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Research Paper

Growth performance and carcass characteristics of broiler chicken fed on black soldier fly larvae meal: a product of fecal sludge waste management

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ABSTRACT

Rearing black soldier fly is an efficient way to dispose of organic waste by converting them into protein-rich feed to substitute animal- and plant-based sources in animal feeds. The objective of this study was to determine the optimal inclusion level of black soldier fly larvae meal (BSFLM) as a substitute for soybean meal (SBM) in broiler diets and evaluate the impact on growth and carcass characteristics. Five isonitrogenous diets (D) (20% crude protein, CP) and isocaloric (3,200 Kcal/kg) were formulated such that BSFLM substituted SBM at 0% (control, D1), 25% (D2), 50% (D3), 75% (D4), and 100% (D5) on a protein basis. A total of 270 broilers (Cobb 500) were randomly assigned to the five treatments in triplicate per diet. BSFLM displayed higher fat content (44.84 $\pm$ 0.08%). Average daily feed intake (ADFI) decreased with an increase in BSFLM in the diets ($p = 0.004$). However, overall weight (OW) was high (1,296.97 $\pm$ 46.19 g) on 100% substitution of SBM with BSFLM (D5). Breast fat content averaged 6.06 $\pm$ 0.97 g for D1 and 15.30 $\pm$ 0.5 g for D5. This study has demonstrated that BSFLM can partially or wholly replace conventional SBM in the diet of broiler chicken.

Key words: black soldier fly, broiler chicken, fecal sludge, growth performance, waste management

HIGHLIGHTS

- Black soldier fly converts organic waste into protein-rich feed for animals.
- Black soldier fly larvae meal diets provided better growth for broiler chicken.
- Carcass characteristics significantly improved on birds fed with black soldier fly larvae meal.

INTRODUCTION

In developing countries, effective and sustainable fecal sludge management poses a sanitation challenge. The application of conventional sewer-based approaches has been limited by the high capital and maintenance requirements. Thus, onsite systems (such as pit latrines and septic tanks) have been widely adopted by 2.7 billion people globally (Strande 2014; Riungu 2021). However, safe collection, transportation, and treatment of the fecal sludge generated from onsite systems are not always guaranteed, and fecal waste is dumped in river bodies, open drains and streets, compromising public health (Lalander *et al.* 2013; Mberu *et al.* 2016).

Recent technological advances have seen the development of cost-effective technologies, such as urine-diverting dry toilets (UDDTs), pee poo bags, pour flush toilets connected to septic tanks (Strande 2014). Several effective, sustainable, and environmentally friendly management technologies have been proposed to manage the waste generated from these systems: biogas, composting, vemi-composting, black soldier fly (BSF), struvite precipitation, etc. (Strande 2014). These technologies have adopted the circular economy model which promotes the conversion of waste generated into valuable resources, i.e. nutrients available in waste are harnessed and thereafter put back in the matter cycle (Riungu 2021).

Rearing BSF (*Hermetia illucens*) technology is an efficient way to dispose of organic waste by converting it into protein- and fat-rich feed (Van Huis *et al.* 2013; Makkar *et al.* 2014; Wallace *et al.* 2017; Danieli *et al.* 2019). In waste management, using BSF larvae has shown a reduction in weight of between 25–55% and 66–70% of total fresh fecal wastes and domestic wastes, respectively (Diener *et al.* 2009; Banks *et al.* 2014). Also, BSF larvae effectively destroy pathogenic microbes found in human or animal fecal wastes (Banks *et al.* 2014). The BSF larvae can then be used to produce black soldier fly larvae meal (BSFLM). The meal can be used as an ingredient in livestock diets because of its high crude protein and lipid content. The BSFLM contains consistent essential amino acids and fatty acids when grown in diverse substrates (Rumpold & Schluter 2013; Spranghers *et al.* 2017; Gasco *et al.* 2018).

In the poultry industry, feed represents 60–70% of production costs where energy and amino acids account for more than 90% of this cost (Kiarie *et al.* 2013; Van Huis *et al.* 2013). The high cost of poultry feed is mainly due to the use of soybean meal (SBM). SBM is a plant-based source of protein and fat in poultry feed but it is scarce and expensive. In terms of nutrients, SBM is limited in sulfur amino acids (methionine and cystine) and contains trypsin inhibitor that hinders the activity of the proteolytic enzyme's trypsin and chymotrypsin in monogastric animals. This results in low protein digestibility (Liu 1997). In contrast, BSF larvae are cheap, easy to rear using domestic organic waste, and can provide high-value protein with a better amino acid profile compared with that of SBM (Tran *et al.* 2015). Studies have indicated that BSFLM can replace SBM in broiler diets to some extent. Onsongo *et al.* (2018) fed 11.0, 37.2, and 55.5% of the crude protein in the finisher feed of diets to broilers and concluded that replacement of SBM with BSFLM did not affect daily body weight gain and feed conversion ratio (FCR). Similarly, Popova *et al.* (2020) fed diets containing 5% full fat and partially defatted BSFLM and found that there was increased body weight gain. However, there was a significant effect on the carcass characteristics. Few studies have examined optimal inclusion levels of BSFLM when replacing SBM in broiler diets. This study, therefore, evaluated the growth performance and carcass characteristics of broiler chicks fed on diets containing BSFLM as a substitute for SBM at the finisher phase.

MATERIALS AND METHODS

Study site

The experiment was conducted at Meru University of Science and Technology, Kenya – Sanitation Research Institute.

Preparation of diets

All feed ingredients (Table 1) were obtained from local reputable animal feed dealers. However, black soldier fly larvae were reared at Meru University of Science and Technology – Sanitation Research Institute using fecal matter as the feed substrate. The larvae were harvested and sundried for 14 days. The dried larvae were then ground into powder. To ensure that the processed larvae were safe for incorporation into animal feed, microbial load (*Salmonella* and *Escherichia coli*) was analyzed by culturing the BSFLM powder on nutrient agar and MacConkey agar. No growth was seen on the media after incubation at 37 °C for 24 h. This was indicative of the unique role of BSF larvae on pathogen inactivation (Lalander *et al.* 2013). Helminths and protozoans were analyzed using light microscopy. Physicochemical properties including human toxins as well as ecotoxins were obtained by analysing the BSFL powder sample using ultraviolet–visible spectrophotometry. The powder was then mixed with other raw materials to formulate five isonitrogenous diets (20% CP) and isocaloric (3,200 Kcal/kg metabolizable energy) such that BSFLM substituted SBM at 0% (D1) – control; 25% (D2); 50% (D3); 75% (D4); and 100% (D5) on crude protein basis (Table 1). The feed was formulated to meet the nutrient requirements for broiler finishers (National Research Council 1994).

Analysis of samples

The proximate analysis of ingredients and diets was carried out as described by the AOAC (1990). Dry matter was calculated by the weight difference between before and after drying the sample in the oven at 135 °C for 2 h. The crude protein was determined using the Kjeldahl method. Ash was determined by heating the samples in a muffle furnace set at 550 °C for 4 h. Ether extracts were carried out through the Soxhlet extraction method. Nitrogen-free extracts (NFEs) were estimated by subtracting the total moisture, crude protein, ether extracts, ash, and crude fiber from 100. Neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL) were determined sequentially by the method of Van Soest *et al.* (1991).

Growth performance trial

In total, 270 ($n = 270$), 1-day-old broiler chicks (Cobb 500) were sourced from Kenchic Limited, Nairobi, Kenya. During the first 2 weeks, chicks were kept together in a brooder, which was a round deep litter floor covered with a thick layer of wood

Table 1 | Ingredient composition (%), calculated crude protein (%), and metabolizable energy (Kcal/kg) of diets for broiler finisher containing black soldier fly larvae meal as a replacement of soybean meal

Ingredient	D1 (0%)	D2 (25%)	D3 (50%)	D4 (75%)	D5 (100%)
Soybean meal	20	15	10	5	0
Black soldier fly larvae meal	0	6.25	12.50	18.75	25
Fishmeal	5	5	5	5	5
Sunflower meal	4	5	5	5	5
Maize germ	14	16	15	14	15
Maize meal	37	34	34	34	32
Wheat pollard	17	16	16	16	15
Dicalcium phosphate	1.3	1.3	1.3	1.3	1.3
Sodium chloride	0.25	0.25	0.25	0.25	0.25
Limestone	0.8	0.8	0.8	0.8	0.8
Methionine	0.05	0.05	0.05	0.05	0.05
Lysine	0.4	0.4	0.4	0.4	0.4
Broiler premix	0.25	0.25	0.25	0.25	0.25
Mycotoxin binder	0.1	0.1	0.1	0.1	0.1
Salinomycin	0.03	0.03	0.03	0.03	0.03
Total	100.18	100.43	100.68	100.93	100.18
Crude protein (%)	19.62	19.58	20.15	19.37	20.82
ME (Kcal/kg)	3,008.44	3,129.70	3,254.82	3,379.33	3,507.37

Diet code: D1, 0%BSFLM +100%SBM; D2, 25% BSFLM +75% SBM; D3, 50% BSFLM +50% SBM; D4, 75% BSFLM +25% SBM; D5, 100% BSFLM +0% SBM.
BSFLM, black soldier fly larvae meal; SBM, soybean meal; ME, metabolizable energy.

shavings bedding. The area was fitted with 250-W infra-red bulbs to provide heating during the brooding period. The birds were fed on commercial broiler starter ration from day 1 to 14. Using a completely randomized design (CRD), the birds were picked and transferred into 15 pen cages; each holding 18 chicks for the five dietary treatments. The initial weight of each bird per cage (replicate) was taken before the commencement of the experiment (day 14). Experimental diets were introduced from day 14 and continued to day 42. Birds had free access to food and water throughout the experiment. All containers were cleaned daily, and clean water was offered to the birds every morning. Average daily feed intake (ADFI), FCR, average daily weight gain (ADG), and overall weight (OW) were calculated. The final weight (FW) and number of dead birds during the entire experimental period were recorded. Average daily gain (ADG) was calculated as the difference between the final body weight at the end of the experiment and initial body weight recorded at the start of the experiment divided by the length of the experimental period in days, Equation (1). ADFI was calculated by Equation (2) where the feed consumed was divided by the total experimental days and the number of chicks. The FCR was calculated by dividing the ADFI by the ADG as shown in Equation (3). OW was calculated by summing up the FW for each treatment and dividing by the number of chicks, Equation (4).

$$\mathrm{ADG} = \frac{(\mathrm{FW} - \mathrm{IW})}{\mathrm{ED}} \tag{1}$$

where ADG is the average daily gain, FW is the final weight, IW is the initial weight and ED is the total experimental days.

$$\mathrm{ADFI} = \frac{(\mathrm{FC}/\mathrm{ED})}{\mathrm{NC}} \tag{2}$$

where ADFI is the average daily feed intake, FC is the feed consumed, ED is the total experimental days and NC is the total number of chicks.

$$FCR = \frac{ADFI}{ADG} \quad (3)$$

where FCR is the feed conversion ratio, ADFI is the average daily feed intake, and ADG is the average daily gain.

$$OW = \sum \frac{FW}{NC} \quad (4)$$

where OW is the overall weight, ΣFW is the summation of the final body weight for each treatment, and NC is the total number of chicks.

Evaluation of the carcass characteristics

At day 42, feed was withdrawn for 12 h but water was provided *ad libitum* in order to empty the digestive tracts. Fifteen birds were randomly selected from the five treatments (three birds from each diet type) and killed following the guidelines of animal welfare (Anderson 2005). Plucked and eviscerated carcasses were obtained after removing the head, neck, and feet. The spleen, liver, heart, gizzard (muscular stomach), and proventriculus (glandular stomach) weights were taken and recorded. The breast and thighs were then excised and weighed.

Data analysis

All data on laboratory analysis, growth performance, and carcass characteristics were subjected to one-way analysis of variance (ANOVA). Statistical Package for Social Science (SPSS) version 23.0 was used at $p = 0.05$ confidence level, to determine whether there were significant differences. Where the differences occurred, mean separation was done by least significance difference (LSD). The basic linear model for the CRD was as in Equation (5).

$$Y_{ij} = \mu + \alpha_i + e_{ij} \quad (5)$$

where Y_{ij} is the observation on the jth chick and ith treatment, μ is the overall population mean, α_i is the effect due to the level of BSFLM {0, 25, 50, 75, and 100%} and e_{ij} is the random error term.

RESULTS

Proximate composition of feed ingredients

The proximate nutrient composition of feed ingredients is shown in Table 2. The main protein ingredients were as follows: BSFLM had a crude protein content of 39.40%, SBM (protein content: 47.10%), sunflower meal (protein content: 20.12%), and fishmeal (*Rastrionaebola argentea*) (protein content: 61.96%) ($p < 0.05$). Lipid content for BSFLM was highest (44.84%) ($p = 0.000$). Ash content was relatively low for all the ingredients except fishmeal (15.79%) but significantly different among the ingredients ($p = 0.000$). The crude fiber was high for wheat pollard (44.50%), sunflower meal (44.38%), and BSFLM (23.08%).

Proximate composition of diets

The proximate composition of the diets containing BSFLM as a replacement for SBM at 0, 25, 50, 75, and 100% on a crude protein basis is shown in Table 3. Crude protein values for the diets ranged between 18.42 and 20.45%. However, there were no significant effects between the treatments, $p = 0.143$. Ash content was highest (13.00%) for diet 1 and statistically different ($p < 0.05$) with D2, D3, D4, and D5. For crude fiber content, all the diets recorded almost similar figures ($p = 0.000$). Ether extracts increased with an increase in levels of BSFLM in the diets and D5 recorded the highest content (12.11%).

Performance of broiler chicks fed BSFLM-based diets

The effects of the replacement of SBM with BSFLM on broiler chicks' performance is shown in Table 4. The highest FW (2,262.26 g) was recorded in diet 5, whereas diet 1 recorded the lowest (2,102.43 g). OW showed a similar trend to that observed for FW. Average daily feed intake was high in diet 1 (144.04 g) and lowest in diet 5 (134.15 g). There was no

Table 2 | Proximate composition of feed ingredients (%) used to formulate broiler finisher diets

Ingredient	Blacksoldier fly larvae meal	Soybean meal	Fishmeal	Sunflower meal	Maize meal	Maize germ	Wheat pollard	*p*-value
Proximate composition (%)								
DM	93.19 ± 0.02^{ba}	88.50 ± 0.08^{f}	89.58 ± 0.42^{ed}	94.02 ± 0.53^{ab}	87.40 ± 0.30^{g}	89.58 ± 0.03^{dec}	90.48 ± 0.26^{cd}	0.000
CP	39.40 ± 1.19^{c}	47.10 ± 0.14^{b}	61.96 ± 0.65^{a}	20.12 ± 0.14^{d}	7.75 ± 0.25^{gf}	8.99 ± 0.14^{fg}	15.64 ± 0.17^{e}	0.000
EE	44.84 ± 0.08^{a}	4.21 ± 0.07^{efg}	10.42 ± 0.08^{c}	14.35 ± 0.12^{b}	4.08 ± 0.02^{feg}	9.52 ± 0.07^{d}	4.02 ± 0.04^{gef}	0.000
Ash	3.93 ± 0.05^{fde}	5.82 ± 0.12^{b}	15.79 ± 0.13^{a}	4.62 ± 0.26^{cde}	1.23 ± 0.10^{g}	4.25 ± 0.29^{dfce}	4.13 ± 0.20^{efcd}	0.000
CF	23.08 ± 0.03^{c}	13.55 ± 0.36^{d}	4.11 ± 0.35^{g}	44.38 ± 0.49^{ba}	5.74 ± 0.19^{f}	8.15 ± 0.21^{e}	44.50 ± 0.20^{ab}	0.000
NFE	18.04 ± 1.16^{de}	17.83 ± 0.62^{ed}	2.70 ± 0.07^{g}	10.55 ± 1.53^{f}	68.61 ± 0.12^{a}	58.67 ± 0.59^{b}	22.19 ± 0.05^{c}	0.000
NDF	39.20 ± 0.69^{c}	34.82 ± 0.03^{ef}	36.01 ± 0.21^{d}	49.81 ± 0.33^{a}	47.80 ± 0.06^{b}	34.23 ± 0.30^{fe}	29.65 ± 0.38^{g}	0.000
ADF	26.57 ± 0.17^{b}	4.33 ± 0.15^{c}	2.25 ± 0.02^{fge}	32.15 ± 0.18^{a}	1.64 ± 0.26^{gfe}	2.36 ± 0.09^{efgd}	3.01 ± 0.03^{de}	0.000
ADL	14.79 ± 0.06^{a}	3.81 ± 0.06^{c}	0.23 ± 0.06^{g}	13.95 ± 0.20^{b}	1.06 ± 0.07^{fde}	1.22 ± 0.04^{dfe}	1.09 ± 0.12^{efd}	0.000

Values are expressed as mean ± SE ($n = 3$). Values in the same row with different superscript letters show differences ($p < 0.05$).
ADF, acid detergent fiber; DM, dry matter; CF, crude fiber; CP, crude protein; EE, ether extract; NDF, neutral detergent fiber; NFE, nitrogen-free extracts.

Table 3 | Proximate composition of broiler finisher diets (%) containing the blacksoldier fly larvae meal as a replacement of the soybean meal at 0, 25, 50, 75, and 100% on CP basis

Diet	D1 (0%)	D2 (25%)	D3 (50%)	D4 (75%)	D5 (100%)	*p*-value
Proximate composition (%)						
DM	88.92 ± 0.25^{decb}	88.78 ± 0.22^{edb}	89.31 ± 0.75^{cdeab}	91.00 ± 0.00^{ac}	90.25 ± 0.75^{bdec}	0.093
CP	18.87 ± 0.34^{dabce}	20.45 ± 0.04^{adbc}	19.66 ± 0.66^{bdace}	19.63 ± 0.44^{cdabe}	18.42 ± 0.61^{edbc}	0.143
EE	6.84 ± 0.17^{d}	6.00 ± 0.00^{e}	9.73 ± 0.31^{bc}	9.12 ± 0.15^{cb}	12.11 ± 0.19^{a}	0.000
Ash	13.00 ± 1.00^{a}	6.75 ± 0.25^{dbce}	8.10 ± 0.80^{bdce}	8.70 ± 0.64^{cdbe}	7.41 ± 0.52^{edbc}	0.008
NFE	41.67 ± 0.49^{dc}	47.23 ± 0.32^{a}	33.22 ± 0.34^{e}	44.05 ± 0.95^{bc}	43.79 ± 0.75^{cdb}	0.000
CF	8.55 ± 0.24^{ced}	8.35 ± 0.31^{ecd}	8.61 ± 0.07^{b}	9.51 ± 0.03^{a}	8.54 ± 0.09^{dce}	0.000
NDF	68.02 ± 0.05^{a}	41.89 ± 0.13b^{c}	41.73 ± 0.14^{cb}	37.86 ± 0.22^{ed}	37.89 ± 0.02^{de}	0.000
ADF	31.09 ± 0.13^{a}	23.31 ± 0.32^{b}	7.27 ± 0.11^{de}	6.98 ± 0.10^{ed}	12.79 ± 0.09^{c}	0.000
ADL	7.43 ± 0.15^{bc}	7.12 ± 0.11^{cb}	1.88 ± 0.01^{e}	9.16 ± 0.03^{a}	3.37 ± 0.16^{d}	0.000

Values are expressed as mean ± SE ($n = 3$). Values in the same row with different superscript letters are statistically different ($p < 0.05$).
Diet code: D1, 0%BSFLM +100%SBM; D2, 25% BSFLM +75% SBM; D3, 50% BSFLM +50% SBM; D4, 75% BSFLM +25% SBM; D5, 100% BSFLM +0% SBM.
ADF, acid detergent fiber; ADL, acid detergent lignin; BSFLM, black soldier fly larvae meal; DM, dry matter; CF, crude fiber; CP, crude protein; EE, ether extract; NDF, neutral detergent fiber; NFE, nitrogen-free extracts; SBM, soybean meal.

treatment effect on FW ($p = 0.530$) and OW ($p = 0.768$). However, average daily feed intake (ADFI) and FCR were significantly different ($p = 0.004$ and $p = 0.000$, respectively).

Carcass and organ characteristics of broiler chicks fed diets containing BSFLM

The results of carcass and organ characteristics are shown in Table 5. Diet 2 recorded the highest dressed weight (2,580.33 g) and diet 5 the lowest (1,928.00 g), $p = 0.949$. There were no significant effects on wings and breast meat ($p = 0.323$ and $p = 0.488$, respectively) between the treatments. Breast fat weight was highest (15.30 g) in diet 5 and lowest (6.06 g) in diet 1. Diet 4 had a higher heart weight (15.99 g) and spleen (3.83 g). Weights of internal organs (kidney and spleen) were statistically similar ($p = 0.340$ and $p = 0.307$, respectively).

DISCUSSION

Proximate composition of ingredients and diets

Proximate analysis is used in the initial evaluation of feeds and feedstuffs to provide information on their major nutrients. In the present study (Table 2), the proximate composition of fishmeal (*Rastrionaebola argentea*), SBM, sunflower meal, and

Table 4 | Performance of broiler chicks fed with diets containing the black soldier fly larvae meal ($n = 270$)

	Dietary treatments					
Parameter	**D1 (0%)**	**D2 (25%)**	**D3 (50%)**	**D4 (75%)**	**D5 (100%)**	***p*-value**
IW (g)	487.29 ± 5.70^{a}	482.67 ± 5.77^{a}	489.67 ± 5.79^{a}	493.19 ± 7.36^{a}	488.14 ± 5.37^{a}	0.808
FW(g)	$2{,}102.43 \pm 43.29^{a}$	$2{,}147.33 \pm 74.40^{a}$	$2{,}218.29 \pm 71.74^{a}$	$2{,}178.43 \pm 84.89^{a}$	$2{,}262.26 \pm 65.85^{a}$	0.530
OW(g)	$1{,}216.99 \pm 41.04^{a}$	$1{,}268.08 \pm 44.36^{a}$	$1{,}279.83 \pm 45.41^{a}$	$1{,}274.11 \pm 45.46^{a}$	$1{,}296.97 \pm 46.19^{a}$	0.768
ADG(g)	57.68 ± 1.61^{ed}	59.45 ± 2.35^{dec}	63.57 ± 2.26^{acde}	64.08 ± 0.64^{abcd}	65.40 ± 1.53^{abc}	0.053
ADFI(g)	144.04 ± 0.89^{abc}	143.38 ± 2.07^{abc}	140.31 ± 1.63^{abcd}	136.63 ± 1.59^{cd}	134.15 ± 1.31^{ed}	0.004
FCR	2.50 ± 0.06^{ab}	2.42 ± 0.06^{ba}	2.21 ± 0.05^{cd}	2.13 ± 0.04^{dce}	2.04 ± 0.03^{ed}	0.000

Values are expressed as mean ± SE. Values in the same row with different superscript letters are statistically different ($p < 0.05$).
Diet code: D1, 0%BSFLM + 100%SBM; D2, 25% BSFLM +75% SBM; D3, 50% BSFLM +50% SBM; D4, 75% BSFLM +25% SBM; D5, 100% BSFLM + 0% SBM.
ADFI, average daily feed intake; ADG, average daily gain; BSFLM, black soldier fly larvae meal; FCR, feed conversion ratio; FW, final weight; IW, initial weight; OW, overall weight; SBM, soybean meal.

Table 5 | Carcass and organ characteristics of broiler chicks fed with diets containing the black soldier fly larvae meal

	Dietary treatments					
Body parts	**D1 (0%)**	**D2 (25%)**	**D3 (50%)**	**D4 (75%)**	**D5 (100%)**	***p*-value**
Dressed weight (g)	$1{,}941.00 \pm 132.04^{dbce}$	$2{,}580.33 \pm 160.15^{abc}$	$2{,}357.67 \pm 61.99^{bdace}$	$2{,}231.66 \pm 115.56^{cdabe}$	$1{,}928.00 \pm 190.14^{edbc}$	0.033
Thighs (g)	566.67 ± 29.24^{ecd}	600.67 ± 38.59^{cebd}	687.67 ± 19.24^{bca}	723.00 ± 26.03^{ab}	577.00 ± 42.53^{dec}	0.021
Wings (g)	204.33 ± 16.27^{a}	232.67 ± 14.24^{a}	237.33 ± 5.55^{a}	222.33 ± 6.33^{a}	206.00 ± 17.62^{a}	0.323
Breast meat (g)	695.00 ± 41.29^{a}	743.67 ± 82.83^{a}	833.33 ± 31.47^{a}	744.33 ± 58.32^{a}	661.00 ± 99.57^{a}	0.488
Breast fat (g)	6.06 ± 0.97^{ed}	12.61 ± 1.74^{debca}	14.89 ± 4.48^{bdca}	14.41 ± 2.81^{cdba}	15.30 ± 0.57^{adbc}	0.134
Internal organs weight (g)						
Liver	42.09 ± 3.81^{edbc}	47.00 ± 4.76^{dbce}	58.18 ± 3.79^{abc}	49.86 ± 3.65^{abcde}	49.38 ± 4.30^{cbeda}	0.163
Heart	12.23 ± 1.34^{dcbe}	13.35 ± 1.39^{cdbea}	13.62 ± 0.88^{bdcae}	15.99 ± 0.75^{acbe}	11.44 ± 0.43^{eabcd}	0.081
Kidney	14.87 ± 1.60^{a}	17.01 ± 2.27^{a}	18.25 ± 1.19^{a}	14.93 ± 0.99^{a}	13.82 ± 1.60^{a}	0.340
Spleen	2.43 ± 0.66^{a}	2.42 ± 0.17^{a}	3.44 ± 0.57^{a}	3.83 ± 0.77^{a}	3.20 ± 0.11^{a}	0.307
Gizzard and proventriculus	75.92 ± 1.70^{edb}	83.07 ± 4.82^{deb}	105.51 ± 6.75^{a}	91.63 ± 8.87^{ced}	94.93 ± 5.00^{bed}	0.044

Values are expressed as mean ± SE ($n = 3$). Values in the same row with different superscript letters show differences ($p < 0.05$).
Diet code: D1, 0%BSFLM + 100%SBM; D2, 25% BSFLM + 75% SBM; D3, 50% BSFLM + 50% SBM; D4, 75% BSFLM + 25% SBM; D5, 100% BSFLM + 0% SBM.
BSFLM, black soldier fly larvae meal; SBM, soybean meal.

maize meal was close to the values obtained by Maina *et al.* (2007); Kirimi *et al.* (2021); and Shumo *et al.* (2019). The disparity observed in nutrient composition could be due to the place of origin, production, processing methods, and adulteration by unscrupulous traders (Anjum *et al.* 2012; Kirimi *et al.* 2021; Munguti *et al.* 2021). In order to minimize variation, the ingredients were purchased from the same animal feed dealer and similar batches were selected. However, this can little address the issue of ingredient adulteration because unscrupulous dealers can add extraneous materials at any point within the animal feed value chain. The analyzed crude protein content for BSFLM was 39.40%, a figure lower than 47 and 43.90% reported by Sumbule *et al.* (2021) and Onsongo *et al.* (2018), respectively, but higher than 36.90% obtained by De Marco *et al.* (2015). Similarly, ether extract content in BSFLM was higher (44.84%) than 32.50 and 34.30% reported by Shumo *et al.* (2019) and Vilela *et al.* (2021). BSF larvae apparently store large quantities of fat as an energy source to carry through pupation. This may be responsible for the high-fat content in the meal (Oluokun 2000). The variation in crude protein and ether extract may be due to the substrate where the larvae are reared (Makkar *et al.* 2014). A study by Shumo *et al.* (2019) on BSF reared on different substrates (chicken manure, kitchen waste, and spent grain) had a crude protein of 41.10, 33.01, and 41.30% and fat content of 30.10, 34.30, and 31.02%, respectively. Thus, the quality and quantity of substrate play a substantial role in determining the body composition of the larvae. Substrates with quality protein and carbohydrates lead to enhanced development of BSF larvae, with high protein and fat content (Holeh *et al.* 2022).

The crude protein content of BSFLM (39.40%) was close to 38% for full-fat SBM (produced by heat treatment of whole soybeans) (Kirimi *et al.* 2021). This is a clear indication that BSF larvae are a good source of protein and fat and can be used as an ingredient in animal feeds (Sauvant *et al.* 2004; De Marco *et al.* 2015). The crude protein content of the experimental diets ranged from 18.42 to 20.45%. This was within the recommended range for broiler finisher feed (NRC 1994). The observed variation in crude protein content for the diets may be attributed to varying the ingredients in order to balance crude protein and other nutrients (Kirimi *et al.* 2021). Failure to analyze the ingredients crude protein prior to formulation might also have led to the variation. To minimize this, it is recommended to use actual analyzed figures when formulating feed. Successive substitution of SBM with BSFLM increased ether extract in the diets. This can be attributed to the high-fat content (44.84%) in BSFLM, the major protein ingredient substituting SBM in the diets. However, the range of fat content in the diets (6.84 and 12.11%) was above the recommended broiler ration (NRC 1994). Therefore, de-oiling BSFLM before inclusion in the broiler diets is necessary not only to reduce the fat content but also to increase the level of crude protein. This can be achieved by applying a tincture press to sliced larvae which facilitates leakage of intracellular fat (Kroeckel *et al.* 2012). The crude fiber content of BSFLM was 23.08%. Besides protein, BSFLM also contains higher levels of chitin which increase the fiber content of the diets. The high crude fiber content in BSFLM was not reflected in the diets. This was probably due to the high crude fiber (13.55%) in SBM hence the small range in variation. The crude fiber content in the diets was higher than recommended (2–5%) in broiler chick ration (NRC 1994). High levels of crude fiber in the diet decrease energy density thereby increasing feed intake (Elfaki & Abdelatti 2015; Bekele *et al.* 2020).

Growth performance and carcass characteristics

In relation to the broiler chicks' growth performance (Table 4), BSFLM-based diets provided better performance than those fed diets containing conventional SBM (D1). Black soldier flies larvae meal being an insect-based ingredient is rich in key nutrients such as a crude protein with a high biological value, fat, and minerals (Makkar *et al.* 2014). There was a noticeable decrease in the average daily feed intake of birds with successive increases in BSFLM (25, 50, 75, and 100%) in the diets. This may be attributed to high-fat content as a result of increased levels of BSFLM with high fat (44.84%). This was translated to the diet, consequently increasing dietary energy density and thereby decreasing feed intake. However, despite a decrease in ADFI with increased levels of BSFLM in the diets, there was an increase in ADG among the birds. This was due to an adequate supply of nutrients to the birds provided by the various diet types (Sumbule *et al.* 2021). Poor growth performance in the control diet (SBM-based, 0% BSFLM) despite similar crude protein levels across the diets implies there was an adequate supply of nutrients to the birds. The nutrients were probably deficient in SBM which was the major protein ingredient being substituted by BSFLM. SBM is deficient in methionine and cystine (Kirimi *et al.* 2020) and contains proteinase inhibitors which reduce the availability of amino acids. However, there was the addition of limiting amino acids (methionine and lysine) across the treatments. This source of nutrients may have provided an extra supply of limiting essential amino acids, though it could not compensate for the deficient nutrients in the SBM-based diet (D1) that led to low growth performance. The quality of feed, therefore, is a function of the ingredients used and how well it meets the nutrient requirements of the birds.

In this study, an increase in organ weight with increasing levels of BSFLM, in the diets was observed (Table 5). The increase in gizzard and proventriculus may be due to the bulkiness of the diets containing BSFLM, hence the bigger volume of the gizzard (Oluokun 2000). The results are consistent with Fathalla *et al.* (2015) and Esonu *et al.* (2006) who reported an increase in gizzard and heart weight. This is attributed to an increased amount of work performed by these organs as a result of increased fiber digestion leading to organ hypertrophy (Molist *et al.* 2009). For the liver and kidney, the increase in weight was probably due to increased metabolism of high energy in BSFLM-based diets (Table 1) (Oluokun 2000). In relation to the breast's fat deposits, there was an increase in fat with increased substitution of SBM with BSFLM such that broiler birds fed a diet with 100% BSFLM (D5) had more breast fat. This may have been due to increased dietary energy intake in excess of body requirements (Ghaffari *et al.* 2007; Fouad & El-Senousey 2014). In this case, as the birds increased in body weight, the excess energy was deposited as breast fat. Excess fat has an effect on the carcass quality. It is worth noting that the dressed weight for the birds on D5 (Table 5) was lower than other diets despite recording the highest final body weight (Table 4). The discrepancy observed might be due to the fact that birds for slaughter were randomly picked and possibly those with lower body weight were selected; hence, low-dressed weight. However, the low-dressed carcass weight of birds despite being of the same strain might be due to metabolic differences and variation within the strain (Sumbule *et al.* 2021; Vilela *et al.* 2021).

CONCLUSION

The results of the present study showed that broiler chicken fed on BSFLM-based diets at all levels performed better in terms of growth and carcass characteristics than 100% SBM. Hence, BSFLM can totally replace SBM in broiler diets without negatively affecting the growth performance and carcass characteristics. However, more research is needed on the optimal inclusion levels. The focus should be more on de-oiling BSFLM in order to reduce the fat content and boost protein levels. The economics of using BSFLM should also be investigated and the possibility of production on a large scale to meet the market demand.

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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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