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Effect of replacing fish meal with black soldier fly larvae meal on growth performance and economic efficiency of Nile tilapia

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ABSTRACT

This study evaluated the effect of replacing fish meal (FM) with black soldier fly (*Hermatia illucens*) larvae meal (BSFLM) on growth performance and economic efficiency of Nile tilapia (*Oreochromis niloticus*) production. The BSFLM replaced FM at 0, 25, 50 and 75% (T1, T2, T3, and T4, respectively). One thousand two hundred (1,200) all-male Nile tilapia fry were stocked in twelve *hapas* at Kenya Marine and Fisheries Research Institute (KMFRI), Sangoro aquaculture research station in Kenya, and hand-fed four times daily for 21 weeks. Thirty (30) fish were sampled biweekly from each *hapa* for measurement of total length and weight. Findings indicated that diet T3 outperformed all the other diets in respect to final body weight (23.20 ± 1.15 g), daily weight gain (0.13 ± 0.02 g), final weight gain (23.09 ± 1.15 g), survival rate (96.74 ± 3.18 %), SGR (1.31 ± 0.03 % day^{-1}), FCR (1.57 ± 0.02), feed efficiency (0.64 ± 0.02), and condition factor (1.92 ± 0.01). The cost per kilogram of feed was highest for control diet (USD 0.91) and lowest for 75% BSFLM diet (USD 0.79). Economic Conversion Ratio (ECR) was lowest for the 50% BSFLM diet (1.26 ± 0.14) and highest for the control diet (1.44 ± 0.14). Economic Profit Index (EPI) was highest for the 50% BSFLM diet (141.82 ± 7.88) and lowest for the 25% BSFLM diet (106.64 ±6.63). The findings reveal that 50 to 75% BSFLM inclusion is an ideal replacement for FM in Nile tilapia diets, and is technically and economically efficient for Nile tilapia production.

1. Introduction

Aquaculture output has increased steadily over the last four decades, reaching 114.5 million tonnes globally, and the aquaculture market is expected to rise by 50% by 2030 (FAO, 2020). Aquaculture in most Sub-Saharan African (SSA) countries, including Kenya, is still dominated by extensive and semi-intensive practices, resulting in low production of fish and often falling short of the projected demand for human consumption (Béné et al., 2016). The survival and growth of fish are dependent on the quality of feeds used. Therefore, feeds have a significant impact on the sustainability of aquaculture (Jamabo et al., 2019). One of the most essential aspects in growth, feed utilization, and the flesh quality of fish in aquaculture is the formulation of high-quality fish feed (Ogueji et al., 2020).

Because majority of rural fish farmers earn less than a dollar per day, industrially prepared feeds are often expensive (Charo-Karisa et al., 2012). Feed price management is critical to the competitiveness and sustainability of aquaculture production since it accounts for more than half of the operational cost (Musa et al., 2021; Wachira et al., 2021). Because of its highly digestible protein, amino acids, and palatability, fishmeal is a prominent component of aquafeed (Li et al., 2017).

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However, increased demand and unpredictable fishmeal supplies have resulted in an increase in aquaculture production costs. Nile tilapia is the most popular fish species in Kenya since it exhibits fast growth rate and has a high consumer preference (Munguti et al., 2014; Musa et al., 2021). The vast majority of fish produced is either consumed by farming households or retailed. However, because of high feeding expenses, among other factors, Kenyan fish farmers have been unable to meet the species' huge market demand. Therefore, there is need to increase production of this highly sought-after farmed fish while utilizing low-cost feeds.

In recent years, research has promoted the use of insect meal (IM) as an alternative source of protein to replace conventional feed ingredients such as fishmeal (Abdel-Tawwab etbal., 2020; Shati et al., 2022; Zarantoniello 2019). The use of insect meal in aquafeeds has improved dramatically in the last decade, resulting in an increase in the quantity of scientific papers on this topic (Belghit et al., 2019; Chia et al., 2020; Li et al., 2020; Limbu et al., 2022; Shati et al., 2022). According to previous studies, insect-based protein meals can be used in aquaculture as a more sustainable alternative to conventional protein (fish or plant protein meals) (Henry et al., 2015; Gasco et al., 2016). Black soldier fly larvae meal (BSFLM) is one potential alternative insect-based aquafeed ingredient. The nutritional composition of BSFLM is mostly determined by the organic substrate's makeup (Liland et al., 2017). BSFLM constitutes 38.5–62.7% crude protein (CP), 14.0–39.2 % fat and 5282 kcal/kg of gross energy on dry matter (Liland et al., 2017). Thus, BSFLM meal is crucial in meeting the nutritional requirements of Nile tilapia which grows well when fed on quality feeds of between 28–40 % CP, depending on the stage of development (Henry et al., 2015).

In commercial aquaculture production, the most important influencing factor in terms of economic advantage is an organism's growth performance. Ingredient inclusion in feed formulation considers not only a balanced composition for best growth performance, but also economic factors such as profitability (Shati et al., 2022). Several studies have been conducted on the effect of replacing conventional protein sources in fish diets with BSFLM (Chia et al., 2019; Shati et al., 2022; Wachira et al., 2021). For instance, Wachira et al., (2021) studied the economic efficiency of BSFLM on Nile tilapia using Cost-benefit Analysis (CBA) and Return on Investment (ROI) indices. Shati et al., (2022) applied partial enterprise budget analysis to determine the economic implications of substituting soybean meal with BSFLM in Nile tilapia diets. Limbu et al., (2022) also used partial enterprise budget analysis to evaluate the cost-effectiveness of BSFLM diets in Nile tilapia production. However, little has been done on its ideal inclusion levels in Nile tilapia diet, considering its implication on economic efficiency. The current study sought to evaluate the effect of replacing fish meal (FM) with BSFLM on (a) growth performance, also referred to as technical efficiency, of Nile tilapia fed on different inclusion levels of BSFLM, and (b) the economic efficiency of BSFLM inclusion in tilapia diet using economic conversion ratio (ECR) and economic profit index (EPI) as the major indicators of economic efficiency. The primary goal is to develop cost-effective feeds with the optimum protein level in order to maximize aquaculture productivity and profitability.

2. Materials and Methods

2.1. Study area

The study was conducted at the Kenya Marine and Fisheries Research Institute's (KMFRI) Sangoro Aquaculture Research Station in Kisumu County, Kenya, at latitude 0° 21' 13" S and longitude 34° 45' 26" E. The trial lasted 21 weeks, from mid-January to early June 2021.

2.2. Source of feed ingredients and formulation of diets

Fish meal, soybean meal, sunflower cake, maize bran, wheat pollard, cassava meal, soybean oil, binder, vitamin premix and trace mineral premix were obtained from KMFRI Sangoro station fish feed processing plant, while sun dried BSFLM were obtained from a farmer in Korowe area of Kisumu County, Kenya. Grinding and combining the ingredients to uniform size was used to produce the experimental diets. Using Pearson's square method, four isonitrogenous diets were created. The protein element, BSFLM, was used to substitute FM produced from silver cyprinid (*Rastrineobola argentea*) at 0, 25, 50, and 75%, denoted as T1 (Control diet), T2, T3, and T4, respectively (Table 1). The control diet included FM as the primary protein source. The diets were designed to satisfy the optimum feeding requirements for tilapia fish. A 1% vitamin and mineral premix was added to the designed feed. The cost of the ingredients used in the formulation of each experimental diet at the time of the experiment was determined by market values at the period of the experiment, with dried BSFLM costing an average of 0.80 US Dollar (USD) (Mutisya et al., 2021). This study used full-fat black soldier fly larvae meal. According to Caimi et al., (2020), defatting may reduce the nutritional and functional value of insect meals due to the possibility of amino acid and antimicrobial protein (AMP) degradation at high temperatures and an increase in the meal's chitin content, which in excess may be considered an anti-nutritional factor that reduces nutrient digestibility. Moreover, by separating the fat, the favourable components of the fatty acid composition, such as the high levels of lauric acid content, are reduced in insect diets (Wang et al., 2019). Additionally, due to the significant energy consumption, labor costs, and additional expenses involved in the processes of fat extraction and protein purification, the use of insect meals can be less profitable and less environmentally sustainable (Liland et al., 2017).

Fifty grams of each formulated diet was taken for proximate analysis at the start of the study to determine their proximate composition. The Kenya Bureau of Standards (KEBS) laboratory in Nairobi, Kenya, performed proximate tests of the feed ingredients. Moisture, CP, fat, crude fibre, ash and nitrogen-free extract (NFE) content were determined using standard protocols (AOAC, 1990). The moisture content was determined by drying the sample in an oven at 103˚C for 20 hours and measuring the water loss. CP was estimated using Kjeldahl laboratory method. Fat content was determined by the Soxhlet method by treating the sample with ether. Crude fiber was determined by boiling the sample in 1.3% H_2SO_4 and then in 1.3% NaOH, and NFE was determined by subtracting the percentages of the other content from the total composition of 100%.

Table 1: Formulation (% dry weight), proximate composition (% dry matter) of experimental diets and cost of ingredients (USD/Kg)

Ingredient inclusion (%)	T1	T2	T3	T4	Cost USDkg^{-1}
BSFLM	0	12.28	22.57	30.16	0.80
Fish meal	36	26.25	16.5	6.5	1.59
Soybean meal	34	33.5	33.4	34	0.85
Sunflower cake	3.6	3.27	3.23	3.6	0.32
Maize bran	11	10.6	10.4	10.8	0.24
Wheat pollard	3	2.5	2.5	2.84	0.24
Cassava meal	8.8	8.4	8.2	8.5	0.30
Soybean oil	3.2	2.8	2.8	3.2	1.90
Binder	0.2	0.2	0.2	0.2	0.20
Vitamin premix	0.1	0.1	0.1	0.1	2.60
Trace mineral premix	0.1	0.1	0.1	0.1	4.00
Proximate composition (%)					
Moisture	1.13	1.06	1.09	1.10	
Crude protein	31.22	30.36	30.53	30.94	
Fat	6.48	6.17	6.23	6.38	
Crude fibre	7.19	7.21	7.35	7.59	
Ash	6.71	6.89	7.18	7.25	
Nitrogen-free extract (NFE)	47.27	48.31	47.62	46.74	

*Note: T1 = Control diet/0%, T2 = 25%, T3 = 50%, and T4 = 75% BSFLM replacement.

2.3. Source of fish, experimental set-up and feeding

A total of 1,200 sex-reversed Nile tilapia (initial average weight of 0.12 ± 0.02 g) fry were obtained from Apondo Fish Farm in Ahero, Kisumu County. Apondo Fish Farm is one of the authenticated fish hatcheries in Western Kenya by Kenya Fisheries Service (KeFS). Nile tilapia was selected for this research as it is highly suited to a variety of environmental situations and is disease resistant (Munguti et al., 2014). The fry were acclimatized and fed on a 35% CP KMFRI Sangoro formulated diet for two weeks.

Following acclimatization, the fingerlings were randomly selected and put into twelve *hapas* of sizes 2 m × 2 m × 1 m (4 m^3) suspended in earthen pond of size 15 × 20 (300 m^2), at a stocking rate of 100 fingerlings per *hapa*. Half a metre distance was maintained between the *hapas* within the earthen pond. The experimental design used in this study was a Completely Randomized Design (CRD) with four treatments in triplicates.

For 21 weeks, the fish were hand-fed to satiation four times a day by distributing feed around the periphery of each *hapa*. The number of fish remaining in each *hapa* was recorded and fresh feeding rates determined and adjusted based on the average weight of the sampled fish and the total number of fish remaining in each *hapa* after each sampling. The amount of feed was varied biweekly, at 8% body weight for the first 14 days, 5% body weight for the next 28 days and 3% body weight for the subsequent 105 days. The assumption was that the fish were feeding solely on the experimental diet administered in the *hapas*.

2.4. Measurement of water quality parameters

Water quality parameters such as dissolved oxygen (mgL-1) and pH, as well as temperature (°C), were monitored in-situ on a weekly basis using a multiparameter water quality meter, model H19828 (Hanna Instruments Ltd., Chicago, IL., USA), by immersing the probe into the surface of water (About 20 -25 cm). There was no aeration, but three quarters of water was pumped out of the pond biweekly and replaced with fresh water from the river. The average water quality parameters were within the range recommended for Nile tilapia (Table 2).

Table 2. Average measurements of water quality parameters during the period of the experiment

Parameter	Mean ± S.E
Alkalinity (mg/L)	184.06 ±10.81
Conductivity (µS/cm)	466.78 ± 11.32
D.O (mg/L)	6.65 ± 0.13
pH	7.33 ± 0.05
Temperature (˚C)	24.78 ± 0.64

2.5. Sampling and evaluation of growth performance

After every14 days, 30 representative fish were randomly picked from each experimental *hapa*. Wet weight (g) and length (cm) were determined using digital weighing scale (Mettler Toledo-AG204, Japan) with a readability of 0.01g and a fish measuring board to the nearest 0.01cm, respectively, to track growth performance. Following weight and length measurements, the fish were immediately released into their *hapas*. Each day, the amount of feed administered was also documented. Weight gain, specific growth rate (SGR), feed conversion ratio (FCR), feed efficiency (FE), and condition factor (K) for each treatment were used to analyze the impact of the respective diets on the growth performance of fish, also referred to as technical efficiency in the current study. The survival rate was calculated at the end of the experiment. The following formulas were used for the various parameters:

Mean Weight Gain (MWG)**=**
$$\text{Final mean weight } (W_1) - \text{ initial mean weight } (W_0)$$

Specific Growth Rate (SGR) =
$$\frac{[\ln(\text{final mean weight}) - \ln(\text{initial mean weight})]}{\text{time in days}} \text{ x } 100$$

$$\text{Survival rate (\%)} = \frac{\text{Number of fish at the end of the experiment}}{\text{Number of fish at the beginning of the experiment}} \times 100$$

$$\text{Feed Conversion Ratio (FCR)} = \frac{\text{Average feed intake (g)}}{\text{Mean weight gain (g)}}$$

$$\text{Feed efficiency (FE)} = \frac{\textit{Live weight gain by fish} \text{ (g)}}{\textit{Total feed fed} \text{ (g)}}$$

$$\text{Condition factor (K)} = \frac{W}{L^b}$$

where W = the total weight of fish (g) and L = the total length of fish (cm) and b = the value obtained from the length-weight equation.

The length-weight relationship of the fish was estimated by a linear regression analysis using the equation:

$W = aL^b$

To calculate parameters ‘a’ and ‘b’, the equation was log-transformed into:

Log W = Log (a) + b Log (TL)

where W = weight of fish (g), L is total length of fish (cm), a is the intercept, and b is the slope of the relationship (Le Cren, 1951).

2.6. Economic analysis

To establish the cost effectiveness and economic efficiency of using BSFLM as a fishmeal substitute, an economic study was undertaken. The economic analysis was conducted to assess the cost of feed required to raise one kilogram of BSFLM-fed fish cultured under controlled conditions. Economic evaluations in this study included calculating the economic conversion ratio (ECR) and the economic profit index (EPI), following the procedure of El-Saidy & Gaber (2003). The higher the EPI, the more economically efficient or profitable the feed.

The economic conversion ratio (ECR) and economic profit index (EPI) were calculated using the following equations respectively:

$$\text{ECR (USD per Kg of fish)} = CF\ X\ FCR$$

$$\text{EPI(USD per fish)} = (WG\ X\ SP) - (WG\ X\ CF)$$

where CF is the cost (USD) per Kg of feed, WG is the weight gain (g), and SP is the selling price (USD). Feed costs were determined using ingredient prices and the amounts of each item used in the dietary regimens. Given that the price of feed is determined by the make-up of the BSFLM meals, we computed the cost of feed necessary to create 1kg of feed. Except for the cost of the feed, all other production and operating costs were considered to remain constant across all dietary treatments. This study is based on the production cost theory, which assumes that aquaculture farmers are rational and aim to maximize profits at the lowest possible cost. The study adopted the single input-single output production function as in equation:

$$Y = f(X_1 / X_2, X_3 \ldots X_n)$$

where Y is the fish biomass harvested in Kg during the production cycle,
X_1 is the feed (variable input) used in fish production
X_2-X_n are the fixed inputs in fish production

Fish from each dietary treatment were collected and valued at USD 3 per Kg, the prevailing market price for 1 Kg of fresh unprocessed Nile tilapia (Musa et al., 2021).
The statistical analyses were performed using SPSS Version 25. The data was examined for normality after transformation. The Shapiro-Wilk and Levene tests were employed to determine normality and uniformity of variance. The effects of the experimental diets on growth performance metrics were calculated using one-way ANOVA and Tukey's post hoc test. Pearson's correlation was used to assess the relationship between the measured data. The results were presented as Mean ± SE. A statistical significance at $p < 0.05$ was used for all the relationships tested.

3. Results

3.1. Growth performance, survival and condition factor

Table 3 presents a summary of the growth performance metrics. The initial mean body weight ranged from 0.10 – 0.15 g whilst the final mean body weight was from 20.41 – 23.20g. In respect to final body weight (23.20 ± 1.15 g), daily weight gain (0.13 ± 0.02 g), weight gain (23.09 ± 1.15 g), survival rate (96.74 ± 3.18 %), SGR (1.31 ± 0.03 % day^{-1})), FCR (1.57 ± 0.02), feed efficiency (0.64 ± 0.02), and condition factor (1.92 ± 0.01), T3 outperformed all other treatments, with no significant differences in initial mean body weight, FCR and FE among the treatments ($p > 0.05$). All growth indices were lower in the diet T2.

Table 3. Summary of the growth performance parameters of Nile tilapia fed on diets with different inclusion levels of BSFLM

Growth Parameters	Diets			
	T1	T2	T3	T4
Initial weight (g)	0.10 ± 0.01^a	0.12 ± 0.02^a	0.11 ± 0.01^a	0.11 ± 0.08^a
Final weight (g)	21.75 ± 0.64^a	20.41 ± 0.49^b	23.20 ± 1.05^c	21.60 ± 0.40^a
Weight gain (g)	21.65 ± 0.64^a	20.30 ± 1.48^b	23.09 ± 1.15^c	21.49 ± 0.11^a
Daily weight gain (g)	0.12 ± 0.02^a	0.11 ± 0.01^a	0.13 ± 0.02^a	0.12 ± 0.01^a
SGR (% day^{-1})	1.23 ± 0.01^a	1.14 ± 0.02^b	1.31 ± 0.03^c	1.21 ± 0.02^a
FCR	1.58 ± 0.01^a	1.62 ± 0.02^a	1.57 ± 0.02^a	1.60 ± 0.01^a
Feed efficiency	0.64 ± 0.01^a	0.62 ± 0.01^a	0.64 ± 0.02^a	0.63 ± 0.01^a
Survival (%)	96.61 ± 1.32^a	93.83 ± 2.86^b	96.74 ± 3.18^a	95.65 ± 1.57^c
Condition factor (K)	1.76 ± 0.02^a	1.73 ± 0.01^b	1.92 ± 0.01^c	1.84 ± 0.01^d

*Note: T1 = Control diet/0%, T2 = 25%, T3 = 50%, and T4 = 75% BSFLM replacement. SGR = specific growth rate, FCR = feed conversion ratio. The values represent the mean ± standard error. A shared superscript in the same row indicates that the values were not statistically significant. Non-identical superscripts imply statistical differences ($p < 0.05$). n =90

Figure 1 depicts a graphical representation of the growth pattern of *O. niloticus* under various feed regimens. For the first ten weeks, Nile tilapia grew gradually. From week 12 to week 20, growth accelerated. There were no statistical changes in growth trends across the experimental diets over the entire study period ($p > 0.05$). T3 did, however, demonstrate somewhat greater growth rates starting at week 14, which was not substantially different from the other diets.

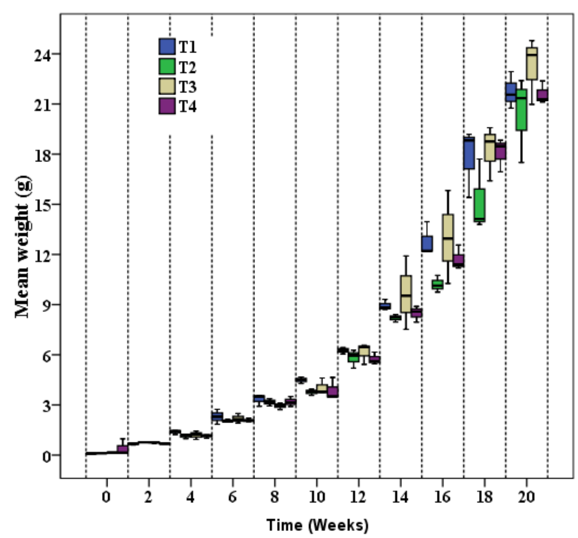

Figure 1. Box plots depicting the growth pattern of Nile tilapia fed on the different experimental diets

Note: T1 represents the control diet, T2, T3, and T4 indicate the substitution of FM with 25%, 50%, and 75% BSFLM meal, respectively. Vertical bars represent the three replicates' mean ± standard deviation.

3.2. Length-weight relationship

Figure 2 depicts the findings of the linear regression of log body weight on log total length for Nile tilapia fed on the varied diets. All the treatments (T1, T2, T3 and T4) had high and positive R^2 values (0.990, 0.985, 0.992 and 0.991, respectively). Additionally, the regression analysis revealed positive 'b' values (2.77, 2.89, 3.11 and 2.87) for T1, T2, T3 and T4 respectively, depicting a positive allometric growth for all the treatments.

3.3. Economic Efficiency

The economic analyses results are presented in Table 4. The unit price of formulation of the diet rations decreased gradually as FM was substituted with BSFLM. The cost per kilogram of feed was highest for fish fed on diet T1 (USD 0.91) and lowest for fish fed on diet T4 (USD 0.79), an equivalent of 13.83% cost reduction. Using diet T3 would result in a cost reduction of 8.94% in comparison to the control diet, T1. During the production cycle, the average biomass harvested was highest for fish fed diet T3 (0.0232 kg) and lowest for fish fed diet T2 (0.0204 kg). The ECR was lowest for diet T3 (1.26 ± 0.14) and highest in diet T1 (1.44 ± 0.14). The ECR followed the decreasing trend as cost per kilogram of feeds, with T1 having the highest ECR and T4 having the lowest ECR. EPI was highest for fish fed on diet T3 (141.82 ± 7.88) and lowest for fish fed on diet T2 (106.64 ±6.63).

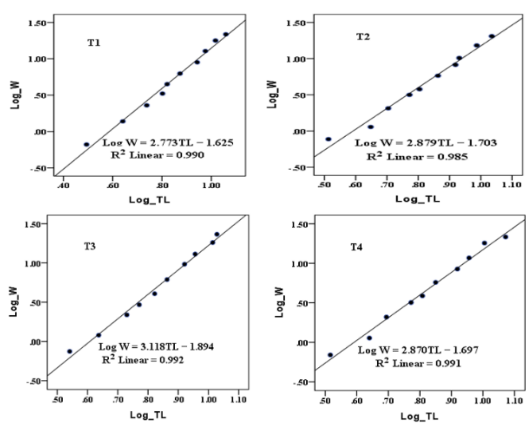

Figure 2. Logarithmic length-weight relationship with regression equation of Nile tilapia fed on the different experimental diets
Note: T1 represents the control diet, T2, T3, and T4 indicate the substitution of FM with 25%, 50%, and 75% BSFLM meal, respectively.

Table 4. Economic analyses result of Nile tilapia fed on the different experimental diets

Parameter	T1	T2	T3	T4
Production period (days)	147	147	147	147
Stocking density (pieces)	100	100	100	100
Average yield of fish (Kg)	0.02175	0.02041	0.02324	0.0216
Value of fish produced/SP (USD)	6.525	6.123	6.972	6.48
Total feed Input (kg)	34	32.9	36.2	34.3
Cost of feed used (USD/Kg)	0.91	0.87	0.83	0.79
Total cost of feed (USD)	30.94	28.62	30.05	27.10
ECR	1.44 ± 0.14[a]	1.41 ± 0.08[b]	1.30 ± 0.12[c]	1.26 ± 0.14[d]
EPI	121.57 ± 7.14[a]	106.64 ±6.63[b]	141.82 ± 7.88[c]	122.28 ± 7.51[d]

*Note: T1 = Control diet/0%, T2 = 25%, T3 = 50%, and T4 = 75% BSFLM replacement. SP = Selling price at USD 3 per Kg. ECR = economic conversion ratio, EPI = economic profit index. The values represent the mean ± standard error. A shared superscript in the same row indicates that the measurements were not statistically significant. Non-identical superscripts imply statistical differences ($p < 0.05$)

4. Discussion

The provision of sufficient and cost-effective fish feed is generally critical to the success of any aquaculture operation. Therefore, producing a more sustainable aquaculture feed will rely on identifying and producing high nutritional novel feed ingredients (Tippayadara et al., 2021). Currently, the aquaculture industry has placed a lot of focus on the feeding strategies that can achieve optimum Nile tilapia growth as an affordable and nutritious source of animal protein. Previous research has identified BSFLM diet as a viable source of protein in fish feeds (Chia et al., 2019; Musita et al., 2016; Tippayadara et al., 2021).

The current study findings show fish fed on 50% BSFLM meal had growth parameters which were significantly different from the other treatments in terms of weight gain, SGR and condition factor. The survival rates were high, showing that the BSFLM did not negatively affect fish survival. Most of the mortalities were observed a day after sampling which could be due to stress posed during length-weight measurements. This implies that the diets offered comparable nutrients to the fish. Higher than 50% BSFLM inclusion level reduced fish growth performance due to reduced palatability. Kroeckel et al., (2012) observed that fish diets with fishmeal replaced with other protein sources have lower palatability, especially if the replacer diet contains anti-nutritional elements. Other ingredients such as soybean meal used in feed formulation have been reported to progressively repress fish growth performance owing to the presence of anti-nutritional factors (Liland et al., 2017). In addition, previous studies have indicated that mono-sex tilapia fed on 50% BSFLM meal replacing fishmeal (FM) show a significant difference in growth performance when compared to conventional diets (Chia et al., 2019; Shati et al., 2022). The daily weight gain and FE, however, were not significantly different among the treatments. These findings are consistent with those of Tippayadara et al., (2021), who found that including 50% BSFLM meal as a replacement for fish meal had no influence on Nile tilapia weight gain and FE.

FCR is a crucial assessment of fish diet quality, with a lower FCR suggesting higher feed utilization. FCR results from Nile tilapia studies appear to be affected by growth stage, feed form, and culture system (Shati et al., 2022). The measured nutrient utilization indices such as FCR and FE were higher in 50% BSFLM replacement with no significant difference with the control diet. In fish farming, measuring FE implies measuring feed intake (Verdalab et al., 2017). FE is the inverse of FCR. Improving FE means reducing feed consumption per kg of fish produced or increasing fish production from the same amount of feed which reflects the technical efficiency of the diet. Improving feed efficiency is therefore key to reducing production costs. The higher the FE, the higher the technical efficiency of a diet. The FCR is also an important indicator of quality of fish feed, a lower FCR indicating better utilization of the fish feed. Thus, 50% replacement was the most technically efficient diet. Lower FCR in the 50% BSFLM replacement indicates greater feed consumption for tissue synthesis and metabolic processes. The same nutrient consumption across diets suggests that BSFLM meal can actually replace FM. These results were similar to those reported in the culture of tilapia (Tippayadara et al., 2021), Rainbow trout (*Oncorhynchus mykiss*) (Dumas et al., 2018), Atlantic salmon (*Salmo salar*) (Fisher et al., 2020), Japanese seabass (*Lateolabrax japonicas*) (Wang et al., 2019), Zebrafish (*Danio rerio*) (Zarantoniello et al., 2019), and European sea bass (*Dicentrarchus labrax*) (Abdel-Tawwab et al., 2020).

The absence of statistical differences in some growth and nutrient utilization indices among the diets could be explained by the high crude fibre content in insects due to their exoskeleton that has content of chitin, a complex carbohydrate which can be poorly digested by the Nile tilapia fry (Fontes et al., 2019), resulting to slow growth rates especially with higher than 50% BSFLM inclusion level. The quality of CP is also an important factor that can affect feed utilization. Even though all the diets were isonitrogenous, decreasing fish meal and increasing the BSFLM meal can reduce the quality of dietary protein. Although the amino acid profile of the components in this study was not examined, Mjoun et al., (2010) stated that the protein quality in fish diets is a function of the proper balance of essential amino acids.

From the growth performance results, 50% BSFLM was the optimal inclusion level and therefore the most technically efficient based on the FE ratio. The optimal BSFLM inclusion in the current study was lower as compared to previous study's findings in Japanese seabass (*L. japonicus*) (64%) (Wang et al., 2019), but higher than in rice field eel (*Monopterus albus*) (15.78%) (Hu et al. 2020), hybrid tilapia (Nile × Mozambique) (30%) (Yildirim-Aksoy et al., 2020), and Atlantic salmon (12.5%) (Weththasinghe et al., 2021).However, the most technically efficient diet may not necessarily be the most profitable diet, as input and output prices have to be considered. Thus, technical efficiency is a necessary condition and not a sufficient condition, which calls for economic efficiency analysis to meet the sufficient condition in identifying the most optimal diet.

In terms of economic efficiency, up to 50% of FM protein in tilapia diets can be replaced with BSFLM without impacting growth performance, feed utilization, or economic efficiency. Thus, replacing FM with BSFLM is economically viable. As BSFLM quantity increased in the diet, the price of developing current Nile tilapia diets decreased. Previous studies have also reported a reduction in the cost of feed when insect based feeds was used to replace FM in diets of Nile tilapia (Shati et al., 2022; Wachira et al., 2021). Because EPI is a better tool for measuring economic viability as it takes into account output, feed expenses, and retail value (Musita et al., 2016), our findings show that substituting 50% of FM protein with BSFLM offers a higher economic return. This is also reflected by the sufficient ECR value implying that BSFLM based diets are economically efficient, findings that are consistent with Musita et al., (2016) and Shati et al., (2022).

5. Conclusion

The study revealed that a 50% BSFLM inclusion level can replace FM in practical Nile tilapia diets under the experimental conditions employed without any adverse effects on growth performance, reflecting higher technical efficiency. The economic efficiency analysis indicated that BSFLM diets were cheaper than FM diets, with a cost savings of 13.83% in 75% BSFLM inclusion in comparison to 0% BSFLM inclusion. Diets containing elevated inclusion levels of BSFLM were therefore economically better. This is because the cost of FM was almost twice the cost of BSFLM per Kg. Overall, the present study suggests that insect protein derived from BSFLM could be an option to improve the economic viability of Nile tilapia feed formulations, with a cost reduction of 8.94% for optimal output. Thus, 50% to 75% of BSFLM can be used to replace FM protein in diets of Nile tilapia without compromising growth performance, feed utilization, and economic efficiency. Cognizant of the fact that the current market price of FM is high and very competitive due to its scarcity and regular bans following overfishing in Kenya, substitution with BSFLM would significantly lower the cost of aquafeed production for tilapia with well-balanced nutrient composition.

5.1. Ethical Approval

The authors confirm that the ethical policies of the journal as noted in the journal's author guideline page, have been adhered to. This project was submitted and approved by Jaramogi Oginga Odinga University of Science and Technology (JOOUST) Ethics Review Committee, protocol no ERC/ 28/10/20-12 and National Commission for Science, Technology & Innovation (NACOSTI) of the Republic of Kenya license number NACOSTI/P/20/8040.

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5.3. Author contribution

KOO: Conceptualization, Investigation, Writing - original draft and Formal Analysis; JBM: Formal Analysis, Investigation and Writing -original draft; AWM: Supervision, Methodology; KOO: Supervision, Methodology and Writing –review and editing; EOO: Visualization and Writing -review and editing; JMM: Visualization, Methodology and Writing -review and editing; and CMT: Writing -review and editing.

5.4. Conflict of interest

The authors declare no conflict of interest.

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