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Assessing the Maximum Inclusion Level of Black Soldier Fly (*Hermetia Illucens*) Larvae Full-Fat and De-Fatted Meals in Broiler Diets

Research Article

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ABSTRACT

The use of insect meals as a substitute for protein sources is a current topic of interest, especially the black soldier fly (*Hermetia illucens*, BSFL) larvae in full-fat (FF) and de-fatted (DF) forms. Nine experimental diets were prepared for broiler starter (Day 14-21) and finisher (Day 21-35) phases. The control diet was formulated to contain, 10% fish meal (FM) (T1). The other eight experimental diets were replaced FM in the control diet with BSFL FF at 2.5% (T2), 5% (T3), 7.5% (T4), and 10% (T5) and BSFL DF at 2.5% (T6), 5% (T7), 7.5% (T8), and 10% (T9), respectively. On day 14, two hundred and sixteen (216) unsexed, Cobb-500 broilers having uniform body weights (BW±SD: 343.5 g/head±13.01) were randomly consigned to 36 battery cages (60 cm×60 cm×60 cm) (04 replicates per treatment, six birds per replicate). From day-14, the birds were evaluated for growth performances. On day-35, 72 birds; two birds from each replicate were selected and evaluated for carcass traits, meat quality, and digestive tract measurements. Sensory characteristics and cost-benefit analysis were also conducted. The feed intake (FI) was influenced ($P<0.05$) by the treatments. The breast yield was enhanced ($P<0.05$) by the birds fed T3. The thigh weight was increased ($P<0.05$) by the birds fed T3 and T6. The back and heart weights were comparable ($P>0.05$) among the birds fed T1, T3 and T5 diets. The length of the large intestine was augmented ($P<0.05$) by the inclusion of FF BSFL above 5% level and DF BSFL from 2.5 to 10%. T3 had the highest sensory attributes and was the most cost-effective diet. In summary, the current study indicates that the inclusion of FF BSFL meal up to 5% into broiler diets did not have any negative impact on the tested parameters.

KEY WORDS black soldier fly larvae, broiler, crude protein, fishmeal, meat traits.

INTRODUCTION

The global population's rapid growth and dietary changes have led to an increase in animal protein consumption, making finding suitable feed for livestock production challenging due to resource scarcity. Finding of appropriate animal feed for livestock production seems difficult due to increasing demand for limited resources (Van Huis, 2013). The industry is exploring alternative crude protein sources (CP), particularly chicken, to improve local socioeconomics, including food security, employment, marketing, and trade, due to the rising cost of conventional CP sources like, fishmeal (FM). The chicken meat industry makes up about 70% of the local meat industry, and the poultry sector faces the problem of feed ingredient shortage, especially imported CP sources such as FM, as well as unstable product prices due to political issues. Since most of the Sri Lankan population has low income, it is difficult to ensure sufficient food production and the consumption of balanced diets at the household level (Alahakoon *et al.* 2016).

Insect meals are gaining popularity in poultry nutrition as a sustainable, economically viable protein source, with black soldier fly (*Hermetia illucens*) larvae (BSFL) being a promising food source (De Marco *et al*. 2015) BSFL is also enriched with a desirable AAs like Lysine, Methionine, minerals like Ca, Mg and required by the chicken, which is readily digestible and has succeeded in replacing conventional poultry protein sources (Mohammed, 2017; Opoku *et al*. 2019). Furthermore, BSFL includes an adequate quantity of essential minerals and fatty acids those require for animal growth (Newton *et al*. 2005). According to Makkar *et al*. (2014), the CP content of BSFL full-fat (FF) is 42.1%, while that of BSFL defatted (DF) is 56.9%. The BSFL-FF meal processing is simpler and slightly less expensive where the BSFL-DF meal is suited for animals with lesser calorie needs or where fat management is required. Both kinds appear to be safe to include in an animal's diet without having a negative impact on the animal's performance or health.

The BSFL has a short life cycle of 40-44 days and can use various types of waste materials. Its nutritional composition changes according to the quality of the substrate it grows on. Therefore, using BSFL meal instead of expensive protein sources could reduce the cost of feed production. The animal protein market prioritizes meat quality, ethical considerations, and production standards to avoid financial losses. Broiler breeding techniques have led to faster protein deposition at lower costs (Cockcroft, 2018).

Modern consumers prefer purchasing carcass parts, making carcass weight analysis crucial for introducing new protein sources. The physical characteristics like, pH, color, juiciness, tenderness, and water holding capacity (WHC) are considered crucial for meat properties and preservation (Mir *et al*. 2017). Apart from that Fat content affects meat organoleptic properties and texture, potentially causing shelf-life impairment. BSFL meal, rich in antioxidants, may slow oxidation and prevent rancidity.

The study hypothesizes that incorporation of full fat and defatted BSFL meal can replace fish meal in broiler diets at indifferent inclusive levels, and it can affect growth performances and meat characteristics quantitatively and qualitatively.

Since, there is a research gap with the lower inclusion levels of both BSFL meal types with respect to the prior research trials, the present study therefore aims to evaluate the growth performances, carcass characteristics, meat quality parameters, organoleptic properties and cost-benefits of FF-BSFL meal and DF-BSFL meal replacing cost-demanded FM at different inclusion levels (2.5%, 5%, 7.5%, and 10%) when fed to broiler chickens.

MATERIALS AND METHODS

Preparation of BSFL full-fat (FF) meal and BSFL defatted (DF) meal

The BSFL were raised on kitchen waste (KW) as growing substrates, consisting of food waste (rotten fruits and vegetables) and swill. They were collected at the termination of their larvae growth stage (L5), washed, and were stored at -20 ˚C until further processing into a fine meal. The frozen larvae were allowed to thaw to room temperature and forced air dried for 20 hrs. under 60 ˚C in a convection oven (Model BOC-V640F. Biobase Biodustry (Shandong) Co; Ltd., China) (Schiavone *et al*. 2017). To produce BSFL FF meal, oven dried larvae were milled into a fine powder and stored at 4 ˚C until used in diets. BSFL DF meal was obtained by mechanical extrusion using a screw press (Model T 15. Henan P and Machinery Equipment Co., Ltd, Henan, China). The screw press ran at 80 ˚C and extracted the fat from the larvae, resulting in BSFL DF meal and a press liquid. The screw pressed BSFL meal was oven dried at 40 ˚C for 24 hrs and then pulverized into a fine powder using a kitchen blender.

Determination of the nutrient composition of BSFL FF, DF meals, and the rearing substrate

The BSFL FF, DF samples and fresh KW substrate samples were collected (n=6) and were analyzed for their proximate composition [ash, CP, crude fiber (CF), ether extract (EE), and moisture], energy, total phosphorus (TP), and calcium (Ca) (AOAC, 2005). The fatty acids content was determined according to AOAC (2005) 969.33 and 996.06 procedures.

Determination of the amino acid profile (AA) of BSFL FF and DF meal and FM and soybean meal (SBM)

The AA profile of BSFL FF meal, BDFL DF meal, FM and soybean meal (SBM) were analyzed according to FST-W101 Chapter 42 (Ref. EZ-FAAST) (LC/MS/MS) methodologies in ISO 17025 in Accredited Intertek Vietnam laboratory.

Birds, diets and management

The study was conducted at the farm premises of Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka according to the guidelines of the current ethical review committee (Reference no. ERC/A/01/2022/01) of the Sabaragamuwa University of Sri Lanka.

A total of three hundred (300) day-old, unsexed, vaccinated broiler chicks (Cobb 500) were purchased from a commercial hatchery in Sri Lanka.

They were fed a commercial diet [12.47 MJ/kg metabolizable energy (ME) and 21% CP] up to day 14 and were raised in a brooder. On day 14, two hundred-sixteen (216) birds having uniform body weights (BW±SD: 343.5±13.01g) were randomly distributed into 36 battery cages (L × W × H: 60 cm × 60 cm × 60 cm) (04 replicates per treatment, 06 birds per replicate). From day 14 to day 35, the birds were assigned to nine treatments and were fed experimental diets.

The nutrient composition of the rearing substrate, BSFL FF meal and BSFL DF meal are presented in Table 1. The FA composition the rearing substrate, BSFL FF meal, BSFL DF meal and the experimental diets are presented in Table 2.

Table 1 Nutrient composition of the kitchen waste, BSFL full-fat meal (FF) and BSFL de-fatted meal (DF) on dry matter (DM) basis

Nutrient[1]	Unit	Kitchen waste substrate (% DM)	BSFL FF meal (% DM)	BSFL DF meal (% DM)
Dry matter	%	95.80	79.00	86.10
Moisture	%	4.20	21.00	13.90
Ash	%	7.41	7.97	7.55
CP	%	3.44	41.39	44.13
CF	%	5.85	7.34	10.22
EE	%	19.60	42.30	33.70
NFE	%	63.70	1.01	4.41
GE	MJ/kg	18.63	23.03	20.82
Ca	%	0.10	0.43	0.94
Total P	%	0.31	0.76	0.70

CP: crude protein; CF: crude fiber; EE: ether extract; NFE: nitrogen free extract; GE: gross energy; Ca: calcium and P: phosphorus.

The amino acid profile (AA) of BSFL FF, DF meal, fish meal (FM) and soybean meal (SBM) used for the experiment are presented in Table 3.

Nine (09) isoenergetic and isonitrogenic experimental diets were formulated to meet National Research Council (NRC, 1994) specifications for broiler starter (Day 14-21) and finisher (Day 21-35) phases. A maize-soybean meal-based diet had 10% FM was used as the control diet (T1). Another eight experimental diets were prepared to replace FM in the control diet at 2.5% (T2), 5% (T3), 7.5% (T4), and 10% (T5) with BSFL FF meal and 2.5% (T6), 5% (T7), 7.5% (T8), and 10% (T9) with DF meals, respectively. All experimental diets were presented in mash form. The Tables 4 and 5 represent the ingredient composition, calculated and analyzed nutrient composition of starter and finisher diets.

Birds were evaluated weekly for their feed intake (FI), body weight gain (BWG), and feed conversion ratio (FCR) from d-14 onwards. Mortality was recorded daily. Birds were fasted overnight (Medugu *et al.* 2010; Diarra and Tabuaciri, 2014) prior to slaughtering. On day-35, 72 birds; two birds from each replicate were chosen based on the average final live weights and were slaughtered humanely by severing the jugular vein. Plucked and eviscerated carcasses were obtained and were stored under -18 ˚C until further analysis is commenced.

Evaluation of carcass characteristics and physical measurements

Average body weight on day-35 (pre-slaughter weight) was obtained for each treatment. Carcass weight measurements were obtained after de-feathering and removal of feet, head, and viscera. Dressing percentage was calculated according to the equation 4.

Dressing percentage (%)= (carcass weight/live weight after fasting) × 100% (4)

The weights of the breast, thighs, wings, back, head and neck, feet, and abdominal fat were measured, and statistically significant parts were expressed as percentages of the eviscerated carcass weight.

The weights of the breast, thigh, back, necks, heart, drumsticks, wings, gizzard, liver, abdominal fat, skin, head, shank were measured and expressed as percentages of the eviscerated carcass weight. The digestive tract segments (esophagus, proventriculus, gizzard, liver, small intestine, cecum and large intestine) were recorded for their weights and lengths.

Carcass physical measurements

The edible portion included lean meat (muscle tissue with intermuscular fat), skin with subcutaneous fat, giblets (gizzard, liver, and heart), and abdominal fat in various forms. Non-edible cuts included blood, bones, feathers, head, feet, gastrointestinal tract with digesta and peri-intestinal fat, abdominal fat and other offal, trachea, lungs and reproductive organs, pancreas, spleen, and kidneys. Those two portions were used to calculate the ratio between edible and inedible parts.

Surface meat color of uncooked meat samples in terms of CIE L*, a*, and b* values was measured using a colorimeter (CR-400 Chroma Meter, Konica Minolta, USA) in which L*, a*, and b* values represent the degrees of lightness (L*), redness (a*), and yellowness (b*), respectively. The pH of the samples was determined using a glass electrode pH meter (Thermo Scientific™ Orion Star™ A211 Benchtop pH Meter, USA.), as described by Straadt *et al.* (2007) with slight modifications. Each breast meat sample (1 g) was chopped with a mortar and pestle and mixed with distilled water in a 1:5 (w/w) ratio. The pH of the prepared mixture was determined.

Table 2 Fatty acid composition of the kitchen waste, BSFL full-fat (FF) meal, BSFL de-fatted (DF) meal, starter diets and finisher diets

Fatty acid (%)	Kitchen Waste Substrate	BSFL full fat meal	BSFL de-fatted meal	Starter diets								
				T1	T2	T3	T4	T5	T6	T7	T8	T9
Caproic acid (C 6:0)	0.38	ND	ND	0.12	0.10	0.03	0.15	ND	0.14	0.17	0.11	0.09
Caprylic acid (C 8:0)	5.88	0.02	0.02	2.49	3.66	2.77	3.11	1.73	4.13	3.89	2.53	3.12
Capric acid (C 10:0)	4.30	0.83	0.78	2.62	3.70	3.46	3.44	3.35	3.98	3.50	3.28	3.30
Undecanoic acid (C11:0)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lauric acid (C 12:0)	38.63	46.63	46.00	27.55	35.75	37.45	39.55	41.46	37.34	36.72	36.92	38.98
Tridecanoic acid (C 13.0)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Myristic acid (C 14:0)	15.94	14.77	14.46	12.62	14.45	14.58	15.30	15.02	15.45	14.05	14.18	14.33
Myristoleic acid (C 14:1)	ND	0.25	0.23	0.02	0.03	0.04	0.04	0.06	0.04	0.04	0.04	0.04
Pentadecanoic acid (C 15:0)	15.94	0.07	0.08	0.08	0.05	0.05	0.04	0.03	0.06	0.05	0.04	0.02
Ginkgolic acid (C 15:1)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Palmitic acid (C16:0)	0.03	14.16	14.46	12.87	11.62	11.86	11.76	11.12	11.95	12.23	12.31	12.11
Palmitoleic acid (C 16:1)	ND	2.50	2.55	0.65	0.56	0.61	0.66	0.61	0.54	0.57	0.62	0.57
Heptadecanoic acid (C17:0)	12.66	0.10	0.11	0.24	0.15	0.11	0.06	0.02	0.15	0.11	0.10	0.04
Cis-10- Heptadecanoic acid (C17: 1)	0.22	0.08	0.08	0.08	0.06	0.05	0.02	0.03	0.06	0.02	0.04	ND
Stearic acid (C 18:0)	0.06	2.45	2.51	3.70	3.28	3.15	2.94	2.77	3.28	3.12	3.01	2.94
Elaidic acid (C18: 1t)	0.02	0.19	0.16	0.19	0.05	0.02	0.09	0.15	0.06	0.05	0.09	0.07
Oleic acid (C18 :1C)	5.61	11.56	11.70	12.86	11.22	11.48	10.33	10.44	10.04	11.18	11.00	11.46
Linolelaic acid (C 18:2t)	0.14	0.04	0.04	0.05	0.03	0.06	ND	ND	0.03	0.02	0.02	ND
Linoleic acid (C 18:2c)	10.37	4.54	4.63	13.93	10.50	11.09	9.45	9.09	8.36	11.21	11.34	11.25
Eicosanoic acid (C 20:0)	ND	0.15	0.16	0.31	0.23	0.22	0.17	0.16	0.19	0.21	0.19	0.18
Linolenic (GLA) acid C (18:3n6)	0.32	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-11-Eicosenoic acid (C 20:1)	0.14	0.46	0.47	0.83	0.63	0.71	0.66	0.61	0.58	0.67	0.68	0.65
Linoleic acid (C18: 3n3)	ND	0.04	0.04	0.18	0.13	0.06	0.10	0.09	0.06	0.12	0.10	0.07
Heneicosanoic acid (C 21:0)	0.02	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-11, 14-eicosadienoic acid (C 20:2)	ND	ND	ND	0.04	0.02	0.02	0.02	ND	0.02	0.02	ND	ND
Cis-8,11,14-Eicosatrieonic acid (C20:3n6)	0.06	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Behenic acid (C22:0)	ND	0.11	0.11	0.14	0.10	0.09	0.07	0.06	0.08	0.08	0.07	0.07
Erucic acid (C22:1)	0.38	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-11,14,17-Eicosatrieonic acid (C20:3n3)	ND	0.08	0.08	0.34	0.18	0.13	0.08	0.05	0.19	0.14	0.09	0.04
Arachidonic acid (C20: 4n6)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tricosanoic acid (C23:0)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
cis-13,16-Docosadienoic acid (C22:2)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Eicosatetraenoic acid (C20:5n3)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tetracosanoic acid (C24:0)	0.06	0.02	0.02	0.17	0.12	0.11	0.08	0.07	0.10	0.10	0.12	0.07
Nervonic acid (C 24:1)	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Decosahevaenoic acid (C 22: 6n3)	0.15	ND	ND	2.11	1.03	0.73	0.29	0.06	0.83	0.66	0.32	0.02
Unknown	0.14	0.92	1.28	5.81	2.35	1.12	1.59	3.02	2.34	1.07	1.80	0.58

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
ND: not detected.

Continued Table 2

Fatty acid (%)	Finisher diets								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
Caproic acid (C 6:0)	0.05	ND	ND	0.07	ND	0.03	ND	0.09	0.04
Caprylic acid (C 8:0)	1.06	0.76	1.39	1.45	0.86	1.61	1.05	1.35	0.94
Capric acid (C 10:0)	1.21	1.83	2.27	2.16	2.26	2.29	2.65	1.32	0.91
Undecanoic acid (C11:0)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Lauric acid (C 12:0)	21.09	28.42	34.79	36.38	32.73	27.39	40.92	24.90	18.52
Tridecanoic acid (C 13.0)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Myristic acid (C 14:0)	11.75	12.37	14.33	14.66	13.40	12.16	13.78	15.13	15.48
Myristoleic acid (C 14:1)	ND	0.03	0.03	0.06	0.04	0.04	0.06	0.04	ND
Pentadecanoic acid (C 15:0)	0.13	0.09	0.07	0.05	0.08	0.10	0.03	0.06	0.04
Ginkgolic acid (C 15:1)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Palmitic acid (C16:0)	15.78	14.03	13.65	13.21	13.41	14.14	12.28	16.16	16.17
Palmitoleic acid (C 16:1)	0.86	0.79	0.79	0.82	0.66	0.73	0.82	0.78	0.57
Heptadecanoic acid (C17:0)	0.33	0.21	0.17	0.10	0.16	0.23	0.05	0.15	0.07
Cis-10- Heptadecanoic acid (C17: 1)	0.10	0.03	0.05	0.06	0.05	0.06	0.02	0.03	0.02
Stearic acid (C 18:0)	4.57	3.70	3.45	3.34	3.85	3.80	2.72	3.95	3.96
Elaidic acid (C18: 1t)	0.29	0.07	0.10	0.03	0.07	0.03	0.03	0.03	0.36
Oleic acid (C18 :1C)	16.04	15.05	13.55	13.28	14.05	15.02	12.03	16.71	16.67
Linolelaic acid (C 18:2t)	0.07	0.04	0.05	0.02	0.04	0.05	ND	0.03	0.03
Linoleic acid (C 18:2c)	16.99	16.81	12.24	12.29	15.23	17.68	12.20	16.85	18.84
Eicosanoic acid (C 20:0)	0.41	0.31	0.26	0.25	0.28	0.33	0.19	0.30	0.29
Linolenic (GLA) acid C (18:3n6)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-11-Eicosenoic acid (C 20:1)	0.83	0.93	0.61	0.63	0.78	0.95	0.72	0.90	1.07
Linoleic acid (C18: 3n3)	0.22	0.17	0.14	0.11	0.13	0.17	0.09	0.13	0.15
Heneicosanoic acid (C 21:0)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-11, 14-eicosadienoic acid (C 20:2)	0.11	0.04	0.10	ND	0.03	0.04	ND	0.02	0.03
Cis-8,11,14- Eicosatrieonic acid (C20:3n6)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Behenic acid (C22:0)	0.10	0.12	0.10	0.09	0.13	0.13	0.08	0.12	0.11
Erucic acid (C22:1)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Cis-11,14,17- Eicosatrieonic acid (C20:3n3)	0.33	0.27	0.11	0.09	0.15	0.26	0.04	0.12	0.10
Arachidonic acid (C20: 4n6)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tricosanoic acid (C23:0)	ND	ND	ND	ND	ND	ND	ND	ND	ND
cis-13,16-Docosadienoic acid (C22:2)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Eicosatetraenoic acid (C20:5n3)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Tetracosanoic acid (C24:0)	0.19	0.23	ND	ND	ND	ND	ND	ND	ND
Nervonic acid (C 24:1)	ND	ND	ND	ND	ND	ND	ND	ND	ND
Decosahevaenoic acid (C 22: 6n3)	1.38	1.50	0.15	0.13	0.16	0.18	0.10	0.15	0.04
Unknown	6.11	2.20	1.20	032	0.80	1.21	0.12	0.33	5.31

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
ND: not detected.

Table 3 Amino acid profile (AA) of BSFL FF, DF meal, fish meal (FM) and soybean meal (SBM) used for the experiment

Amino acid	Unit	BSFL-FF	BSFL-DF	Fishmeal	Soybean meal
4-Hydroxyproline	%	ND	ND	1.59	0.10
Alanine	%	2.61	2.56	3.51	1.93
Arginine	%	1.43	1.38	2.69	2.64
Aspartic acid	%	2.62	3.05	3.91	4.35
Cystine	%	0.22	0.29	0.29	0.55
Glutamic acid	%	4.74	5.56	8.14	9.02
Glycine	%	1.69	1.78	3.31	1.71
Histidine	%	0.36	0.31	0.58	0.84
Hydroxylysine	%	ND	ND	ND	ND
Isoleucine	%	1.76	1.74	2.15	1.89
Leucine	%	1.60	1.90	2.55	2.47
Lysine	%	2.37	2.58	3.78	3.07
Methionine	%	0.61	0.68	1.49	0.52
Phenylalanine	%	1.26	1.55	2.00	2.06
Proline	%	1.88	1.94	2.22	2.07
Serine	%	0.87	1.00	1.36	1.49
Threonine	%	1.08	1.16	1.54	1.58
Tryptophan	%	0.59	0.67	0.70	0.83
Tyrosine	%	2.11	2.76	1.88	1.68
Valine	%	2.07	2.33	2.40	1.74

BSFL-FF: black soldier fly larvae full-fat meal and BSFL-DF: black soldier fly larvae de-fatted meal.
ND: not detected.

The texture properties of cooked breast meat samples were analyzed using a texture analyzer, as described by Combs (2018) and by Brookfield's catalog (Manual No. M/08- 371). Texture Pro CT software was used in the data processing.

The drip loss was measured using the method described by Gamage *et al.* (2017) and Saelin *et al.* (2017) The drip loss was calculated using the below formula.

Drip loss (%)= $[(W_2-W_3) / W_1] \times 100$ (5)

Initial sample weight (W1), sample weight after hanging in the polythene bag (W2), sample weight after hanging two days at 4 ˚C temperatures (W3).

Cooking loss of thigh meat samples were determined according to the methodologies described by Gamage *et al.* (2017) and Gao *et al.* (2015) with slight modifications.

Each meat sample was slightly blotted with paper towels, weighed (W1), and placed in an electric oven (Model T 15. Henan P and Machinery Equipment Co., Ltd, Henan, China) at 218 ˚C. The internal temperature was maintained at 75 ˚C. The cooked meat samples were blotted, and the final weight was recorded (W2).

Cooking loss %= $[(W1-W2) / W1] \times 100$ (6)

The cooking yields of breast meat samples were determined using the equation (Equation 7) below, (Gamage *et al.* 2017). The breast meat samples were cooked in an electric oven (Model T 15. Henan Pand Machinery Equipment Co., Ltd, Henan, China) at 218 ˚C to an end point temperature of 75 ˚C. To calculate cooking yield, each chicken breast meat sample was weighed before cooking (W1) and then again after cooking (W2).

Cooking yield %= $(W2/W1) \times 100$ (7)

Chicken meat were evaluated by 37 untrained panelists for their sensory properties using a pre-designed questionnaire with 6-point hedonic scale. The sensory properties evaluated include toughness, color, aroma, flavor, and overall acceptability. All the samples were cooked in an electric oven (provide model, manufacturer details) at 218 ˚C till the internal temperature reached 75 ˚C. Meat samples were prepared for presentation by cutting into 2 cm cubes. To facilitate proper color identification of the samples, the cubes were served to the panelists in white plates. Each plate was labeled with a random number and placed in a random order for each panelist. Each panelist was given a glass of water between two plates to rinse their mouths between samples.

Economic analysis

The economic analysis of the experiment was expressed in-terms of cost-benefit analysis (CBA) and return on investment (ROI).

Cost-benefit analysis (CBA)

Cost benefit analysis is expressed in monetary terms in evaluating all costs and benefits of the experiment methodically to determine its economic viability against existing broiler feeds production. Total cost of production was calculated considering all the production parameters where the cost of the feed was considered during the time of experiment conducted considering two growth phases in Sri Lankan Rupees (LKR) and the rest were assumed to be constant for all the treatments. Feed costs were calculated based on the quantities of each ingredient used in the dietary feed treatments. The revenues generated from the sale of broilers at the end of the feeding phase were assumed to represent the entire benefit of the experiment. The BCR is defined as the ratio of experiment revenue to experiment cost (Equation 8). If cost-benefit ratio greater than one indicates that the experiment's benefits outweighed its costs, and *vice versa*.

Benefit – Cost ratio= total revenue of the experiment / total cost of the experiment   (8)

Table 4 Ingredient and calculated nutrient composition (%, as fed) of the starter diets fed to broiler chickens

Ingredient	Unit	Diets								
		T1	T2	T3	T4	T5	T6	T7	T8	T9
Maize	%	51.85	50.76	49.67	48.56	47.39	51.40	50.07	48.76	47.40
Rice polish	%	2.00	1.67	1.34	1.00	0.55	1.67	1.34	1.00	0.67
Soybean meal (CP: 44%)	%	27.00	27.67	28.34	29.00	29.80	27.40	28.17	28.94	29.72
Coconut oil	%	6.05	6.34	6.63	6.93	7.12	6.43	6.69	6.93	7.20
Fish meal (CP: 64.2%)	%	10.00	7.50	5.00	2.50	0.00	7.50	5.00	2.50	0.00
BSFL-FF	%	0.00	2.50	5.00	7.50	10.00	0.00	0.00	0.00	0.00
BSFL-DF	%	0.00	0.00	0.00	0.00	0.00	2.50	5.00	7.50	10.00
DCP	%	0.49	0.66	0.83	1.00	1.13	0.66	0.83	1.00	1.17
Limestone 38%	%	1.40	1.43	1.46	1.50	1.57	1.43	1.47	1.52	1.57
Salt	%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
DL-methionine	%	0.10	0.23	0.36	0.50	0.63	0.00	0.21	0.42	0.63
L-lysine	%	0.10	0.23	0.36	0.50	0.80	0.00	0.21	0.42	0.63
Vitamin premix[1]	%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mineral premix[2]	%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mold inhibitor[3]	%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Toxin binder[4]	%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Coccidiostat[5]	%	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Antioxidant[6]	%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Calculated nutrient composition										
ME	MJ/kg	13.40	13.40	13.40	13.41	13.39	13.41	13.41	13.40	13.41
CP	%	23.10	22.80	22.40	22.10	22.00	22.50	22.60	22.70	22.70
Ca	%	1.10	1.10	1.00	1.00	1.00	1.10	1.00	1.00	1.00
Total P	%	0.68	0.68	0.68	0.68	0.66	0.68	0.68	0.68	0.67
Avl. P	%	0.45	0.45	0.45	0.46	0.45	0.45	0.45	0.46	0.46
DL-methionine	%	0.87	0.89	0.91	0.94	0.97	0.67	0.77	0.88	0.99
L-lysine	%	1.20	1.30	1.50	1.60	1.90	1.10	1.30	1.60	1.80
EE	%	9.00	10.20	11.50	12.80	13.90	9.70	10.30	10.90	11.50
CF	%	3.20	3.30	3.50	3.60	3.70	3.50	3.80	4.10	4.40
DM	%	84.80	84.20	83.50	82.80	82.10	84.60	83.80	83.10	82.40

[1] Vitamin and [2] Mineral premix (IU/mg per kilogram): vitamin A: 15000000; vitamin D3: 800000; vitamin E: 30000; vitamin K: 2500; vitamin A: 15000000; vitamin B1: 2500; vitamin B 2: 6000; Calcium pantothenate: 12000; vitamin B 6: 5000; vitamin B12: 24; Niacin: 40000; Folic acid: 1200; Biotin: 180; Choline chloride: 2000; Iron: 40000; Copper: 10000; Zinc: 60000; Manganese: 80000; Iodine: 1000; Cobalt: 200 and Selenium: 150.
[3] Mold inhibitor: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
[4] Toxin Binder: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
[5] Coccidiostat: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
[6] Anti-Oxidant: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
BSFL-FF: black soldier fly larvae full-fat meal; BSFL-DF: black soldier fly larvae de-fatted meal; DCP: calcium phosphate; ME: metabolizable energy; CP: crude protein; Total P: total phosphorus; Avl. P: available phosphorus; EE: ether extract; CF: crude fiber and DM: dry matter.

Return on investment (ROI)

Return on investment refers to the amount of profit or loss generated by an investment in comparison to the amount of money invested. It is calculated as a percentage by dividing the profit by the cost (Equation 9). Profit is defined as the difference between experiment revenue and experiment cost.

Return on investment= ((experiment revenue–experiment cost)/(experiment cost)) × 100 (9)

Statistical analysis

The statistical analysis was performed using SAS (2004) software and data were tested by one-way ANOVA with $P < 0.05$. Duncan's Multiple Range Test (DMRT) was used to compare mean values.

RESULTS AND DISCUSSION

During the experimental period the birds kept well and healthy. The mortality rate of the experiment is summarized under Table 6.

Table 5 Ingredients, calculated and, analyzed nutrient compositions (%, as fed) of finisher diets fed to broiler chickens

Ingredient	Unit	Diets								
		T1	T2	T3	T4	T5	T6	T7	T8	T9
Maize	%	62.30	59.80	57.30	54.80	51.80	60.30	58.00	56.05	53.93
Rice polish	%	2.50	2.20	1.90	1.60	1.30	2.20	1.90	1.60	1.30
Soybean meal (CP: 44%)	%	18.80	20.68	22.56	24.40	26.80	20.30	22.00	23.50	25.10
Coconut oil	%	4.00	4.67	5.34	6.00	6.70	4.55	5.20	5.70	6.27
Fish meal (CP: 64.2%)	%	10.00	7.50	5.00	2.50	0.00	7.50	5.00	2.50	0.00
BSFL-FF	%	0.00	2.50	5.00	7.50	10.00	0.00	0.00	0.00	0.00
BSFL-DF	%	0.00	0.00	0.00	0.00	0.00	2.50	5.00	7.50	10.00
DCP[4]	%	0.04	0.15	0.26	0.37	0.48	0.15	0.26	0.37	0.48
Limestone 38%	%	1.20	1.34	1.48	1.62	1.76	1.34	1.48	1.62	1.76
Salt	%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
DL-methionine	%	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
L-lysine	%	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Vitamin premix[1]	%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mineral premix[2]	%	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mold inhibitor[3]	%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Toxin binder[4]	%	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Coccidiostat[5]	%	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Antioxidant[6]	%	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Calculated nutrition composition										
ME	MJ/kg	13.40	13.41	13.42	13.41	13.40	13.40	13.41	13.40	13.39
CP %	%	20.50	20.30	20.10	20.00	20.00	20.40	20.40	20.40	20.40
Ca %	%	0.91	0.91	0.91	0.91	0.91	0.91	0.91	0.90	0.90
Total P	%	0.58	0.57	0.56	0.55	0.55	0.57	0.56	0.55	0.54
Avl. P	%	0.35	0.35	0.34	0.33	0.33	0.35	0.34	0.33	0.32
DL-methionine	%	0.74	0.64	0.53	0.43	0.33	0.64	0.54	0.44	0.34
L-lysine	%	1.03	1.07	1.12	1.16	1.22	1.07	1.13	1.17	1.22
EE	%	7.30	8.90	10.50	12.10	13.80	8.20	9.10	9.90	10.80
CF	%	2.89	3.08	3.27	3.45	3.67	3.22	3.55	3.88	4.22
DM	%	86.60	85.90	85.10	84.30	83.60	86.00	85.40	84.80	84.20

[1] Vitamin and [2] Mineral premix (IU/mg per kilogram): vitamin A: 15000000; vitamin D3: 800000; vitamin E: 30000; vitamin K: 2500; vitamin A: 15000000; vitamin B1: 2500; vitamin B 2: 6000; Calcium pantothenate: 12000; vitamin B 6: 5000; vitamin B12: 24; Niacin: 40000; Folic acid: 1200; Biotin: 180; Choline chloride: 2000; Iron: 40000; Copper: 10000; Zinc: 60000; Manganese: 80000; Iodine: 1000; Cobalt: 200 and Selenium: 150.
[3] Mold inhibitor: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
[4] Toxin Binder: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
[5] Coccidiostat: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
[6] Anti-Oxidant: Farmchemie Manufactures (Pvt.) Limited, Homagama, Sri Lanka.
T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
BSFL-FF: black soldier fly larvae full-fat meal; BSFL-DF: black soldier fly larvae de-fatted meal; DCP: calcium phosphate; ME: metabolizable energy; CP: crude protein; Total P: total phosphorus; Avl. P: available phosphorus; EE: ether extract; CF: crude fiber and DM: dry matter.

Table 6 The mortality rate of each experimental diets from Day 14 to Day 35

Item	Diets								
	T1	T2	T3	T4	T5	T6	T7	T8	T9
Mortality rate[1] (%)	0	0	0	0	0	0	0	0	0.46

[1] Mortality rate calculated for the experimental period (from Day 14 – day 35).
T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.

The Table 7 summarizes the boiler production performances throughout the experimental period. The FI was different ($P<0.05$) among the tested treatments where the highest FI was recorded from T5 during the starter phase. The maximum FI during the finisher phase was shown in chicks fed the T2 diet. The birds fed T4 diet showed the highest FI for the entire experimental period. The lowest FI for the starter phase was recorded from the birds fed T6 whereas T9 showed the lowest FI during the finisher period and the entire experimental period. Experimental treatments did not have a significant effect on BWG and FCR during the experimental periods.

Table 7 The average feed intake (FI, g/bird/period), average weight gain (AWG, g/bird/period) and feed conversion ratio (FCR) of broilers as influenced by inclusion of BSFL FF meal and BSFL DF meal

Phase	Parameter	Diets									P-value	SEM
		T1	T2	T3	T4	T5	T6	T7	T8	T9		
Starter period d14-21	FI	585.5^{d}	582.8^{de}	595.9^{c}	615.5^{b}	634.4^{a}	540.5^{g}	616.8^{b}	579.4^{e}	556.3^{f}	<0.05	1.32
	AWG	479.9	488.4	480.1	457.8	432.5	436.6	457.4	446.6	424.6	0.922	15.2
	FCR	1.23	1.20	1.24	1.35	1.48	1.26	1.35	1.30	1.33	0.087	0.06
Finisher period d21-35	FI	1788.1^{c}	1895.7^{ab}	1845.0^{abc}	1904.0^{a}	1781.3^{c}	1808.2^{bc}	1869.2^{abc}	1831.0^{abc}	1605.1^{d}	<0.05	31.4
	AWG	914.3	977.8	970.1	824.8	890.3	884.9	886.8	872.9	788.8	0.291	53.6
	FCR	1.98	1.95	1.94	2.44	2	2.04	2.11	2.11	2.05	0.863	0.19
Total period d14-35	FI	2373.6^{bc}	2478.5^{ab}	2440.9^{ab}	2519.5^{a}	2415.7^{bc}	2348.7^{c}	2486.0^{ab}	2410.4^{bc}	2161.4^{d}	<0.05	31.4
	AWG	1394.2	1466.2	1450.2	1282.6	1322.8	1321.6	1344.1	1319.5	1213.2	0.166	62.8
	FCR	1.72	1.70	1.70	2.01	1.83	1.78	1.85	1.84	1.79	0.160	0.110

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
The means within the same row with at least one common letter, do not have significant difference (P>0.05).
SEM: standard error of the means.

Table 8 Average broiler carcass measurements as influenced by inclusion of BSFL FF meal and BSFL DF meal

Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9	P-value	SEM
Avg. body weight at D35 (g/bird)	1780.04	1854.73	2006.48	1811.84	1821.85	1858.97	1795.21	1794.15	1721.96	0.160	61.51
Carcass weight (g/bird)	1154.71	1209.55	1305.37	1182.58	1160.23	1208.12	1141.79	1147.99	1111.7	0.182	45.20
Dressing percentage (%)	64.97	65.20	64.95	65.44	63.76	65.00	63.58	63.97	64.71	0.856	1.12
Breast (g)	385.70^{bcd}	398.10^{bc}	471.20^{a}	364.20^{bcde}	338.80^{de}	409.90^{b}	330.70^{e}	356.30^{cde}	370.50^{bcde}	<0.0001	16.64
Thigh (g)	253.80^{bc}	280.35^{bc}	315.76^{a}	273.99^{bc}	256.33^{bc}	286.59^{ab}	254.30^{bc}	262.53^{bc}	247.93^{c}	0.007	11.63
Back (g)	134.11^{ab}	141.46^{ab}	154.41^{a}	105.41^{c}	134.80^{ab}	125.38^{bc}	119.64^{bc}	126.45^{bc}	120.43^{bc}	0.013	8.06
Neck (g)	33.84^{d}	40.72^{abc}	44.58^{a}	44.78^{a}	38.29^{cd}	41.48^{abc}	43.53^{ab}	40.24^{abc}	39.56^{bc}	0.001	1.62
Heart (g)	10.52^{abc}	9.47^{c}	11.76^{a}	9.98^{bc}	11.18^{ab}	9.83^{bc}	10.43^{abc}	11.66^{a}	9.77^{bc}	0.012	0.48
Drumsticks (g)	153.12	163.42	188.78	158.15	160.55	168.69	160.74	164.11	156.85	0.050	6.84
Wings (g)	114.37	117.51	131.94	118.23	116.8	119.61	108.54	127.87	113.96	0.535	7.57
Gizzard (g)	24.94	23.95	25.35	20.50	21.50	24.79	23.51	23.35	22.37	0.173	1.30
Liver (g)	33.28	33.09	34.84	29.50	30.03	30.35	30.83	28.63	32.37	0.516	2.14
Abdominal fat (g)	68.41	70.77	64.63	72.44	80.92	75.44	94.90	76.49	77.66	0.523	2.31
Skin (g)	154.90	170.53	159.68	168.78	191.98	139.27	159.73	159.23	153.76	0.051	9.55
Head (g)	44.58	48.96	47.96	44.89	46.07	46.77	43.56	44.34	42.24	0.209	1.760
Shank (g)	71.79	80.32	90.19	79.31	82.28	81.8	77.3	80.36	73.84	0.073	3.670
Breast (%)	33.40^{ab}	32.91^{b}	36.10^{a}	30.80^{bc}	29.20^{b}	33.93^{ab}	28.96^{b}	31.04^{bc}	33.33^{ab}	0.000	0.484
Thigh (%)	21.98	23.18	24.19	23.17	22.09	23.72	22.27	22.87	22.30	0.699	0.307
Back (%)	11.61^{a}	11.70^{a}	11.83^{a}	8.91^{b}	11.62^{a}	10.38^{ab}	10.48^{ab}	11.01^{ab}	10.83^{ab}	<0.0001	0.244
Necks (%)	0.03	0.03	0.03	0.04	0.03	0.03	0.04	0.04	0.04	0.110	0.072
Heart (%)	0.91^{abc}	0.78^{c}	0.90^{abc}	0.84^{bc}	0.96^{ab}	0.81^{c}	0.91^{abc}	1.02^{a}	0.88^{abc}	0.016	0.017

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
The means within the same row with at least one common letter, do not have significant difference (P>0.05).
SEM: standard error of the means.

The complete FM replacement by BSFL FF meal resulted a higher FI (P<0.05) whereas BSFL DF meal resulted a lower FI (P<0.05) compared to the control diet.

Cockcroft (2018) mentioned that the fat content of the insect meal has the appetite lipophilic growth stimulants which enables the bird to consume more feed. Further the defatting technique could result in losing lipophilic growth stimulants. The EE content of BSFL meals (Table 3) clearly verifies the variation of FI of birds. Reduced insect fat in meals can reduce palatability stimulants and Butcher and Nilipour, (2002) ensure higher broiler production with an average daily gain of 50g, FCR of 1.85, and slaughter live weight of 1.5-2 kg at 35 days under the best management and nutrition supplement. FI may be influenced by BSFL-incorporated diets due to habitual consumption, and is further influenced by increased levels of propionate in BSFL meals, which can induce satiety and play a role in appetite regulation (Abd El-Hack *et al.* 2020).

The inclusion of BSFL in various processing techniques significantly influences FI and consumer willingness to consume. Up to 15% BSFL FF was found to increase FI in broiler diets, while increasing BSFL meal inclusion levels reduced FI and BWG (Marono *et al.* 2017; Cockcroft, 2018). Chitin in monogastric animals may cause poor performance due to its inability to be digested easily, and the presence of unidentified growth factors in FM may influence growth differences (Longvah *et al.* 2011; Ravindran, 2013).

The control diet showed higher BWG than T4, T5 and those fed all the other BSFL DF meal incorporated diets, possibly due to the availability of insect derived protein from dietary BSFL supplementation, which enhances intestinal absorption by antimicrobial peptides against gastrointestinal microbiota (Józefiak and Engberg, 2017). The study reveals that FI is crucial for broiler growth, promoting increased BWG while reducing maintenance energy. Modern genetic potential can enhance appetite while ensuring dietary, management, and bird factors. The study suggests that the use of mash diets in broiler nutrition may result in reduced growth performances due to the smaller particle size, despite previous studies indicating the benefits of pelleted diets.

Limited research on replacing FM with BSFL in broilers shows no significant effect on growth performances (Mohammed, 2017; Dzepe *et al.* 2021). However, Opoku *et al.* (2019) found significantly lower growth performance in broilers fed a control diet. Importantly FM replacement by BSFL DF meal is hardly evidenced in the past research studies. Studies have shown that incorporating BSFL meal can improve growth performance in poultry, replacing conventional feed ingredients like SBM and FM (Uushona, 2015; Kierończyk *et al.* 2020; Kim *et al.* 2020; Sypniewski *et al.* 2020; Dabbou *et al.* 2021).

The effects of experimental treatment effect on carcass characteristics is summarized in Table 8. The major carcass parts including breast, thigh and back weights and the rest of the parts inclusive of neck and heart weights were affected (P<0.05) by the treatments. The highest heart weight (P<0.05) was seen in birds fed with T8. The meat market prioritizes quality and budget, with consumers opting for cut meat over whole carcasses. "Value for money" encourages heavier carcass purchases due to higher protein content (Sprole and Kendall, 1986; Fisher, 2013). The experiment showed that replacing 50% FM with BSFL FF improved carcass weight and protein deposition, but increased BSFL inclusion led to decreased performance. Neck areas are popular for carcass parts, and BSFL FF meals outperform carcass parts weights. Up to 50% application of FM portion has positive modulations economically over significant carcass characteristics.

In a similar study where the FM was replaced by BSFL FF meal at 33% inclusion level in 49-d old Cobb 500, chickens also had not significant effect on tested carcass characteristics except the dressing percentage (76.12%) (Mohammed, 2017). Considering complete replacement of FM by BSFL FF meal, major carcass parts were outperformed by the control treatment (Opoku *et al.* 2019). The study found a similar trend between control and T5 treatments, suggesting that BSFL FF meal may not be an economical or effective complete replacement for FM or BSFL DF meal may also not be effective from the production sense. A study involving BSFL and dietary inclusion at 75:25 and 50:50 levels showed significant increases in carcass weight, thigh, and breast weights (Mutisya *et al.* 2021). Onsongo *et al.* (2018) found that incorporating 5% BSFL FF meal resulted in the highest final body weight for 49-day-old Cobb 500 broiler chicken without any treatment effect.

Previous research indicated that over a few broiler studies have found no significant effect of BSFL meal on carcass characteristics when compared to other conventional protein sources (Schiavone *et al.* 2018; Kim *et al.* 2020; Dabbou *et al.* 2021). But, Cockcroft (2018) experienced an increasing thigh weight for broiler (32 day old) who fed 15% BSFL FF meal replacing SBM in their diets. Meanwhile, Schiavone *et al.* (2019) who incorporated 15% partially defatted BSFL meal into male broilers (Ross 308, 35 day old) had obtained the highest carcass weight. Therefore, it is suggested that BSFL meal replacement for the conventional feed in different inclusion levels can positively affect the broiler carcass characteristics.

The effects of treatment on the digestive tract is summarized in Table 9.

Table 9 Average broiler digestive tract measurements as influenced by inclusion of BSFL FF meal and BSFL DF meal

Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9	P-value	SEM
Proventriculus (g)	6.99^{bc}	7.27^{b}	8.29^{a}	6.43^{bc}	6.75^{bc}	6.89^{bc}	6.42^{bc}	6.73^{bc}	5.93^{c}	0.028	0.40
Large intestine length (cm)	9.69^{c}	9.48^{bc}	9.47^{c}	11.47^{a}	11.81^{a}	11.49^{a}	11.58^{a}	11.14^{ab}	11.35^{ab}	0.003	0.44
Full- Small intestine (g)	55.02	56.12	60.02	55.44	58.91	57.55	49.96	55.74	54.33	0.265	2.55
Empty intestine (g)	38.93	40.27	44.10	39.42	40.51	40.96	35.87	39.07	39.20	0.516	3.60
Large intestine (g)	4.06	3.61	4.61	3.66	3.35	3.83	3.66	4.31	3.60	0.424	0.39
Ceca (g)	12.43	11.04	12.49	11.99	10.31	9.25	9.92	10.05	10.55	0.136	0.90
Small intestine length (cm)	177.87	174.77	188.54	181.36	187.64	158.10	167.97	179.84	167.52	0.593	12.88
Ceca length (cm)	20.64	22.22	22.63	22.19	21.47	21.16	19.68	21.65	21.42	0.273	0.82

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
The means within the same row with at least one common letter, do not have significant difference (P>0.05).
SEM: standard error of the means.

The highest proventriculus weight (P<0.05) was seen in chicks fed with T3. When increasing BSFL FF meal beyond 5% level and BSFL DF from 2.5 to 10% increased (P<0.05) the large intestine length. Further, the BSFL meal in any form had not significant effect for the rest of the intestinal morphometry investigated. The proventriculus, or true stomach, initiates digestion by breaking down feed with hydrochloric acid and digestive enzymes like pepsin, Hence, the initial ingested food digestion is well functioned in T3, which facilitating efficient absorption and growth performance.

The large intestine is the final location of water reabsorption. An increased absorption indicated for T4-T9. Similarly, Mohammed (2017), Onsongo (2017), Opoku *et al.* (2019), and Mutisya *et al.* (2021) reported no treatment's impact on the digestive organs when replacing FM by BSFL FF meal into broilers. Further, the numerous experiments conducted for replacing other conventional protein sources by BSFL meal, (Uushona, 2015; Onsongo, 2017; Schiavone *et al.* 2017; Kim *et al.* 2020; Dabbou *et al.* 2021) did not evidenced any effect over gut morphometry. Therefore, inclusion BSFL meal either FF or DF forms into broiler diets had no negative effect functional properties of digestion.

There was no significant difference in the meat quality characteristics examined (P>0.05) (Table 10). The study found no negative impact of incorporating BSFL meal into broiler diets, as the color of the meat is the primary factor determining consumer purchasing intent. Notably, the L* (paleness) value of the tested carcass samples had exceeded the pale, soft, and exudative (PSE) threshold level as well as within the normal broiler meat color range which strengthens the purchasing intent of consumers.

Muscle pH affects meat color, texture, and biochemical state, affecting muscle to meat conversion, tenderness, and juiciness properties, and is above the isoelectric point (pH 5.3) of major proteins (Van Laack *et al.* 2000; Cockcroft, 2018). Low pH or denatured proteins in meat cause weak gel formation, soft texture, and drip loss, affecting meat palatability due to water, iron, and protein leakage through myofibers. Pale meats have permeable cell membranes and lower WHC, indicating moisture loss and high protein fluid loss (Guo and Dalrymple, 2022). This affects cooking loss, raw muscle protein characteristics, and meat quality in further-processed products. Nevertheless, a number of investigations found no difference in the physical characteristics; the color (Schiavone *et al.* 2019; Popova *et al.* 2020; Murawska *et al.* 2021) and pH (Dahiru *et al.* 2016) variation was observed with BSFL inclusion level and its pigments. The experiment results align with normal broiler meat quality ranges, suggesting that any BSFL meal inclusion level may not negatively impact the meat's physical properties.

The effect of dietary treatments and the organoleptic properties are presented in Figure 1. The sensory attributes as suggested by the Friedman test were significant (P<0.05). The highest score was recorded for T3 which was followed by the least score was recorded for T2. The highest attribution for aroma, color, flavor and overall were seen in T3 whereas highest juiciness was reported for T5. Both T4 and T9 were ranked for tenderness at their highest levels. The fact content may have a greater effect over the meat's flavor and palatability.

Moreover, even the small amount of oxidized fatty acid content may have significantly affect for meat flavor (Mutisya *et al.* 2022).

Table 10 Average (± standard error) physical properties as influenced by inclusion of BSFL FF meal and BSFL DF meal

Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9	P-value	SEM
L*	54.82	57.11	58.49	57.38	53.89	55.92	54.93	56.55	58.67	0.267	1.17
a*	12.39	11.62	12.11	11.9	12.41	13.29	12.97	11.14	12.77	0.362	0.65
b*	20.11	18.4	15.53	16.29	18.38	20.4	16.81	16.97	19.11	0.687	1.48
pH	5.82	5.69	5.73	5.74	5.59	5.81	5.75	5.7	5.64	0.413	0.08
Texture (N)	5.77	5.54	7.18	5.82	6.37	6.71	5.38	6.72	8.24	0.916	0.16
Drip loss %	4.35	3.82	5.50	4.99	3.85	3.54	3.74	3.27	3.30	0.885	0.358
Cooking loss %	44.23	46.19	53.57	48.02	53.39	44.4	46.68	48.22	46.89	0.351	1.37
Cooking yield %	56.64	54.42	47.24	52.09	47.01	56.33	54.58	52.06	54.85	0.174	1.41

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
L*: lightness; a*: redness and b*: yellowness.
SEM: standard error of the means.

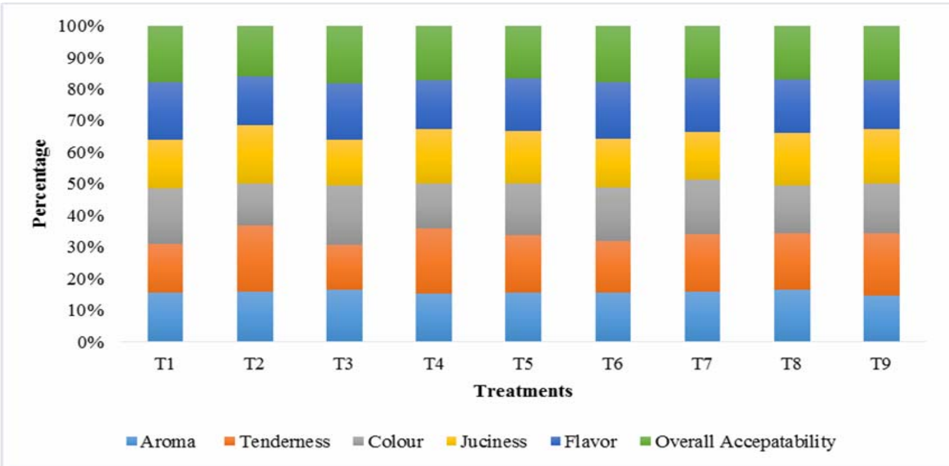

Figure 1 Evaluation of organoleptic properties of breast meat of broiler chickens fed different dietary treatments

Table 11 The economic analysis of the experiment

Item	T1	T2	T3	T4	T5	T6	T7	T8	T9	P-value	SEM
Cost of feed (LKR/kg)											
Starter feed	356.63	360.82	365.02	369.56	375.09	354.14	361.00	367.69	374.63	-	-
Finisher feed	319.24	324.66	330.08	335.22	342.17	323.13	328.23	331.75	336.02	-	-
Feed intake											
Starter phase (kg)	0.585^{d}	0.583^{de}	0.596^{c}	0.580^{b}	0.634^{a}	0.540^{g}	0.617^{b}	0.580^{e}	0.556^{f}	<0.05	1.32
Finisher phase (kg)	0.840^{c}	0.898^{ab}	0.907^{abc}	0.926^{a}	0.914^{c}	0.872^{bc}	0.906^{abc}	0.876^{abc}	0.780^{d}	<0.05	31.36
Cumulative feed intake (kg)	1.425^{bc}	1.481^{ab}	1.503^{ab}	1.506^{a}	1.549^{bc}	1.412^{c}	1.523^{ab}	1.456^{bc}	1.336^{d}	<0.05	31.36
Cost of feed (LKR/bird)											
Starter phase	208.54^{f}	210.45^{e}	217.64^{c}	214.16^{d}	237.90^{a}	191.32^{g}	222.64^{b}	213.08^{d}	208.39^{f}	<0.05	2.00
Finisher phase	268.08^{c}	291.54^{ab}	299.32^{ab}	310.47^{a}	312.83^{a}	281.77^{bc}	297.35^{ab}	290.72^{ab}	262.0^{c}	<0.05	3.43
Total feed cost (LKR)	476.62^{d}	501.99^{c}	516.97^{bc}	524.63^{b}	550.73^{a}	473.10^{d}	519.99^{bc}	503.80^{bc}	470.40^{d}	<0.05	4.76
Slaughter weight (kg)	1.154	1.209	1.305	1.182	1.160	1.208	1.141	1.147	1.099	0.141	15.40
Sales of birds (LKR)	1269.4	1329.9	1435.5	1300.2	1276	1328.8	1255.1	1261.7	1208.9	0.177	16.93
Gross profit margin	792.78	827.91	918.53	775.57	725.27	855.70	735.11	757.90	738.50	0.177	18.20
Cost benefit Ratio	2.7	2.6	2.8	2.5	2.3	2.8	2.4	2.5	2.6	0.061	0.04
Return on investment	166.333	164.923	177.677	147.832	131.692	180.873	141.369	150.435	156.993	0.061	4.22

T1: control diet; T2: fishmeal replaced in control diet at 2.5% with BSFL full-fat meal; T3: fishmeal replaced in control diet at 5% with BSFL full-fat meal; T4: fishmeal replaced in control diet at 7.5% with BSFL full-fat meal; T5: fishmeal replaced in control diet at 10% with BSFL full-fat meal; T6: fishmeal replaced in control diet at 2.5% with BSFL de-fatted meal; T7: fishmeal replaced in control diet at 5% with BSFL de-fatted meal; T8: fishmeal replaced in control diet at 7.5% with BSFL de-fatted meal and T9: fishmeal replaced in control diet at 10% with BSFL de-fatted meal.
The means within the same row with at least one common letter, do not have significant difference (P>0.05).
SEM: standard error of the means.
Sales of 1kg slaughtered weight of broiler at the time of selling was Rs.1100.

Onsongo *et al.* (2018), and Cullere *et al.* (2019) reported no effects in regards to any sensory feature. But, Mutisya *et al.* (2022) experienced a positive correlation when broilers fed a diet replacing FM by 25%:BSFL 75% completely for its sensory attributes. In contrast, Murawska *et al.* (2021) observed a higher response for the control treatment with a decreasing linearly when BSFL meal replacement into SBM. Further, odor, flavor and texture attributes were not affected when quails fed with 10% and 15% BSFL meal incorporated diets (Cullere *et al.* 2018).

The economic analysis in-terms of CBR and ROI replacing fishmeal with BSFL meal in broiler diets are summarized under Table 11. With respect to the FI and the cost of feed consumed per kilogram, a gradual increment was indicated with increasing inclusion of BSFL meal in FF basis. But T9 found to be the cheapest diet amongst and T5 found the most expensive diet in both phases. Even though the rest economical parameters were affected by BSFL replacement, T3 for FF and T6 for DF BSFL included meals indicated the profitable diet in-terms of economic and production sense.

CONCLUSION

There were no negative effects identified when birds fed with BSFL meals. When BWG and FCR are concerned inclusion of FF or DF BSFL from 2.5 to 10% in broiler diets had not negative impact during the starter, finisher or whole period tested. Inclusion of DF-BSFL meal resulted the lowest FIs of birds during starter (2.5%), finisher (10%) and entire period (10%) tested. Inclusion of FF BSFL at 5% level improved breast weights. The birds fed with FF BSFL at 5% level yielded the highest thigh, back, neck and heart weights. The meat quality parameters were not affected by BSFL inclusion. Inclusion of FF BSFL up to 5% level and inclusion of DF BSFL at 2.5 to 10% increased the large intestine length. Sensory data suggests that the meat obtained from the birds fed 5% FF BSFL and 2.5% DF BSFL ranked the best in their respective diet's series. Feeding 10% FF BSFL is beneficial in-terms of cost of feed per bird. Considering all the tested attributes, 5% FF BSFL from FF treatments and 2.5% DF BSFL from DF treatments showed the best performance among experimental treatment.

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