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Growth and economic performance of Nile tilapia (*Oreochromis niloticus*) fed on black soldier fly larvae raised on human fecal sludge and organic waste: a circular economy approach

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ABSTRACT

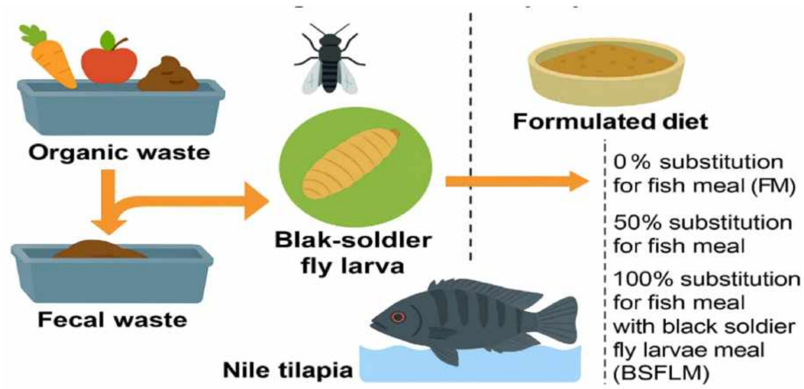
With increasing population growth, sustainable waste management remains a global challenge. This study evaluated the effects of using defatted black soldier fly larvae meal (BSFLM) instead of fishmeal (FM) on the growth performance of Nile tilapia (*Oreochromis niloticus*). The black soldier fly larvae were reared using fecal sludge and organic waste as substrates, harvested at the prepupal stage, and then defatted. Three isonitrogenous diets (30% crude protein) were formulated in which BSFLM substituted FM at 0% (control, diet 1), 50% (diet 2) and 100% (diet 3) on a protein basis. A 90-day feeding trial was conducted using 270 Nile tilapia fingerlings (9.62 ± 0.22 g) in a completely randomized design. The fingerlings were distributed into three groups of three replicates (30 fingerlings per net hapa). There was a decrease in final body weight (47.73, 42.98 and 34.57 g) with increased substitution of BSFLM for diets 1, 2 and 3, respectively ($p = 0.018$). Diet 2 exhibited the highest survival rate (95.56%). The economic profit index recorded for diets 1 and 2 was not significantly different. Based on these results, BSFLM can effectively replace fish meal by 50%, with no detrimental effect on growth.

Key words: aquafeed, black soldier fly, fish meal, growth performance, Nile tilapia

HIGHLIGHTS

- Nile tilapia survival rates were highest in D2 (50% BSFLM) outperforming both control (D1) and full BSFLM (D3).
- Growth performances varied significantly across all diets.
- BSFLM can replace up to 50% of fish meal for optimal growth, economic viability, and environmental sustainability.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Waste management pose a significant environmental and public health challenge particularly in developing countries (Ferronato & Torretta 2019). Poorly managed wastes contributes to contamination of water sources, spread of disease, and greenhouse gas emissions (WHO 2021). In low-resource settings, conventional waste treatment methods such as conventional activated sludge (CAS) treatment systems, incineration, land filling, and composting are costly, resource-intensive and difficult to sustain. Several effective, sustainable, and environmentally friendly management technologies have been proposed to manage the waste; biogas, composting, vemi-composting, black soldier fly (BSF), struvite precipitation, etc. (Strande 2014). However, black soldier fly (BSF) (*Hermetia illucens*) is a sustainable, low cost, and environmentally friendly solution to this challenge. It efficiently converts organic waste and faecal matter into high-value biomass. Thus assist in waste reduction and resource recovery (Tomberlin & Van Huis 2020; Matheka *et al.* 2021; Van Huis 2021). Black soldier fly larvae is rich in crude protein (35–45%), essential amino acids, and lipids, and can be produced sustainably on organic by products (Tippayadara *et al.* 2021; Lu *et al.* 2022; Zulkifli *et al.* 2022).

Aquaculture in Kenya is rapidly expanding due to increased fish consumption. It is estimated that per capita fish consumption has roughly doubled over the last five decades (Naylor *et al.* 2021). This has in turn increased the demand for aquafeeds. Fishmeal is the major protein ingredient in aquafeed because of its well-balanced amino acid composition and excellent digestibility (Fawole *et al.* 2021). However, dependence on fishmeal has put pressure on wild fish stocks, biodiversity loss and overall increase in price (FAO 2020; Lu *et al.* 2022; Mirzabaev *et al.* 2023; Boakes *et al.* 2024). High costs and scarcity of fishmeal has posed economic challenges for aqua feed manufacturers and fish farmers. Hence, concerted effort to identify alternative protein sources that can partially or completely replace fish meal component without compromising growth performance, feed efficiency, or fish health (Macusi *et al.* 2023). The use of plant protein sources in fish feeds has expanded considerably in recent years. However, deficiency in essential amino acids like lysine, methionine, cysteine, presence of ant-nutritional factors and low digestibility is a major limitation with plant-based protein sources (Ogunji *et al.* 2008). Based on this, incorporation of BSFL meal into aquafeed production systems can be cost-effective and nutritionally superior ingredient that supports growth and health of fish.

Nile tilapia (*Oreochromis niloticus*) is one of the most widely farmed freshwater species in Kenya due to its high growth performance, adaptability to different culture conditions and high consumer acceptance (El-Sayed & Fitzsimmons 2023). However, the sustainability and cost of intensive tilapia production is heavily influenced by fishmeal component in aquafeed. Research has demonstrated that BSFL meal can replace a portion of fish meal in diets for various aquaculture species without adverse effects on growth or feed utilization (Fawole *et al.* 2021; Kirimi *et al.* 2021; Wachira *et al.* 2021). However, replacement levels may vary across species with high replacement rates leading to reduced palatability or nutrient imbalance. Full fat BSFL meal can partially replace fish meal at 25–50% in diets of Nile tilapia, with no significant differences in body weight gain (Li *et al.* 2020; Wachira *et al.* 2021; Munguti *et al.* 2023). However, information on optimal inclusion levels for defatted BSFL meal, long-term effects on growth and economic performance is limited. This study therefore aimed to evaluate the effects of partially and wholly replacing fish meal with defatted black soldier fly larvae meal on growth and economic performance of Nile tilapia.

2. MATERIALS AND METHODS

2.1. Study site

The experiment was conducted at the Sanitation Research Institute (SRI) of Meru University of Science and Technology (MUST), located in Meru County, Kenya. The site is approximately 1,660 meters above sea level, latitude 0°08′05″ N and longitude 37°42′30″ E (Figure 1). The region experiences warm, temperate climatic conditions, with ambient temperatures ranging from 12 to 28 °C and an annual mean rainfall of approximately 1,233 mm. The site provides a controlled environment suitable for BSFL production and aquaculture.

2.2. Black soldier fly larvae production and processing

Black soldier fly larvae (BSFL) were obtained from the MUST-SRI production site, where they were reared in plastic lined troughs inside a climate-controlled chamber at a temperature of 28–30 °C and a relative humidity of 60–70%, using fecal sludge and organic waste as substrates (Dortmans *et al.* 2017; Matheka *et al.* 2021). Once the prepupal stage was reached, indicated by a light to dark brown cuticle (Salam *et al.* 2022), the larvae were harvested using a 3 mm sieve, washed with

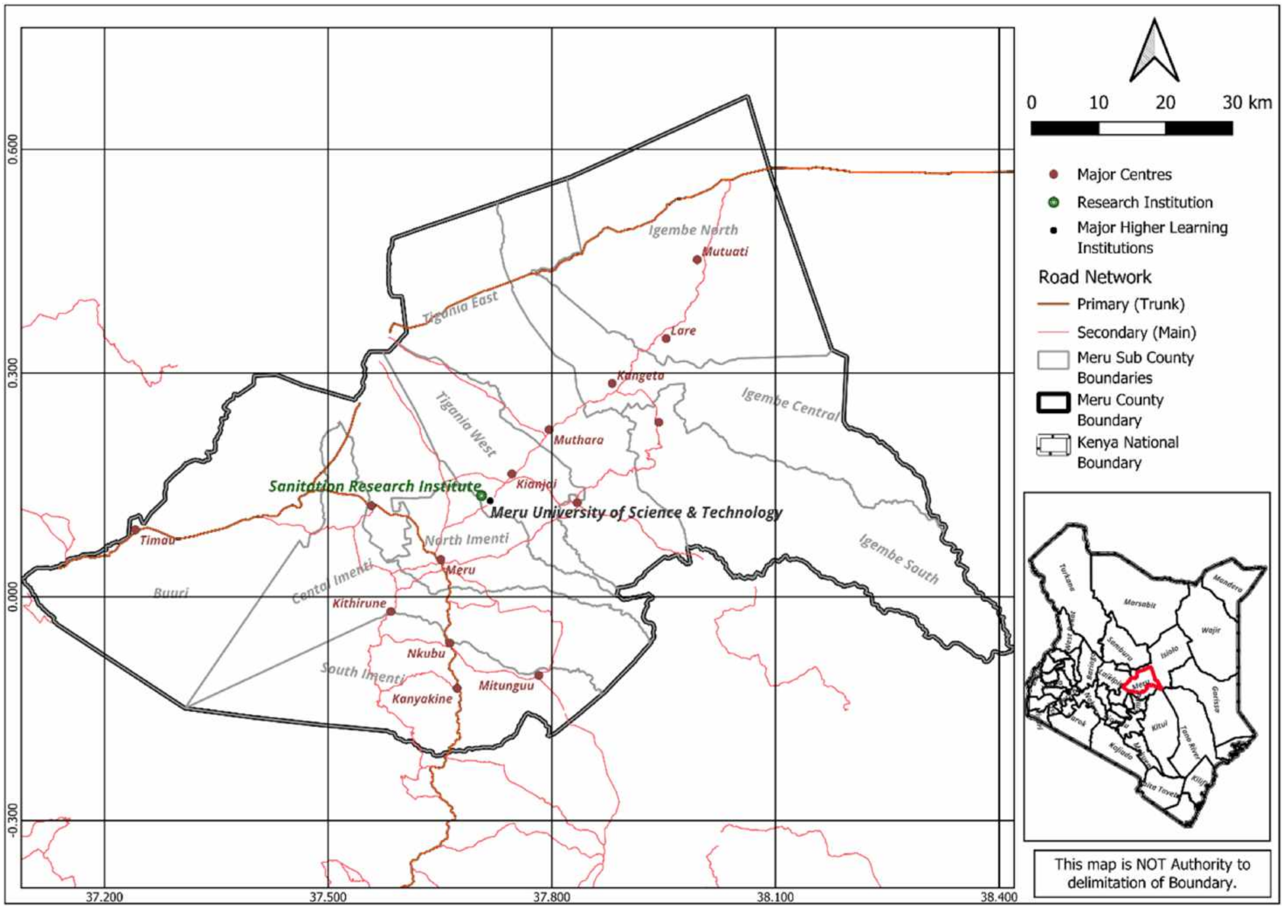


Figure 1 | A map showing the study area.

distilled water, sun dried for five days, and defatted using an electric oil press. Defatted BSFLM was tested using standard procedures for salmonella *spp* (ISO 6579-1), *Escherichia coli* (ISO 16649-2), lead and cadmium (EPA 6020A) and mercury (EPA 7473) prior to diet formulation (Gold *et al.* 2021; Jane *et al.* 2023).

2.3. Preparation of diets

The resulting BSFL meal (BSFLM) was used to formulate the diets. The ingredients FM, soybean, sunflower cake, wheat bran, wheat pollard meal and fish premix was procured from local feed dealers. Proximate composition of ingredients was done and results used as the basis for feed formulation using an excel spreadsheet. Three isonitrogenous diets (30% crude protein) were formulated such that BSFLM substituted FM at 0% (control, diet 1), 50% (diet 2) and 100% (diet 3) on a protein basis. Each diet feed mixture was grinded, thoroughly mixed and pelleted by adding little water. The resultant pellets were dried in a shaded environment and subsequently preserved in opaque, airtight containers throughout the duration of the experiment.

2.4. Proximate analyses of feed ingredients and experimental diets

The moisture, crude protein, crude fat, crude fibre and ash content were determined using the standard AOAC (1995) protocols. Moisture content was determined by drying the sample in an oven at 110 °C for 24 hours and measuring the water loss. Crude protein content was estimated using the Kjeldahl laboratory method. The fat content was determined using the Soxhlet method, which involved treating the sample with ether. The crude fiber content was determined by boiling the sample in 1.3% H_2SO4 and then in 1.3% NaOH.

2.5. Experimental set up

Nile tilapia fingerlings were obtained from the Desert Garden Fish Farm hatchery in Tharaka Nithi County-Kenya and acclimatized for four weeks in a hapa net within -liner pond, at SRI. During the acclimation period, the fish were fed on commercial floating feed twice daily (Kirimi *et al.* 2021; Ani *et al.* 2022). Using a completely randomized design (CRD), 270 Nile tilapia fingerlings with an average weight of 9.62 ± 0.22 g were randomly assigned to nine net hapas. Each hapa measured 2.0m × 1.0m × 1.0m and was stocked with 30 fish. Once the adaptation phase was complete, the fish's initial weight was recorded prior to the commencement of the feeding trials. The fingerlings were fed twice a day at 10:00 hours and 14:00, at 5% of their body weight. The feeding experiment was carried out over a period of 90 days.

2.6. Feeding and data collection

The fish were weighed and measured fortnightly to monitor the growth trends and adjust the feed. Growth response was determined based on parameters, such as daily weight gain (DWG), specific growth rate (SGR), relative growth rate (RGR), feed conversion ratio (FCR) and survival rate (SR), as detailed in Equations (1)–(5) (Abarike *et al.* 2012).

$$\mathrm{DWG}\ \% = \frac{(\mathrm{FBW} - \mathrm{IBW})}{(\mathrm{IBW} \times \mathrm{ED})} \times 100 \tag{1}$$

where DWG is the daily weight gain, FBW is the final body weight, IBW is the initial body weight and ED is the total experimental days.

$$\mathrm{SGR}\ \% = \frac{(\ln \mathrm{FBW(g)} - \ln \mathrm{IBW\ (g)})}{\mathrm{ED}} \times 100 \tag{2}$$

where SGR is the specific growth rate, FBW is the final body weight, IBW is the initial body weight, ED is the total experimental days and ln is the natural logarithm.

$$\mathrm{RGR}\ \% = \frac{(\mathrm{FABW\ (g)} - \mathrm{IABW(g)})}{\mathrm{FABW(g)}} \times 100 \tag{3}$$

where RGR is the relative growth rate, FABW is the final average body weight, IABW is the initial average body weight.

$$\mathrm{FCR} = \frac{\mathrm{FP(g)}}{\mathrm{WG(g)}} \times 100 \tag{4}$$

where FCR is the feed conversion ratio, FP is the feed provided, and WG is the weight gain.

$$\mathrm{SR}\ \% = \frac{\mathrm{FN}}{\mathrm{IN}} \times 100 \tag{5}$$

where SR is the survival rate, FN is the final number of fish, and IN is the initial number of fish.

2.7. Economic analysis

The economic efficiency of using BSFLM as a substitute for fish meal was established. Economic evaluations focused on calculating the economic conversion ratio (ECR), profit index (PI) and the economic profit index (EPI), as shown in Equations (6)–(8).

$$\mathrm{ECR} = \mathrm{CF} \times \mathrm{FCR} \tag{6}$$

where ECR is the economic conversion ratio, CF is the cost of feed, and FCR is the feed conversion ratio.

$$\mathrm{PI} = \frac{\mathrm{VF}}{\mathrm{CF}} \tag{7}$$

where PI is the profit index, VF is the value of fish, CF is the cost of feed.

$$EPI = [(WG \times SP\ ) - WG \times CF] \tag{8}$$

where EPI is the economic profit index, WG is the weight gain (g), SP is the selling price. CF cost of feed

Additionally, gross profit (GP) and return on investment (ROI) was calculated to further assess the financial performance of each diet as in Equations (9) and (10).

$$GP = TR - TCP \tag{9}$$

where GP is the gross profit, TR is the total revenue, TCP is the total cost of production

Ingredients prices in Kenya at the time of experiment were used to calculate feed cost based on the proportion included in each diet. Except for the cost of the feed, all other production and operating costs were considered to remain constant across all dietary treatments.

$$RoI = \frac{GP}{CP} \times 100 \tag{10}$$

where RoI is the return on investment, GP is the gross profit, CP is the cost of production.

2.8. Data analysis

Proximate, growth and economic analysis data were analyzed using the statistical package for social sciences (SPSS, version 27.0) software. One -way analysis of variance (ANOVA) was used to test for significant at $\alpha = 0.05$. Least significance difference (LSD) was used to separate means where differences occurred. The basic linear model for CRD was as in Equation (11)

$$Yij = \mu + ti + eij \tag{11}$$

where Y_{ij} is the j^{th} observation of the i^{th} treatment, μ is the population mean, ti is the effect due to the level of BSFLM (0, 50 and 100%), and e_{ij} is the random error term.

3. RESULTS

3.1. Microbial and heavy metal contamination for black soldier fry larvae meal

Results on microbial and heavy metal contamination is as shown in Table 2. There was no observable microbial growth in BSFLM. Heavy metals mercury, lead and cadmium levels were below detectable limits.

3.2. Growth performance and trends

The growth performance and trends of Nile tilapia fed diets with varying levels of fish meal replacement by BSFLM is depicted in Table 3 and Figure 2. Survival rates were consistently high across all dietary treatments, ranging from 83.33 to 95.56% ($p = 0.251$). Notably, fish fed diet 2 demonstrated the highest survival rate (95.56 ± 2.94%). Initial body weight for all the treatments were statistically similar ($p = 0.518$). Fish fed diet 1 had the highest final body weight (47.73 ± 1.80 g) but was not significantly different from Diet 2. Initially, all groups showed similar growth rates, but from sampling week 3 onwards, fish fed on Diet 3 gained weight more slowly. By sampling week 8, this group lagged by over 13 grams compared to the control Diet 1 (Figure 1). Fish fed on diet 1 exhibited the highest DWG (0.425 ± 0.021 g/day) while diet 3 showed the least growth rate (0.274 ± 0.011 g/day) ($p = 0.013$), although no significant difference was recorded in DWG between diet 1 and diet 2. Diet 1 recorded the highest FCR (1.80 ± 0.13) ($p = 0.010$), although the difference between diet 1 and diet 2 was not statistically significant.

3.3. Economic analysis

The economics of partially or complete substitution of FM with defatted BSFLM in Nile tilapia rations are represented in Table 4. The unit cost for preparing experimental diets and harvested biomass was progressively lowered as FM was replaced with BSFLM. ECR and ROI were not significantly different across diets ($p < 0\ .05$). The Profit Index (PI) was highest for diet 3 (0.53 ± 0.01) suggesting that complete substitution from fish meal led to the greatest positive profit for investment

Table 1 | Ingredients and proximate composition (%) of diets with black soldier fly larvae meal for Nile tilapia

Diets	D1 (0%)	D2 (50%)	D3 (100%)
Ingredients			
Black soldier fly larvae meal (defatted)	0.00	12.00	24.00
Fish meal *(Rastrionaebola argentea)*	22.00	11.00	0.00
Soyabean meal	23.00	23.00	23.00
Sunflower seed meal	9.00	9.00	9.00
Wheat bran	37.00	35.00	34.00
Wheat pollard	7.00	8.00	8.00
Fish premix	2.00	2.00	2.00
Total	100	100	100
Analysed proximate compositions (%)			
Dry matter	90.6 ± 0.18	90.85 ± 0.05	90.67 ± 0.08
Crude protein	30.48 ± 0.32	31.77 ± 0.12	30.93 ± 0.18
Crude fat	4.39 ± 0.01	5.26 ± 0.10	5.77 ± 0.10
Ash	10.16 ± 0.50	8.52 ± 0.11	6.57 ± 0.39
Crude fibre	10.49 ± 0.15	11.08 ± 0.10	13.39 ± 0.15

Diet code: D1, 0% black soldier fly larvae meal; D2, 50% black soldier fly larvae meal; D3, 100% black soldier fly larvae meal.

Table 2 | Microbial and heavy metal contamination in black soldier fry larvae meal

Parameter	Results	WHO limits
Microbial contaminants		
Staphylococcus aureus (cfu/swamb)	ND	absent
Total Coliforms (cfu/swamb)	ND	absent
E. Coli (cfu/g)	ND	absent
Heavy metal contaminants		
Mercury	ND	0.001 mg/L
Lead	ND	0.01 mg/L
Cadmium	ND	0.003 mg/L

Table 3 | Growth parameters of Nile tilapia fed diets with varying levels of defatted black soldier fly larvae meal

	Treatment			
Growth Parameters	D1	D2	D3	*p*-values
Initial mean weight (g)	9.43 ± 0.24^{a}	9.40 ± 0.26^{a}	9.84 ± 0.22^{a}	0.518
Final mean weight (g)	47.73 ± 1.80^{a}	42.98 ± 1.44^{b}	34.57 ± 0.86^{c}	0.015
Daily weight gain (DWG, g/day)	0.425 ± 0.02^{a}	0.375 ± 0.04^{ab}	0.274 ± 0.01^{b}	0.013
Specific growth rate (SGR, %)	1.80 ± 0.04^{a}	1.69 ± 0.09^{a}	1.39 ± 0.06^{b}	0.011
Relative growth rate (RGR, %)	80.17 ± 0.65^{a}	77.98 ± 1.65^{a}	71.43 ± 1.49^{b}	0.009
Survival rate (%)	83.33 ± 1.92^{a}	95.56 ± 2.94^{a}	87.78 ± 7.29^{a}	0.251
Feed conversion ratio (FCR)	1.11 ± 0.05^{a}	1.28 ± 0.12^{a}	1.80 ± 0.13^{b}	0.010

Note: Values are expressed as mean ± SE of triplicate samples: Values in the same row with different superscript letters show differences ($p < 0.05$).
Diet code: D1, 0% black soldier fly larvae meal; D2, 50% black soldier fly larvae meal; D3, 100% black soldier fly larvae meal.

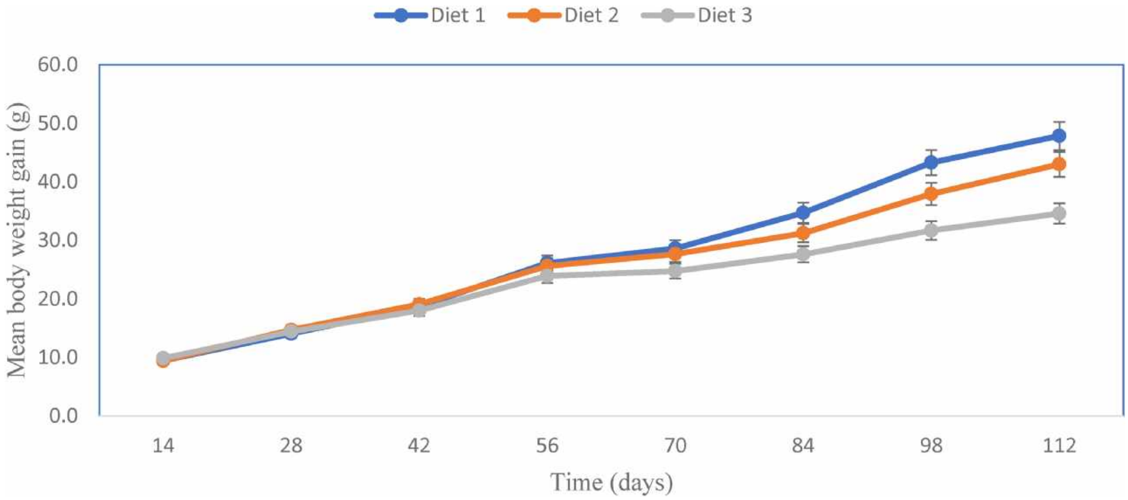


Figure 2 | Growth trends of Nile tilapia fed on black soldier fly larvae meal as a replacement of fishmeal.

Table 4 | Economic performance of Nile tilapia under different levels of black soldier fly larvae meal

Parameter	D1	D2	D3	*p*-values
Harvested biomass (Kg/Hapa)	1.43 ± 0.06^{a}	1.29 ± 0.09^{ab}	1.04 ± 0.02^{b}	0.0147
Cost of feed used (USD/kg)	1.01	0.84	0.68	
Total feed cost (USD)	1.20	1.04	0.62	
Selling price (USD/kg)	3.87 ± 0.00	3.87 ± 0.00	3.87 ± 0.00	
Economic conversion ratio	145.13 ± 6.08	139.16 ± 12.90	158.15 ± 11.66	0.479
Profit index (PI)	0.32 ± 0.00^{a}	0.39 ± 0.01^{b}	0.53 ± 0.01^{c}	0.000
Economic profit index (EPI)	424.00 ± 20.89^{a}	396.00 ± 37.43^{ab}	305.10 ± 12.61^{b}	0.040
Gross profit (USD)	3.15 ± 0.20^{a}	2.85 ± 0.38^{ab}	1.96 ± 0.15^{b}	0.042
Return on investment (ROI%)	245.57 ± 14.58	266.77 ± 38.07	219.09 ± 23.25	0.501

Note: Values are expressed as mean ± SE of triplicate samples: Values in the same row with different superscript letters show differences ($p < 0.05$).
Diet code: D1, 0% black soldier fly larvae meal; D2, 50% black soldier fly larvae meal; D3, 100% black soldier fly larvae meal.

according to feeding cost (the control), even though it produced less biomass. Gross Profit also significantly differed across diets ($p = 0.042$). However, diet 2 (USD 2.85 ± 0.38) did not significantly differ from either diet 1 or diet 3 thus remained competitive in the realm of economics.

4. DISCUSSION

4.1. Growth performance

In the present study, fish fed control diet (0% BSFLM) achieved the highest final weight gain followed closely by fish fed 50% BSFLM. The notable differences in final body weight among dietary groups may be attributed to the level of fish meal in the diets (Kirimi *et al.* 2023). In aqua feeds, fish meal is the most desirable animal protein ingredient due to its high protein content, balanced amino acid profile, high digestibility, palatability and $n-3$ polyenoic fatty acids. Hence probable reason for the high final body weight observed in control diet (diet 1). However, high costs and scarcity of fishmeal are the major limitations to its use (Kirimi *et al.* 2023; Munguti *et al.* 2023). Despite similar crude protein levels across the diets (Table 1), fish fed 100% BSFLM diet exhibited significantly reduced growth. This was likely due to nutritional deficiencies especially lysine and methionine because there was no fishmeal inclusion (Sayed 2018; Kirimi *et al.* 2020; Zulkifli *et al.* 2022; Agbohessou *et al.* 2024). Thus, reducing efficiency of protein deposition for growth. Also, black soldier fly larvae contain chitin in the exoskeleton and this could have translated into the 100% BSFLM diet. High levels of chitin reduce nutrient digestibility and absorption efficiency (Nairuti *et al.* 2021; Munguti *et al.* 2023). According to Agbohessou *et al.* (2024), black soldier fly larvae have lower levels of long-chain polyunsaturated fatty acids (PUFAs) such as Eicosapentaenoic acid (EPA) and Docosahexaenoic acid (DHA). Based on this, 100% inclusion of BSFLM (diet 3) could be deficient in long-chain polyunsaturated fatty acids (PUFAs) which are crucial for fish growth and health. Therefore, feed quality is a function of how well it meets the nutrients requirement of fish (Kirimi *et al.* 2023).

Moreso, diet 3 (100% BSFLM) had high crude fibre content (Table 1) of 13.39 ± 0.15% than the recommended (8–9%) (El-sayed & Fitzsimmons 2023). High crude fibre content could have accelerated gut transit time thereby reducing nutrient absorption (Munguti *et al.* 2025). Diet 1 exhibited higher ash content compared to the other diets (10.16 ± 0.50%). This is most likely due to the use of fish meal, which is naturally rich in minerals such as calcium and phosphorus (Nairuti *et al.* 2022). Adequate mineral availability supports skeletal growth, metabolic functions and overall performance. In the formulation of the diets, fish premix (vitamin and mineral) was added. Also, the fertilized liner pond offered fish extra nutrition i.e supply of limiting essential amino acids. However, these sources could not compensate for the deficient nutrients in 100% BSFLM (diet 3) that led to poor growth performance.

The present study results were in-line with study done by other researchers. There was decreased weight gain in Nile tilapia fed diets containing 100% black soldier fly larvae meal as substitute of fish meal (Ouko *et al.* 2024). Final body weight was similar when BSFLM substituted fishmeal at 50 and 100% in Nile tilapia diets (Nairuti *et al.* 2021; Shati *et al.* 2022; Munguti *et al.* 2023). Study done using African catfish (*Clarius gariepinus*) under aquaponic conditions exhibited optimal weight gain and feed utilization up to 50% black soldier fly larvae meal inclusion (Maranga *et al.* 2023). Beyond this level, fish growth was suppressed, likely due to reduced nutrient bioavailability. Replacing fish meal entirely with black soldier fly larvae meal in African catfish diets reduced both final body weight and specific growth rate hence need for nutrient balancing (Kyule *et al.* 2023).

Feed conversion ratio (FCR) reflects the efficiency with which fish convert feed into biomass. Thus, a lower FCR denotes more effective feed utilization, reducing both production costs and environmental impacts. In the present study, 100% BSFLM (diet 3) had highest FCR and this translated into poor growth performance observed. This was probably due to the high crude fibre content, reduced nutrients and low digestibility. High inclusion levels of black soldier fly larvae meal can increase FCR in fish due to elevated crude fiber and reduced protein retention (Agbohessou *et al.* 2024; Ouko *et al.* 2024).

4.2. Survival rate

The survival rates observed in the present study were high across all the treatments (>83%). This is an indication that despite low final weight gain observed in black soldier fly larvae meal-based diets, it had no negative effect on fish survival. High mortalities were recorded in week 3 post-sampling. This was likely attributed to stress during sampling. The highest survival rate (95.56%) was observed in diet 2 (50% BSFLM). It implies that BSFLM is a biologically safe protein for Nile tilapia. Black soldier fly larvae have bioactive components, such as lauric acid, antimicrobial peptides and chitin, that enhance immune responses and improve gut health (Koutsos *et al.* 2022; Rawski *et al.* 2025). Study by Tippayadara *et al.* (2021), Limbu *et al.* (2022) and Munguti *et al.* (2023) showed improved survival and immunity of tilapia fed diets containing black soldier fly larvae meal.

4.3. Economic analysis

The trends of decreased feed cost with increased BSFLM inclusion validated BSFLM as an economically viable lower value protein source. Diet 3 (100% BSFLM) had the least cost of feed compared to diet 1 and diet 2. The results of feed cost reduction are also echoed by other researchers. Limbu *et al.* (2022) showed feed cost advantages from inclusion of BSFLM in diets fed to tilapia. The economic conversion ratio (ECR) that calculates the cost to produce a unit of biomass, did not indicate significant differences between treatments. Diet 2 yielded the best ECR considering both cost and output. Vodounnou *et al.* (2025) similarly found diets with 50 and 60% BSFLM inclusion had similar or better ECR values than controls in Nile tilapia feeding trials. This concurs with other studies that partial inclusion reduces cost of production without adverse effects on growth performances. The profit index (PI), which describes the profit per unit cost of feed, was greatly impacted by the level of inclusion of BSFLM in the diet. While all diets with 100% BSFLM produced the highest profit index due to the low input costs, they had a large negative impact on the economic profit index (EPI) due to decreased biomass production. Agbohessou *et al.* (2024), also noted the trade-off between growth performance and economic viability. These findings are also consistent with the work of Ouko *et al.* (2024), who presented evidence that any diet with 100% BSFLM produced lower EPI compared to diets with some level of substitution of FM, which further confirms our findings that 100% FM replacement is not commercially viable at this time. Diet 2 generated a gross profit that was not significantly different from either diet 1 or diet 3, showing that partial replacements yield the best mix of cost reduction and biological output. This concurs with previous work by Maranga *et al.* (2023), who showed that 50% replacement of BSFLM in African catfish (*Clarias gariepinus)* diets had high economic benefits in aquaponic settings while still impacting biomass yields and growth. In tilapia, Nairuti *et al.* (2021) found that tilapia diets (50% BSFLM replacement) produced similar weight gain and economic returns as diets based on FM, although they produced substantial economic savings simply from reduced feed cost. The ROI revealed no significant differences across treatments, although diet 2 had the greatest ROI. This indicates that while the full replacement of FM (diet 3) increased the PI because of reduced cost inputs, the partial replacement (diet 2) demonstrated a better overall investment plan (Barwani *et al.* 2024; Mathai 2025). These results are consistent with study by Li *et al.* (2020); Munguti *et al.* (2023). That the maximum practical inclusions of BSFLM of 25–50% on a protein basis provide an environmentally sustainable and profitable aquaculture industry.

5. CONCLUSION

In summary, partial replacement (50%) of fish meal with defatted BSFLM can sustain or even enhance growth performance and survival in Nile tilapia. However, excessive replacement (as in diet 3) may negatively affect growth efficiency, suggesting the need to optimize inclusion levels for commercial application. Conversely, a 50% inclusion level emerges as an optimal point, balancing feed cost reduction, and maintaining competitive ECR, PI, gross profit, and ROI values. These outcomes position BSFLM as a sustainable and economically viable ingredient for aquaculture, particularly when used at moderate levels. Additionally, integrating BSFL meal into aquaculture diets aligns with circular economy principles by valorizing organic waste streams into high-quality proteins. This source of protein would reduce over reliance on the decreasing marine resources, and hence closing the nutrient loops within the food production system.

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ETHICS STATEMENT

The study protocol was reviewed and approved by Meru University of Science and Technology and granted permit by the National Commission for Science, Technology and Innovation (NACOSTI), Kenya, license number NACOSTI/P/25/4175541.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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