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Influence of different levels of black soldier fly larvae meal on growth performance and carcass quality of broiler chickens

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HIGHLIGHTS

- In this study the soybean meal was replaced by different levels of Black soldier larvae meal in the diets of broiler chickens.
- The present study demonstrated that 12 % full-fat BSFL meal can be used from 1 to 28 days of age in broilers without negative effects on growth performance, nutrient utilization, and meat quality.

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ABSTRACT

A study was conducted to examine the impact of two inclusion levels of Black soldier fly larvae meal (BSFLM) replacing soybean meal on growth performance, nutrient utilization, carcass characteristics and meat quality of broilers. Three experimental diets based on corn-soybean meal were developed to contain 0 (control), 6 (BSF 6) and 12% (BSF 12) BSFLMfor both starter and grower phases. Each experimental diet was randomly allotted to six replicate pens (eight birds per pen). The birds were offered starter pellets from 0 to 14 day post-hatch and grower pellets from 15 to 28 day post-hatch. The experimental diets were tested for pellet durability index (PDI). There was an interaction between diet and growth phase ($P < 0.001$) for pellet durability index where starter diets had always a higher PDI than the grower diets, but the difference was greater for control diet than BSF 6 and BSF 12 diets. Apparent metabolizable energy (AME) of diets and coefficients of apparent ileal digestibility (CAID) of nutrients were measured on day 28 using titanium dioxide marker ratios in the diet and excreta/ileal digesta. On day 28, the weights of live body, carcass, fat pad, breast and gizzard were recorded, and then breast meat quality (meat pH, drip loss and cooking loss) was examined. Inclusion of BSFLM of up to 12 % did not reduce live weight gain or feed intake. Live weight and carcass weight were heavier in broilers fed 12 % BSFLM than controls ($P < 0.02$), but were not different than those fed 6 %, while controls were not different than those fed 6 %. Breast weight (percentage live weight) was lower in birds offered 12 % BSFL than in others ($P < 0.04$). No differences were observed between diets for the percentage weight as carcass, fat, pad and gizzard. The AME and AMEc of diets were the highest in broilers fed 6 % BSFLM diet ($P < 0.005$), but there were no differences between controls and those fed 12 % BSFLM. The CAID of DM, ash and N in birds fed 6 % BSFLM were greater than ($P < 0.03$) birds fed 12 %, but were not different than controls, which were also not different than those fed 12 %. Broiler breast meat quality was unaffected by dietary treatments. In conclusion, BSFLM at 12 % can be used effectively as a SBM replacement in starter and grower diets, without affecting the growth performance, nutrient utilization, carcass characteristics and meat quality of broiler chickens.

Abbreviations

AME	apparent metabolisable energy
AMEn	AME N corrected
BSFLM	Black Soldier Flies Larvae Meal
CAID	coefficient of apparent ileal digestibility
CP	crude protein
DM	dry matter
FCR	feed conversion ratio
GE	gross energy

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N nitrogen
NDF neutral detergent fibre
PDI pellet durability index
SBM soybean meal
TiO_2 titanium dioxide
WB woody breast
WS White stripping

1. Introduction

The increasing demand for high-quality feed ingredients and the increasing price of soybean meal (SBM) constantly increases the cost of poultry feed. Poultry feed accounts for approximately 70 % of the production costs which in turn causes more expensive poultry products.. There is a necessity to look for other potentially unconventional feed sources that are less used or inedible for human consumption. Also, market volatility and increased prices have always prompted poultry nutritionists to explore the utility of locally accessible or alternative feed ingredients. Moreover, growing SBM has negative consequences such as greenhouse gas emissions (Hörtenhuber et al., 2011), deforestation, and overuse of water (Costa et al. 2021). Insect meal as an alternative to SBM in diets of nonruminants is a potential solution, owing to its superior nutritional value and reduced environmental impact (Makkar et al. 2014; Gasco et al. 2020; Kieronczyk et al. 2022a; Sajid et al., 2023). Insect meal can be obtained from black soldier fly (*Hermetia illucens*) larvae, mealworms, house fly (maggot or pupae), locusts, grasshoppers, crickets, silkworm pupae, etc. (Makkar et al. 2014; Sajid et al., 2023). Black soldier fly larvae (BSFL) meal can be used as an alternative to SBM as a protein source (Schiavone et al., 2019) or to soy oil as an energy source (Kim et al., 2021) for poultry. This product can be used in full-fat or defatted forms. The average crude protein (CP) concentration of BSFL is 415 g/kg (range: 216 to 655 g/kg, DM basis). The fat content of full-fat and defatted BSFL is 353 g/kg (294 to 515 g/kg, DM basis) and 69 g/kg (46 to 99 g/kg, DM basis), respectively (Lu et al., 2022). The apparent metabolizable energy (AME) and nitrogen corrected AME (AME_n) of BSFL fat are 37.9 and 37.7 MJ/kg, respectively, which is comparable to the AME (35.7 MJ/kg) and AMEn (37.7 MJ/kg) of soy oil (Kieronczyk et al. 2022b). In New Zealand, due to their high health status, broiler chickens achieve the best growth performance world wild, with FCR below 1.4. The optimum inclusion level of BSFL in broiler diets has not been determined for high performing birds. The objective of this study was to examine the effects of dietary inclusion of full-fat BSFL at 0, 6 and 12 % on pellet durability of feed and growth performance, nutrient utilization, carcass characteristics and meat quality of 28 day old broiler chickens.

2. Material and methods

Experimental procedures were approved by the Massey University Animal Ethics Committee (MUAEC 23/34). The experiments were carried out at the Massey University Poultry Unit, Palmerston North, New Zealand.

2.1. Preparation of BSFL meal

Black soldier fly larvae (BSFL) were collected from Massey University's laboratory colony in Palmerston North. BSFL were produced and meal prepared as described by Mahmoud et al. (2023). Briefly, the collected larvae were first dehydrated at 65 °C in an Unitherm Drier for 24 hrs, ground in a hammer mill to pass through a 4 mm screen.and stored at 4 °C.

2.2. Experimental diets

All diets (Table 1) were developed in accordance with Ross 308 (2022) nutrient requirements for broiler starters and growers. Diets were steam conditioned at 70 °C prior to pelleting using die-holes of 3 mm for starter and 4 mm for grower diets. The basal diet contained corn-SBM-soy oil with 0 % BSFLM (control) while the next two diets included 6 and 12 % BSFLM (BSF6 and BSF12, respectively). All diets were formulated to have 12.4 MJ/kg AME and 230 g/kg (CP) for starter diets and 12.8 MJ/kg AME and 215 g/kg CP for grower-finisher diets. The diets were formulated using AME and standard ileal digestible amino acid values previously determined by Mahmoud et al. (2013) for BSFL of the same colony. The values for the other ingredients were obtained from Evonik (2016). The 12 % maximum inclusion level of BSFLM in the diet was based on the results from Schiavone et al. (2019) and Dabbou et al. (2018). The high-fat content of BSFLM will also limit their inclusion level, as dietary fat levels over 7–8 % have a negative both on broiler performances and pellet durability. Titanium dioxide was added as a undigestible marker to the grower-finisher diets (5 g/kg).

Table 1
Ingredient and nutrient composition of experimental diets (g/kg, as fed basis).

Ingredient	Starter			Grower		
	Control[1]	BSF6	BSF12	Control	BSF6	BSF12
Corn	546.4	575.8	536.4	585.5	608.5	594.4
Soybean meal	386.1	321.4	268.2	349	287.6	230.21
Soy oil	23.57	0.00	0.00	30.00	8.57	0.00
BSFLM	0.00	60.0	120.0	0.00	60.0	120.0
Dicalcium phosphate	11.88	9.62	28.09	4.50	3.37	2.54
Limestone	15.00	16.00	30.00	15.00	16.00	25.79
L-Lys	2.98	3.26	3.37	3.22	2.46	2.64
DL- met	4.22	4.33	4.53	3.70	3.79	3.95
L-Thr	1.73	1.79	1.85	1.29	1.31	1.37
Salt	1.00	2.50	0.00	1.00	2.50	5.00
Sodium bicarbonate	2.50	0.72	3.00	2.34	1.50	10.0
Choline Cl −70 %	2.61	2.57	2.62	2.37	2.34	2.36
Mineral Premix[2]	1.00	1.00	1.00	1.00	1.00	1.00
Vitamin Premix[3]	1.00	1.00	1.00	1.00	1.00	1.00
Titanium dioxide[4]	5.00	5.00	5.00	5.00	5.00	5.00
Calculated analysis						
Dry Matter (g/kg)	884	886	892	884	886	890
Crude protein (g/kg)	230	230	230	215	215	215
AME (MJ/kg)[5]	12.4	12.4	12.4	12.8	12.8	12.8
Fat (g/kg)	52	46	62	58	55	63
Ash (g/kg)	32	31	30	29	29	29
Crude Fibre (g/kg)	29	27	24	28	26	23

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM), BSFLM (Black soldier fly larvae meal).
[2] Supplied per kilogram of diet: vitamin A (trans-retinyl acetate), 12,000 IU; cholecalciferol, 4000 IU; thiamine, 3 mg; riboflavin, 9 mg; pyridoxine, 10 mg; folic acid, 3 mg; biotin, 0.25 mg; cyanocobalamin, 0.02 mg; dl-α-tocopherol acetate, 80 IU; niacin, 60 mg; Ca-D pantothenate, 15 mg; menadione, 4 mg; choline chloride, 600 mg.
[3] Supplied per kilogram of diet: Co, 0.25 mg; I, 1.5 mg; Mo, 0.25 mg; Se, 0.26 mg; Mn, 100 mg; Cu, 10 mg; Zn, 80 mg; Fe, 60 mg; antioxidant, 100 mg.
[4] 5 g of Titanium dioxide were added to the diets.
[5] AME: Apparent Metabolizable Energy.

2.3. Birds and housing

A total of 144, day-old male broilers (Ross 308) were obtained from a commercial hatchery and raised on floor pens for 28 days. Birds were individually weighed and randomly allocated (mean ± SD, 44.35 ± 3.4 g) to 18 floor pens having wood-shavings litter. Experimental diets were allotted to six replicate pens (eight birds each). Experimental starter diets were offered from day 0 to 14, and grower diets from day 15 to 28. For each pen, one bell drinker and one feeder were provided during performance trials. Birds had free access to clean water and feed. Birds were housed in an environmentally controlled poultry house kept at 31 °C for the first four days before being gradually reduced to 22 °C by the end of week three. Birds were exposed to fluorescent lighting for the first

24 h and then 20 h daily from day 2 to 28. Ventilation was controlled by a central ceiling inlet and wall extraction fans.

2.4. Growth performance

Individual body weight and pen feed intake were recorded on days 0, 7, 14, 21, and 28. Weekly average feed intake, body weight gain and feed conversion ratio (FCR) were calculated. Mortality and culls were recorded daily and FCR was corrected for the body weight of any dead/culled birds as described by Dersjant-Li et al. (2014).

$$FCR = \frac{\text{feed intake}}{\text{body weight} + \text{weight gain of all mortality and culled birds}}$$

2.5. Determination of AME and apparent ileal nutrient digestibility

On day 28, six birds per pen with uniform body weights were randomly assigned to a cage to measure AME using the titanium dioxide (TiO_2) marker ratios in the diet and excreta. Birds had free access to water and feed. Excreta samples were collected on days 28 and 29 and pooled within a cage. Pooled excreta were thoroughly mixed, and representative samples were taken and freeze-dried. Dried excreta samples were ground to pass through a 0.5 mm sieve and stored in sealed plastic containers until laboratory analysis. Diet and excreta samples were analyzed for gross energy (GE), nitrogen (N) and TiO_2 concentrations.

On day 29, all birds in each cage were euthanized by an intravenous injection (0.5 mL per kg body weight) of sodium pentobarbitone (Provet NZ Pty Ltd, Auckland). The digestive tract was removed and the ileal digesta was collected from the lower half of the ileum following a procedure described by Ravindran et al. (2005). The ileum was defined as that portion of the small intestine extending from the Meckel's diverticulum to the point of 40 mm proximal to the ileo-caecal junction. The digesta of the lower ileum were gently flushed with distilled water into plastic containers. The digesta from birds of respective cages were pooled, freeze-dried, and then ground to pass through a 0.5 mm sieve and then stored in airtight containers at 4 °C pending laboratory analysis

2.6. Measurement of carcass characteristics and meat quality

Hot carcass weight was obtained after removing the head, neck, feet, and internal organs. Weights of the breast, fat pad, and gizzard were recorded, and their relative weights were calculated as a percentage of body weight.

For meat quality, both right and left breasts from the six birds per replicate were collected. A breast was patted dry with paper toweling and pH was measured at 3 points using a calibrated pH meter (pH spear, Oakton Instruments, Vernon Hill, IL).

The drip loss and cooking loss were measured based on the methods described by Honikel (1998). Breast samples were weighed and stored in airtight plastic bags at -20 °C for 10 days. The left breast was then thawed at room temperature for 8 h. When thawed, it was cut into one 40 mm and two 25 mm thick slices to measure drip loss and cooking loss, respectively. The 40 mm piece was cut into two 40 × 40 × 40 mm cubes, weighed, and suspended in separate plastic bags at 4 °C. Cubes were re-weighed after 24 and 48 h to measure chilled weight loss. The 25 mm slices of left breast were placed into separate, sealed plastic bags and cooked in a water bath at 70 °C for 90 min. Cooked meat pieces were allowed to cool for 30 min at room temperature and then 3 h at 4 °C before being re-weighed.

Trained personnel examined thawed breasts for the existence of myopathies using internal scoring techniques created by Aviagen (2023). White striping (WS) was graded according to severity, whereas wooden breast (WB) and deep pectoral myopathy (green muscle) were reported as either present or absent. The severity of WS was assessed using a 4-point score: 0, no striping; 1, mild striping covering a portion of the breast; 2 moderate striping covering a significant portion of the breast surface; and 3, severe striping covering a large portion of the breast surface with extremely thick stripes (Fig. 1; Bailey et al. 2015). Hardness of breast muscle was used to indicate WB (Fig. 2).

2.7. Chemical analyses

The chemical composition of BSFLM, diets, ileal digesta and excreta were determined by the Nutrition Laboratory, Massey University, Palmerston North, New Zealand. Dry matter (DM), ash, nitrogen (N) crude fat, neutral detergent fibre (NDF), gross energy (GE) and Titanium dioxide were determined using standard procedures. Dry matter was determined by the methods 925.10 and 930.15 and ash by the Furnace 550 °C method 942.05 (AOAC, 2023). N was determined by the Dumas method 968.06 (AOAC, 2023). Concentration of CP was calculated as *N* × 6.25. The Mojonnier method 954.02 (AOAC, 2023) was used to determine crude fat. BSFLM and diets were analyzed for NDF using Tecator Fibertec™ (FOSS Analytical AB, Höganäs, Sweden) as described (method 2002.04; AOAC, 2023). Bomb calorimetry, calibrated with benzoic acid, was used to determine GE (Gallenkamp Autobomb, Weiss Gallenkamp Ltd, Loughborough, UK). Concentration of TiO_2 was measured using a colorimetric method (Jagger et al. 1992; Short et al. 1996).

2.8. Pellet durability index

Diet pellet durability was tested using a Holmen Pellet Tester (New Holmen NHP100 Portable Pellet Durability Tester, Tek Pro Ltd., Willow Park, North Walsham, Norfolk, UK). Briefly, a 100 g sample of clean, fine-free pellets was rapidly circulated in an air stream around a perforated test chamber for 30 s at room temperature (9 subsamples of each diet were tested). Resulting fines were continually eliminated through the test cycle and the subject pellets were ejected and weighed manually. Pellet durability index (PDI) was calculated as the ratio of retained pellet weight after agitation to initial pellet sample weight.

2.9. Calculations

The apparent energy metabolisabale coefficient (AMEc) of diets was calculated by the marker method using the following formula:

$$\text{AMEc diet} = \left[(GE/Ti)_{diet} - (GE/Ti)_{excreta}\right]/(GE/Ti)_{diet}$$

and the AME (MJ/kg) of the diet was calculated as:

$$AME(\text{MJ}/\text{kg}) = GE_{diet}\,\text{xAMEc}$$

The coefficient of apparent ileal digestibility (CAID) of nutrients was calculated using Ti marker ratios in the diet and ilea digesta as indicated below:

$$\text{CAIDofnutrients} = \left[(\text{ nutrient }/Ti)_{diet} - (\text{ nutrient }/Ti)_{ileal}\right]/(\text{ nutrient }/\text{Ti})_{diet}$$

The PDI was calculated using the following formula (Abdollahi and Ravindran, 2013):

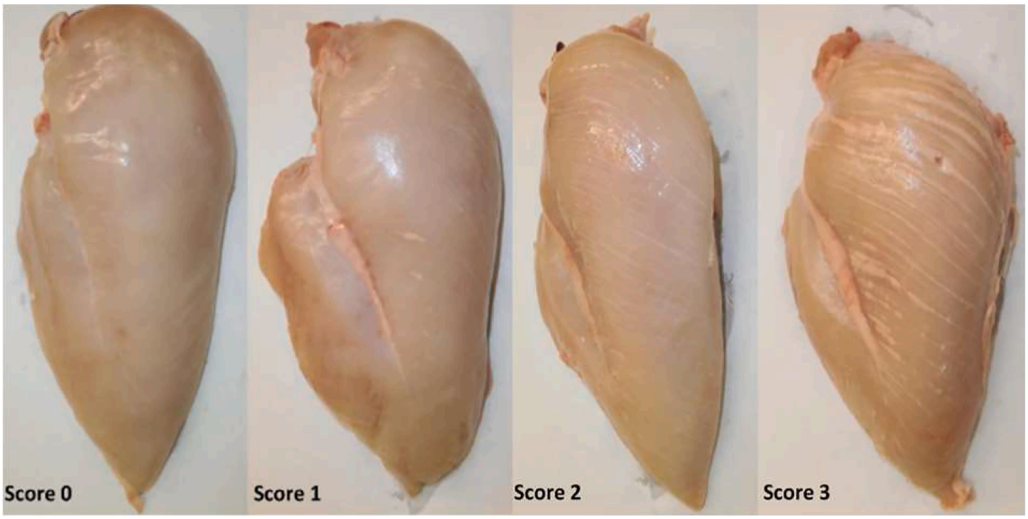

Fig. 1. Severity scores (from 0 to 3) of white stripping of chicken breast (Adapted from Bailey et al., 2015).

Fig. 2. Normal vs woody breast of broilers (Aviagen 2023. Broiler myopathies handbook.).

$$PDI = \frac{\text{mass of pellets retained on sieve after agitation}}{\text{mass of initial pellets}} \times 100$$

2.10. Statistical analysis

A linear model with diet as a fixed effect was fitted to growth performance, AME and CAID data (Proc GLM; SAS, 2016). Pen/cage served as the experimental unit. A mixed linear model with diet as a fixed effect and cages nested within diets as a random effect was fitted to the individual carcass and meat quality data with individual bird as the experimental unit (Proc GLM; SAS, 2016). Where appropriate, differences between LSmeans were determined by the Tukey post-hoc test where $P < < 0.05$ was deemed significant. Mortality and muscle myopathies were analyzed as binomial data with diet as a fix effect (Proc Genmod; SAS, 2016). Data on pellet durability index were analyzed as a 3 × 2 factorial arrangement of treatments to examine the main effects of diet and growth phase and their interaction using the GLM procedure of SAS (SAS, 2016).

Table 2
Analyzed chemical composition of Black soldier fly larvae meal, (BSFLM) starter and grower diets (g/kg, as fed basis, unless otherwise mentioned).

Nutrient	BSFLMl	Starter diets			Grower-finisher diets		
		Control[1]	BSF6	BSF12	Control	BSF6	BSF12
DM[2]	912	885	881	892	884	871	873
Ash	59.8	54.2	51.4	77.5	50.0	49.2	60.9
Crude protein	428	207	208	209	190	187	188
GE (KJ/g)	22.98	16.54	16.27	16.38	16.30	16.42	16.30
Fat	213	39.3	14.5	25.6	35.2	23.9	20.6
NDF	172	81.7	91.8	90.8	99.5	101	100

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM).
[2] DM – dry matter; GE – Gross energy; NDF – Neutral detergent fiber.

Table 3
Effect of Black soldier fly larvae meal (BSFLM) on the growth performance of broilers.

Parameters	Control[1]	BSF6	BSF12	SEM	*P* value
Weight gain (g/bird/day)	58.9	61.2	61.5	1.52	0.43
Feed intake (g/bird/day)	77.9	81.0	79.4	2.11	0.58
Feed conversion ratio	1.32[b]	1.32[b]	1.29[a]	0.078	0.01

[1] Control (0 % BSFLM), BSF6 (6 % BSFML) and BSF12 (12 % BSFL)M.
[a,b]Means having different superscripts within a row are significantly different.

Table 4
Effect of different inclusion levels of Black soldier fly larvae meal (BSFLM) on the carcass characteristics and related parameters of broilers.

Parameters	Control[1]	BSF6	BSF12	SEM	*P* value
Live body weight (g)	1841[b]	1911[ab]	2011[a]	35.1	0.0133
Hot Carcass (g)	1363[b]	1444[ab]	1494[a]	29.9	0.0236
Dressing (%)[2]	74.0	75.5	74.2	0.43	0.0643
Fat Pad (%)[2]	0.64	0.75	0.64	0.04	0.0977
Breast (%)[2]	20.8[a]	20.8[a]	19.8[b]	0.26	0.0367
Gizzard (%)[2]	1.55	1.52	1.49	0.031	0.4513

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM).
[2] Percentage of body weight.
[a,b]Means having different superscripts within a row are significantly different.

3. Results

3.1. Diets and growth performance

Fat, CP and GE contents of full-fat BSFLM meal were determined to be 213 g/kg, 428 g/kg, and 22.98 KJ/g, respectively (Table 2). Analysed CP and fat contents of starter (207 to 209 g/kg and 14.5 to 39.3 g/kg, respectively) and grower-finisher (187 to 190 g/kg and 20.6 to 35.2 g/kg, respectively) were slightly lower than calculated values estimated when diets were formulated.

Dietary inclusion of full-fat BSFLM did not affect weight gain or feed intake of broilers, however, FCR improved 3 % in broilers fed BSF12 compared with control and BSF6 ($P < 0.01$; Table 3).

3.2. Carcass characteristics

Live body and carcass weights were greater in BSF12 birds than controls ($P < 0.05$), however, weights for BSF6 were not different from controls or BSF12 (Table 4). Percentage of live weight as carcass (dressing %), fat pad, and gizzard were not different between diets. However, the dressing % was tended to increase ($P = 0.06$) in birds fed 6 % BSFL diet. The weight of breast expressed as a percentage of live weight was lowest ($P = 0.04$) in birds fed 12 % BSFL.

3.3. AME and CAID of nutrients

The AME and AMEc were highest in broilers fed 6 % BSFL ($P < 0.005$), and there were no differences between controls and BSF12 (Table 5). The CAID of DM and CP were higher ($P < 0.03$) in birds fed 6 % BSFL than those fed 12 %, but not different from controls. The CAID of ash was higher ($P < 0.001$) in controls and BSF6 than in birds fed 12 % BSFL.

3.4. Meat quality

Parameters of breast meat quality, incidences of myopathies, and mortality were not affected by dietary treatment (Tables 6 and 7).

Table 5
Influence of Black soldier fly larvae meal (BSFLM) on the apparent metabolisable energy (AME, MJ/kg), coefficient of apparent energy metabolisability (AMEc) and the coefficient of apparent ileal digestibility (CAID) of dry matter (DM), ash and crude protein (CP) in 28-day broilers.

Item	Control[1]	BSF6[1]	BSF12[1]	SEM	*P* value
AME (MJ/kg)	12.00[b]	12.75[a]	12.08[b]	0.131	0.002
AMEc	0.738[b]	0.776[a]	0.741[b]	0.008	0.005
CAID of DM	0.691[ab]	0.723[a]	0.687[b]	0.010	0.034
CAID of ash	0.467[a]	0.481[a]	0.363[b]	0.017	< 0.001
CAID of CP	0.779[ab]	0.797[a]	0.738[b]	0.014	0.022

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM).
[a,b]Means having different superscripts within a row are significantly different.

Table 6
Effect of Black soldier fly larvae meal (BSFLM) on the breast meat quality of broilers.

Parameters	Control[1]	BSF6[1]	BSF12[1]	SEM	*P* value
Defrost loss (%)	8.5	9.8	8.9	0.91	0.62
pH Fresh	6.76	6.82	6.77	0.129	0.98
pH Defrost	5.69	5.68	5.75	0.051	0.35
Drip loss 24 h (%)	3.8	4.8	4.1	0.29	0.82
Drip loss 48 h (%)	5.5	7.0	6.0	0.43	0.91
Cooking loss (%)	25.5	26.9	28.1	1.33	0.40

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM).

3.5. Pellet durability

The results of the PDI of the experimental diets are presented in Table 8. Overall, the starter diets had higher PDI than the grower-finisher diets ($P < 0.001$), and PDI were different between the three types of diets being the highest for the control diets and the lowest for the BSF 12 diets ($P < 0.001$). There was an interaction between diets and phase ($P < 0.001$), starter diets had always a higher PDI than the grower-finisher diet, but the difference was greater for the control diet than the BSF 6 and BSF 12 diets.

4. Discussion

The primary protein source in poultry diets is SBM. Nevertheless, SBM is becoming more costly because of its limited supply and increasing demand. Various protein sources are being investigated as alternatives to SBM in animal diets. The high CP content of BSFL meal (216–655 g/kg; Lu et al., 2022) makes it a good alternative to SBM. As reported by Eggink et al. (2022) and Ewald et al. (2020), nutrient content of BSFL is greatly influenced by rearing substrate and larval growth stage. Eggink et al. (2022) reported a range of CP values for larvae, from 436 g/kg CP for those reared on chicken feed, to 598 g/kg CP for larvae reared on brewer's spent grain. Similarly, they reported fat content in larvae to range from 216 g/kg for those reared on mitigation mussels, to 329 g/kg for larvae reared on chicken feed (Eggink et al., 2022). Analysed values for CP and fat in BSFL meal used in the current study were at the bottom of ranges reported by Eggink et al. (2022), however, values

Table 7
Effect of Black soldier fly larvae meal (BSFLM) on the mortality and breast muscle myopathies (woody breast and white stripping).

Item	DF	Chi-Square	Pr > ChiSq	Control[1]	BSF6[1]	BSF12[1]
Mortality	2	2	0.368	4.20 %	4.20 %	10.50 %
Woody Breast	2	0.29	0.867	5.55 %	8.55 %	8.57 %
White Stripping	2	0.15	0.926	11.10 %	11.10 %	8.57 %

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM).

Table 8
Influence of Black soldier fly larvae meal (BSFLM) inclusion level on pellet durability index (PDI) of experimental diets.

Diets[1]	Phase	PDI (%)
Control	Starter	80.4[a]
	Grower	72.1[b]
BSF 6	Starter	72.4[b]
	Grower	70.0[c]
BSF 12	Starter	68.2[c]
	Grower	65.0[d]
SEM		0.71
Main effect		
Diets		
Control		76.3[a]
BSF6		71.2[b]
BSF12		66.6[c]
SEM		0.50
Phase		
Starter		73.7[a]
Grower		69.1[b]
SEM		0.41
P value		
Diets		< 0.001
Phase		< 0.001
Diet x Phase		< 0.001

[1] Control (0 % BSFLM), BSF6 (6 % BSFLM) and BSF12 (12 % BSFLM).
Means having different superscripts (a-d) within the column are significantly different .

for GE, ash and NDF were comparable with those reported for BSFL meal prepared using similar methods (Mahmoud et al., 2023).

The authors are aware of only one other study that examined the effect of BSFL on pellet quality. Weththasinghe et al. (2021) reported a pellet durability index of 99.1, 98.9, 96.3 and 98.8 % for the fish diets containing 0, 6.25, 12.5 and 25 % BSFL meal, suggesting that there was no influence of BSFL inclusion on pellet durability. However, the same study reported a reduced pellet expansion with increasing BSFL meal inclusion. In contrast, in the present study, increasing BSFL meal inclusion reduced the pellet durability of experimental diets. The same conditions (moisture, temperature and screw speed) were employed for pelleting of all diets in the current study. According to Weththasinghe et al. (2021), increased fat decreases pellet quality by lowering dough temperature because of decreased friction. Abdollahi et al. (2013) stated that higher fat would reduce friction force generated in the die holes and result in decreased pellet quality. However, the analysed fat content of BSFL diets were lower than the control diets in the current study which was unexpected. Therefore, reduced pellet quality of BSFL-diets in the current study cannot be related to the fat content of BSFL meal. Nevertheless, an influence of different fat (or fatty acids) type of soy oil (control diet) and BSFL on the pellet quality of diets in the current study is questionable. Hence, further studies may be warranted with different inclusion levels of both soy oil and BSFL meal to study the pellet quality. The pellet durability was higher for starter diets than for grower diets, regardless of the same inclusion levels of BSFL in both diets in the current study, which could be related to the size of pellets. Because smaller pellets undergo greater mechanical heating which results in more durable pellets (Abdollahi et al., 2013).

The present study examined the influence of three BSFL inclusion levels (0, 6 and 12 %) on the growth performance of broilers over four weeks and the results revealed that 12 % BSFL diet reduced the FCR of broilers when compared to other diets (1.29 vs 1.32). However, Dabbou et al. (2018) reported that FCR (1.59–1.60) was similar in broilers fed 0, 5 and 10 % partially defatted-BSFL meal, but a higher (1.72) in broilers fed 15 % BSFL. The same study (Dabbou et al., 2018) also reported a similar daily feed intake and daily weight gain in birds on the last week (24–35 days), regardless of different BSFL meal inclusion, but an increased feed intake (1–10 days) and weight gain (1–10 and 10–24 days) on the early weeks at 10 % BSFL inclusion. The present study also examined the effect of BSFL inclusion on carcass characteristics and the results demonstrated a positive response in terms of live weight and hot carcass weight. Similar finding has been reported by Dabbou et al. (2018), where a partially defatted-BSFL meal inclusion of 10 % increased the live weight of 35-day old broilers when compared to control, 5 % and 15 % BSFL diets. These findings agree with the results of Schiavone et al. (2019) who reported heavier live weight and carcass weight in broilers that received 10 % defatted-BSFL compared to those that received 0, 5 and 15 % BSFL.

Results on AME of nutrients showed that broilers fed 6 % BSFL had greater nutrient utilization. In addition, similar CAID of DM and CP in birds fed control vs BSF6 and BSF12 suggested that BSFL can be used effectively in replacing SBM. The lack of a positive response in nutrient utilization with birds receiving BSF12 could be attributed to greater chitin content (De Marco et al., 2015). As indicated by Hossain and Blair (2007), chitin is digested by the enzyme chitinase, which is of endogenous origin or from gut microorganisms, but the ability of chickens to digest chitin appears to be limited. Marono et al. (2016) demonstrated that digestibility of CP in BSFL was inversely proportional to its chitin content and suggested that chitin was the primary factor influencing digestibility of protein in BSFL meal under laboratory conditions. Therefore, further work may be warranted to measure the chitin content of BSFL meal along with other nutrients before formulating diets.

Broiler breast meat quality and myopathies were not affected by dietary treatments. Similarly, Schiavone et al. (2019) did not find any difference between meat quality parameters (pH, drip loss, and cooking loss) of birds receiving 0, 5, 10, and 15 % defatted BSFL meal. In addition, Pieterse et al. (2019) did not report any differences in meat quality parameters of birds fed similar inclusion rates of BSF pre-pupae meal in broiler diets. However, higher inclusion of BSFL (above 30 %) was shown to reduce sensory quality (Murawska et al., 2021). Similar to the current findings with myopathies, Ipema et al. (2020) did not find a difference between a control and BSFL group for white striping in broilers at 42 days of age. White striping and woody breast are the common myopathies seen in breast meat of modern broilers with fast growth rates (Kuttappan et al., 2016; Bordignon et al., 2022). Breast meat myopathies are potentially caused by age, gender, genetic, nutrition, growth rate and toxicity (Kuttappan et al., 2016; Fernandes et al., 2022).

According to literature, several studies were conducted to study inclusion rates of both full-fat and defatted BSFL for broilers. According to Schiavone et al. (2019), 10 % defatted BSFL can be used in broiler diets without any negative effects on birds' performance. This finding agrees with results from Dabbou et al. (2018) who showed a negative effect of 15 % defatted BSFL inclusion on FCR and gut morphology. However, Mat et al. (2022) studied four inclusion rates (0, 4, 8, and 12 %) of defatted BSFL for broilers and reported that 4 % BSFL was the most suitable level for broilers. In the case of full-fat BSFL, Murawska et al. (2021) reported a negative effect on growth performance and meat sensory qualities when replacing more than 50 % SBM with BSFL. However, according to Vilela et al. (2021a), 20 % full-fat BSFL can improve performance and reduce immune-response energy expenditure in 42-day old broilers. Further, a recent study evaluating effect of BSFL on caecal microbiota of broilers found that BSFL can be included at up to 20 % of broiler grower and finisher diets without affecting caecal microflora (Vilela et al., 2021b).

Overall, the present study demonstrated that 12 % full-fat BSFL meal can be used from 1 to 28 days of age in broilers without negative effects on growth performance, nutrient utilization, and meat quality. However, from an economical point of view it is unlikely that BSFLM will be used in commercial poultry production. Least-cost diet formulation was used to find out the shadow price of BSFLM. In September 2025 price of soybean meal in New Zealand was NZ$950 / t, and the shadow price for BSFLM was NZ$1130. However, to our knowledge, it is unlikely that BSFLM can be purchased at this price, to be competitive with Soy Bean meal or other sources of protein.

CRediT authorship contribution statement

S.H. Baderuddin: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **L.S. David:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation. **T.J. Wester:** Writing – review & editing, Investigation. **P.C.H. Morel:** Writing – review & editing, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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