended protein requirement for the Nile tilapia. Crude fiber remained relatively constant (4.56–4.71%), while ether extract increased gradually with higher inclusion of BSFLM (3.35% in D1 to 10.80% in D4). Ash content varied more markedly (9.11–16.80%), which may reflect the mineral contribution of BSFLM. Nitrogen-free extract decreased with increasing BSFLM levels, indicating a shift from carbohydrate-based to lipid-based energy sources. Despite these differences, gross energy values (4387–4461 kcal/kg DM) and metabolizable energy (346.42–353.98 kcal/kg DM) remained within a narrow range, suggesting that the diets were energetically comparable. Protein–energy ratios (83.14–85.42 mg CP/kcal ME) also confirmed that all formulations were well balanced for tilapia nutritional needs. These results are consistent with earlier reports emphasizing the suitability of insect meals as alternative protein sources in aquafeeds. **Tacon and Metian (2008)** and **Kishawy *et al*. (2022)** highlighted the increasing demand and rising costs of conventional protein sources such as fish meal, animal by-products, and plant proteins due to the intensification of aquaculture. Similarly, **Obirikorang *et al*. (2015)** argued that modern feed formulation strategies must consider not only nutrient content but also cost, sustainability, and ingredient availability. The present findings align with this perspective, supporting the use of insect meals as sustainable replacements. Several studies have documented the successful incorporation of insect meals into aquafeeds for different species. **Fitches and Smith (2018)** demonstrated the nutritional adequacy of insect larvae meals for the Nile tilapia, while **Cummins *et al*. (2017)** reported similar findings in Pacific white shrimp. Comparable results have also been reported for the rainbow trout **(Renna *et al.*, 2017)** and Atlantic salmon **(Belghit *et al*., 2019)**. **Abozaid *et al*. (2024c)** further confirmed that *Galleria mellonella* larvae are highly nutritive, with even higher lipid content than BSFLM, contributing to elevated gross and metabolizable energy values. These collective findings suggest that insect-based ingredients are not only nutritionally sufficient but also offer a sustainable and cost-effective solution for aquaculture feed production.

In the present study, the incorporation of BSFLM at different inclusion levels significantly ($P< 0.05$) enhanced the growth performance of the Nile tilapia, as reflected by the increased FW, TBWG, ADG, SGR, and RGR values. The best growth responses were obtained with the 15% BSFLM diet (D22), while survival remained 100% with zero mortality across all treatments. These findings confirm the suitability of BSFLM as a safe protein source for the Nile tilapia. Our results are consistent with those of **Kishawy *et al*. (2022)**, who reported that substituting fishmeal with processed BSFLM up to 100% did not significantly affect growth performance of the Nile tilapia. Similarly, several studies have demonstrated that BSFLM can replace fishmeal without compromising performance in different aquaculture species, including the rainbow trout **(Renna *et al*., 2017)**, the Atlantic salmon **(Belghit *et al*., 2019)**, the Japanese sea bass **(Wang *et al*., 2019)**, the European sea bass **(Abdel-Tawwab *et al*., 2020)**, the Siberian sturgeon **(Caimi *et al*., 2020)**, and the Nile tilapia **(Tippayadara *et al*., 2021)**. **Devic *et al*. (2018)** also showed that up to 80% fishmeal replacement with BSFLM did not negatively affect final body weight or survival in the Nile tilapia. The positive effects observed in this study may be attributed to the high nutritional value of BSFLM, particularly its balanced amino acid and fatty acid profile, which closely resembles conventional protein sources. Our results are further supported by **Abozaid *et al*. (2024c)**, who observed improvements in growth performance and survival when soybean meal was partially replaced with insect meal. Likewise, **Fayed *et al*. (2023)** reported that inclusion of BSFLM up to 25% significantly improved growth performance, feed conversion, and survival in the Nile tilapia, although performance declined at 30% replacement, likely due to increased chitin content.

The role of chitin in limiting nutrient digestibility has been highlighted in several studies. **Alegbeleye *et al*. (2012)** and **Karlsen *et al*. (2017)** pointed out that chitin, when included at high levels, can act as a filler with low digestible energy and hinder amino acid absorption, leading to reduced growth rates. This may explain why in our trial the best performance was obtained at 15% BSFLM, while higher levels showed diminishing responses. Similar declines at high inclusion levels have been reported in the Nile tilapia **(Dietz & Liebert, 2018)**, meager **(Guerreiro *et al.*, 2020)**, and other species.

Incorporation of BSFLM into the Nile tilapia diets significantly enhanced feed utilization parameters. Feed intake (FI) and crude protein intake (CPI) increased in groups fed BSFLM-based diets compared to the control group (0% BSFLM). Notably, the group fed 15% BSFLM (D2) exhibited the highest FI (1133 g) and CPI (334.24 g). Feed conversion ratio (FCR) also improved significantly ($P< 0.05$) in fish fed BSFLM diets (D2, D3, and D4), with the best efficiency observed in D2 (4.569) compared to D1 (9.229), D3 (6.838), and D4 (6.875). Similarly, protein efficiency ratio (PER) improved in all groups receiving BSFLM. These results suggest that partial replacement of conventional protein with BSFLM, particularly at 15%, promotes better nutrient utilization in tilapia. Comparable outcomes have been reported in earlier studies. **Kishawy *et al*. (2022)** noted that replacing fish meal protein with partially defatted BSFLM at 25–100% did not adversely affect FCR, specific growth rate (SGR), PER, or protein retention efficiency (PRE), and that all diets were equally accepted by fish. Likewise, **Rawski *et al.* (2020)** observed that feed intake did not differ among treatments, but both FCR and PER improved in insect-fed groups, with the greatest improvements at lower inclusion levels (5% BSFLM). These findings support the current results, where the most favorable feed conversion occurred at moderate inclusion (15% BSFLM), while higher levels yielded smaller improvements.

The positive influence of BSFLM on feed utilization may be attributed to several functional properties of insect-derived nutrients. Insects are rich in antimicrobial peptides (AMPs), medium-chain fatty acids (notably lauric acid), and chitin, all of which have been reported to enhance gut health, nutrient absorption, and immune responses **(Park *et al*., 2015; Kasumyan, 2016; Lee *et al*., 2020; Moretta *et al*., 2020)**. Such bioactive components may explain the improved feed conversion and protein efficiency observed in the present study.

In addition, other feed additives such as methionine supplementation and probiotics (e.g., *Saccharomyces cerevisiae*) have been shown to improve feed efficiency in the Nile tilapia. **Abozaid *et al*. (2024a, b)** reported enhanced FCR and PER when methionine or yeast were included in tilapia diets, while **Abozaid *et al*. (2024c)** demonstrated significant improvements in FI, FCR, CPI, and PER when soybean meal was partially replaced with *Galleria mellonella* larvae meal. These findings align with the present study and reinforce the concept that alternative protein sources and functional ingredients can improve nutrient utilization and reduce dependence on traditional fish meal.

Inclusion of BSFLM at different levels (15–45%) significantly affected the whole-body composition of the Nile tilapia, with the exception of organic matter (OM). Incorporation of BSFLM resulted in higher crude protein (CP%) and moisture levels, whereas dry matter (DM%), ether extract (EE%), ash, and gross energy (GE) declined. The highest CP value (62.51%) was obtained in fish fed 45% BSFLM (D4), suggesting that BSFLM can enhance protein deposition in tilapia muscle tissue. These findings are partly consistent with earlier reports. **Kishawy *et a*l. (2022)** observed no significant differences in DM and CP contents of the Nile tilapia fed PD-BSFLM up to 100%, although they reported reductions in lipid and ash content, including calcium and phosphorus, at higher replacement levels. Similarly, studies of **Dumas *et al*. (2018)** and **Amer *et al*. (2021)** on the rainbow trout, and that of **Reyes *et al*. (2020)** on the sea bass found that dietary BSFLM did not alter whole-body CP content, but consistently reduced lipid levels. The reduction in lipid deposition has been attributed to the high lauric acid content of BSFLM, which is easily oxidized and less likely to accumulate in fish tissues **(Williams *et al*., 2006; Liland *et al*., 2017)**.

Declines in ash content with higher BSFLM inclusion have also been reported in the rainbow trout **(Caimi *et al*., 2021)** and tilapia **(Kishawy *et al*., 2022)**. This reduction may be linked to the relatively low mineral content of insect meals compared to fish meal. On the other hand, several studies confirmed that insect meal inclusion does not negatively affect protein quality or amino acid composition of fish fillets **(Mancini *et al*., 2018; Belghit *et al*., 2019; Caimi *et al*., 2021)**. However, the relatively low methionine level in BSFLM has been highlighted as a factor that may limit body methionine content unless supplemented **(Liland *et al.*, 2017)**. These findings are consistent with **Abozaid *et al.* (2024c)**, who reported enhanced ER% in the Nile tilapia fed *Galleria mellonella* larvae meal, although PPV% declined at higher inclusion levels, highlighting possible differences between insect species or inclusion thresholds. Similarly, **Abozaid *et al.* (2024b)** noted significant improvements in ER% and PPV% when diets were supplemented with methionine, while **Abozaid *et al.* (2024a)** observed enhanced PPV% but reduced ER% when *Saccharomyces cerevisiae* was incorporated. Collectively, these studies suggest that dietary interventions improving amino acid balance and digestibility can enhance nutrient utilization in tilapia. The improved ER and PPV observed in the current study may be partly attributed to the balanced protein–energy ratio of BSFLM diets, along with functional properties of insect-derived nutrients such as medium-chain fatty acids and chitin that support efficient nutrient metabolism.

Economic evaluation further confirmed the advantages of BSFLM inclusion. Feed costs decreased from 21.860 LE/kg in the control diet to 21.810, 20.250, and 20.691 LE/kg in D2, D3, and D4, respectively, with net feed cost improvements of 50.38%, 24.00%, and 24.14%. This aligns with **Kishawy *et al*. (2022)**, who reported reduced feed cost and enhanced economic efficiency with partial or full replacement of fish meal by BSFLM. Similar reductions in feed cost and improvements in profitability with BSFLM inclusion have been observed in tilapia **(Abdel-Tawwab *et al*., 2020; Fayed *et al*., 2023)** and other aquaculture species **(Stejskal *et al*., 2020; Rawski *et al*., 2021)**. **Luna *et al*. (2019)** further emphasized that reliance on fish meal and fish oil is increasingly unsustainable and uneconomical, underscoring the importance of alternative protein sources such as insect meals.

CONCLUSION

The present study demonstrated that partial replacement of fishmeal with black soldier fly larvae meal (BSFLM) at levels of 15–45% in the Nile tilapia diets significantly improved energy retention (ER%) and protein productive value (PPV%) compared to the control diet. The best results were obtained at 15% and 30% inclusion levels, indicating efficient nutrient utilization and protein deposition. Moreover, incorporation of BSFLM substantially reduced feed formulation costs and improved economic efficiency, confirming its potential as a cost-effective and sustainable alternative to fishmeal. Therefore, BSFLM can be recommended as a promising protein source in the Nile tilapia diets to enhance growth performance, nutrient retention, and profitability, while contributing to the sustainability of aquaculture production systems.

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