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Cost-Effectiveness of Black Soldier Fly Larvae Meal as Substitute of Fishmeal in Diets for Layer Chicks and Growers

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Abstract: The acceptance of eco-friendly black soldier fly larvae meal (BSFLM) as sustainable alternative protein ingredient in poultry feeds continues to gain momentum worldwide. This study evaluates the impact of BSFLM in layer chick and grower diets on the growth, carcass quality and economic returns. Mean weekly weight gain and total live weight per chick and grower varied significantly. The highest final weight gain was achieved when birds were provided diet with 25.6% BSFLM. Average daily feed intake (ADFI), average daily weight gain (ADG) and overall weight gain of the chick varied significantly, except for the feed conversion ratio (FCR). For grower birds, ADFI, ADG, FCR and overall weight gain did not vary significantly across the various feeding regimes. The weight of the wings and drumsticks had a quadratic response with a maximum weight obtained at 33% inclusion of BSFLM. The weight of the internal organs were not significantly affected by dietary types. Positive cost–benefit ratio and return on investment was recorded for diet types with higher BSFLM inclusion levels (>75%). Diets with 25% and 100% BSFLM inclusion were the most suitable and cost-effective, respectively. Thus, BSFLM represents a promising alternative source of protein that could be sustainably used in the poultry industries.

Keywords: black soldier fly; insect-based feed formulation; chicken layers; carcass and organs yield; profitability; sustainable intensification

1. Introduction

Poultry farming is one of the fastest livestock sub-sector that has rapidly grown in recent decades globally. The fast-growing poultry sector continues to attract formation of small-scale farmer cooperatives across the world, employing millions of people directly in the production and marketing, and indirectly through linkages with input suppliers (day-old-chicks, feeds, and veterinary services) [1]. Due to the rapid growth in the poultry sector, poultry farming has become a much attractive agribusiness to resource poor communities because of they require low starting capital, space and maintenance costs [1]. This demand in turn is driven by rapid economic growth as a result of the alarmingly growing population that has created an increasing need to consume more animal proteins [2]. The demand in developing countries for poultry products is projected to increase by 70% to feed 9.2 billion people worldwide by 2050 [3], thus putting even more pressure on the need to produce more animal proteins such as poultry eggs and meat.

Isa Brown (IB) chicken is one of the most common commercial layers bred and supplied to enfranchised local companies for multiplication worldwide. In many countries, the current focus is to upscale improved hybrid layer birds to smallholder households [2] because they are commercially highly productive and profitable. The IB chicken are considered an excellent bioconverters of compounded feeds to high quality eggs, consume a relatively low amount of feed and yet produce more eggs with better shell quality than other common layer breeds [4]. Thus, the poultry farmers make very quick returns on investment because of the short generation time required before the hen lays eggs. Although, the fast-rising section continued to attract formation of many small-scale farmer co-operatives across different countries, the lack of high-quality feed has hampered most of the birds from being able to express their full genetic egg laying potential.

Good nutrition is key for efficient and profitable poultry production but the high price of poultry feeds, which represents over 70 percent of total cost of production, has hampered the sector from realizing its full potential [5,6]. This cost is mainly driven by the growing scarcity of feed protein ingredient resources like fishmeal (FM) and soybean [7]. The prices of fish and soya bean have doubled globally during the last 5 years [7], leaving farmers with very limited profit margins. Furthermore, FM in many countries have been reported to be adulterated, leading to lower quality being available in the market. Low crude protein (CP) values ranging from 40.3% to 55.1% DM have commonly been reported against the expected CP content of >65% DM of FM [8–10]. Continued dependence on FM and SBM for poultry feed is not a sustainable option, especially for smallholder farmers, thus necessitating the search for sustainable alternatives such as insect-based larval proteins [5,11].

In recent years, the utilization of insect meal as high-quality ingredients in chicken, pig and fish diets has grown rapidly [7,12,13]. Insects have high, good quality protein contents and can be mass produced with a low environmental footprint due to low generation of greenhouse gases [14]. The use of insect meals in animal diets is economically more competitive compared to diets containing conventional protein ingredients in poultry diets [7]. Morever, consumers have also been reported to accept products from livestocks reared on compounded feeds containing insect meal [15].

Hermetia illucens L is commonly called black soldier fly (BSF), are potentially low-cost nutrient-rich alternative protein source, that is similar or superior in protein quality to FM and plant sources [16,17]. The processed larvae of this insect is rich in nutrients such as crude protein content (38.5–62.7%) with well-balanced amino acids profile, good quality fatty acids (14.0–39.2%) and micronutrients such as iron and zinc [7,11,13,17]. However, the nutritional status of these insects might vary depending on the species, developmental stage, and rearing substrates [18,19]. Several studies on the use of BSF larvae meal (BSFLM) in commercial feeds have largely focused on broiler [7], pig [13] and fish [12]) rather than layers. In literature, few studies on chicken layers have largely focused from the point of egg laying both for non-defatted BSFLM [20] or defatted BSFLM [21,22] based feeds. Also, chick, pullet, and layer birds, each has its own specific nutritional requirements, which must be considered when formulating their feed [23]. The studies described illustrated differences in body weight only at the onset of egg production because it is a major factor influencing the efficiency of egg production [20–22]. Although, laying hen are not raised for meat, the lack of information on the growth of the visceral organs could have a detrimental impact on egg productivity. For example, the weights of some *visceral organs* have been shown to be affected by dietary treatment [24]. Also, during feed restriction or change, the physical development of birds usually gives priority to the development of the internal organs, which are capable of recovering more quickly than other parts of the body [25]. According to Obeng et al. [26], changes of internal organs in growing birds could improve or hinder the utilization rate of energy, protein, amino acids, and other nutrients required to enhance their performance and resistance to many diseases. Globally, the effects of diets with varying inclusion levels of non-defatted BSFLM on IB chick and pullet (growers) are less well understood, though these developmental stages of the birds are considered to be highly susceptible to changes in dietary nutrients [24]. Therefore, the aim of this study was to evaluate differences in performance, feed utilization efficiency, body weight composition (carcass parts and internal organ development) and potential returns of investment of layer IB chick and grower bird fed *ad libitum* on diets with strategically inclusion levels of non-defatted BSFLM.

2. Materials and Methods

2.1. Ethical Approval

Ethical approval for the study was provided by the Institutional Animal Care and Use Committee (IACUC) of Kenya Agricultural and Livestock Research Organization (KALRO)-Veterinary Science Research Institute (VSRI); approval Code No.: KALRO-VSRI/IACUC019/30082019.

2.2. Experimental Facility

The experiments were conducted at the Poultry Research Unit of the Kenya Agricultural and Livestock Research Organisation (KALRO), Naivasha. We ensured adequate care and the conditions of the chickens were maintained following the procedures established by the Federation of Animal Science Societies [27]. The facility is located at 1800 m, above sea level, (0°43′12.85″ S, 36°25′ 42.71″ E) and receives mean annual rainfall of 1000 mm and has an ambient temperature ranging from 17 to 22 °C.

2.3. Experimental Birds and Housing

Before commencement of the experiment, 250 one-day-old female IB chicks had an initial average body weight of 36.39 ± 0.18 g when sourced from Kenchic Limited, Nairobi, Kenya. During the first two weeks of acclimatization, all the 1-day old birds (chicks) were kept together in a brooder, which was a round deep litter floor covered with a 7.6 cm-thick layer of wood shavings bedding. The area was fitted with 250 Watts infra-red bulbs to provide heating during the brooding period. For a period of 14 days, the young birds were provided the control (100% FM inclusion ratio) diet and water *ad libitum* for 14 days. However, birds that showed sign of deformity or weakness (25 chicks) were carefully removed. After14 days, they were weighed and kept in different floor pens (1 m × 1 m) each with five chicks. The chicks were assigned randomly to one of the five feeding regimes using completely randomized design throughout the entire developmental feeding phase. The pens were constructed in a house with cemented floor and separated from each other using wire mesh. Each experimental set-up was replicated nine times. Plastic feeders (73 cm by 26 cm width by 48 height) with open top and 8 small holes were provided to allow the birds access feeds. A 3 litre plastic drinking containers were placed in each chicken pen. The birds were given access to both feed and clean water *ad libitum* daily. The conditions inside the rearing facility were kept at 30 ± 1 °C with relative humidity (RH) of 70 ± 2%. Within the first 4 weeks, 24 h of lighting was used to stimulate feed and water intake among the chicks. This was later followed by gradual decrease of hours of lighting to adapt to natural conditions with dark: light cycle of 12 h:12 h by the end of chick stage. Further lighting conditions were maintained with dark: light cycle of 12:12 h throughout the grower phase.

The vaccination programme of the birds followed the generally agreed guidelines for the prevention of any disease-causing bacteria/virus that could build up by boosting the birds' immunity [28]. Vitamins were administered in water each time a new batch of feed was introduced and after vaccination [28]. All drinkers were cleaned daily, and clean water offered to the birds every morning. Feeds were placed in plastic feeders each morning at 08:30 h. Sawdust were used as bedding in the pens and changed every 3 weeks to avoid ammonia build up and bacterial infection.

2.4. Determination of Nutrient Composition in Feed Ingredient and Diet Types

All ingredients required for the formulation of the various diet types for both the chicks (Table 1) and pullets (grower) (Table 2) were sourced from well-known feed miller in the region, Josiche General Traders Ltd. (Nakuru, Kenya). The larvae of BSF used for the feeding experiment were obtained from the International Centre of Insect Physiology and Ecology (*icipe*), located in Nairobi, Kenya. The larvae were raised on barley spent grains obtained from the Kenya Breweries Limited. The conditions of the production facility were kept at 28 ± 1 °C, relative humidity of 60–70% and 12: 12 (light: dark) photoperiod. Once the larvae became 5th instars, they were harvested and washed by deeping them in a container boiling water (84 °C) for 8–10 min. Thereafter, the larvae were dried using stainless-steel trays in a food drying machine (Model: CT-C-III, Henan, China) at 120 °C for 2 h 30 min to ensure that the processed larvae were safe for incorporation into animal feed. Several studies to date have raised concerns of the safety levels of *H. illucens* due to the contaminated nature of the rearing substrates [29,30], despite the excellent nutritional properties.

The sterilized and dried larvae were then ground into powder and mix up with other raw materials to formulate five diet types for the chick and grower pullets. Calculated estimate of the ingredients used in the formulated diets followed the nutrient requirements guidelines for chicks and grower [23]. The insect meal was used to replace FM partially and completely at various inclusion levels: Diet 1 (control) (100% FM + 0% BSFLM); Diet 2 (75% FM + 25% BSFLM); Diet 3 (50% BSFLM + 50% FM); Diet 4 (75% BSFLM + 25% FM) and Diet 5 (100% BSFLM + 0% FM). The diet formulation was based on BSFLM crude protein (CP) content of 46.8% dry matter [13]. Average CP content of fishmeal was 47.7%, which is within the range commonly reported in Kenya against the expected CP content of >65% DM [8–10]. All diets for the entire experimental period were formulated at once by Josiche General Traders Ltd. following standard protocols to meet the nutrient requirements of the birds [23]. The slight variation observed in nutrient values presented in Tables 1 and 2, is a clear shortcoming, which might be attributed to processing procedures. Though, the method described above is commonly used in Sub-Saharan Africa, future research should formulate poultry diet based on standardized ileal digestibility (SID) of amino acids (AA) and ideal protein concept as described by Zhang and Adeola [31]. This is because insect meal, particularly BSFLM has been shown to exhibit low and variable sulphur amino acids (Methionine and Cysteine) concentration, that are the least digestible [32,33].

Thereafter, comprehensive analytical estimates of the nutrient quality of the formulated diets were also undertaken to ensure the crude protein levels for each treatment diet was within the acceptable values for chick and grower birds before the commencement of the experiments as described below. The method described by chia et al. [13] was used to determine the dry matter content of the diets based on gravimetric water loss. Using a muffle furnace the ash content was established by ignition of diets at 550-degree celcius (°C). Samples were sent to Crop Nutrition (CROPNUTS) Laboratory Services Ltd., Kenya for analysis, whereby the diets were subjected to electromagnetic scan using absorbance mode in near infrared (NIR) spectroscopy. Standard laboratory procedures were used to determine the protein content, fat content, starch content, lipid (fat), acid detergent fibre, sugar, neutral detergent fibre, and digestibility values [34–37]. Metabolizable energy of diets were calculated according to recommended procedures described by NRC [23], Rosales et al. [38], Núñez-Sánchez et al. [39] and De Marco et al. [40].

The amino acids in the formulated diet types and the insect meal were analyzed by AMINOLab® (Evonik Industries, Hanau, Germany) using conventionally acceptable methods [41–46] and the results are presented in Tables 1 and 2. The mineral composition of the diets was analyzed by CROPNUTS, which included boron, calcium, cobalt, copper, iron, manganese, magnesium, molybdenum, potassium, phosphorus, sodium, sulphur and zinc, [47–50]. The results of the diets for the chicks and the growers are presented in Tables 3 and 4, respectively.

2.5. Performance of the Birds Fed on Various Diet Types

The initial weight of each bird per cage (replicate) was taken before the commencement of the experiment. On a weekly basis, the total weight gain of each bird was recorded using a digital electronic scale (TXB6201L, Shimadzu corporation, Kyoto, Japan) and average daily feed intake (ADFI), feed conversion ratio (FCR) and average daily weight gain (ADG) were calculated weekly. The final weight, overall weight gain and number dead birds during the entire experimental period were also recorded. This was performed for both chick (0–8 weeks) and grower (8–20 weeks) birds.

2.6. Evaluation of the Carcass Yeild and Organs of Birds Fed on various Diet Types

Twenty-five birds randomly selected from the five treatments (five from each diet type) and slaughtered at the age of 20 weeks carefully following all the strict guidelines of animal welfare [13]. This exercise was undertaken to assess the influence of various diet types on the visceral organs (liver, kidney, gizzard, and heart) development and carcass yield (thighs, breast, wings, and drumsticks) of the birds. Previous study by Leeson and Summers [51] have shown that the body of birds between 15 to 19 weeks of age (i.e., before on-set of egg production) can significantly influence egg weight during the egg laying phase of the hen. Prior to the slaughtering process, selected birds were starved for 12 h and weighed individually to determine live body weight after slaughtering. The birds were killed using an electric stunner on a rotating bleeding stainless steel table. An electrically heated water bath was used for scalding at 60 °C. The feathers of the birds were removed mechanically. The dressed carcass weight of each bird was taken after removal of the head, feet, and internal organs.

2.7. Economic Analysis of Birds Fed on Various Diet Types

The approach of return on investment (RoI) and cost-benefit ratio (CBR) were utilized to assess the economic implications of substituting fishmeal with insect meal in the diets for the birds [13]. Total costs comprised of medication, feed cost, human labor, housing, electricity, water, feeders, and chicken drinkers. The cost of feed was calculated based on the quantities of each ingredient added in each dietary treatment multiplied by the respective unit prices at the time of the experiment. The difference in ratio of production revenue and total production cost was used to account for the CBR and values observed to be more than 1 implied that the benefits of production was greater than that of the production costs and vice versa. Return on investment was used to measure the financial gain/loss and higher values were considered to be better representation of the RoI [7,52].

The profit (Pr) = selling price per birds (Sp) (amount at final market size or weight)–cost price of feed consumed per chicken (Cp); CBR = Sp/Cp; RoI = Pr/Cp $\times$ 100. The final body weight, Sp, Pr, CBR and RoI were expressed as mean $\pm$ standard error of the mean.

2.8. Statistical Analysis

Polynomial regressions were employed to evaluate the influence of incorporating BSFLM in the diet types and the control diet (%BSFLM + 100%FM) on different parameters (feed intake, final weight gain, daily weight gain, live weight, dressing weight, weight of internal organs, FCR and economics) fed to the birds. Given five treatment levels; 0%, 25%, 50%, 75% and 100% increasing levels of BSFLM, we evaluated the linear, quadratic, cubic and quartic effects of diet on the measured response variables. We used the *polynom* package to estimate the maxima of quadratic polynomial curves [53] whose regression coefficients were significant at $\alpha = 0.05$. The data on cost and profit were subjected to ANOVA R software packages (version 3.5.1).

3. Results

3.1. Determination of Nutrient Composition in Feed Ingredient and Diet Type

The composition of the raw materials and BSF amino acids used in the chick and grower diet types are shown in Tables 1 and 2, respectively. While the mineral and proximate composition of the chick and grower diet types for each treatment are presented in Tables 3 and 4, respectively. There was variation in the mineral content of the various diets for the chick and growers.

Table 1. Ingredient composition, amino acid content of insect meal and formulated experimental diets fed to the chick for a period of eight (8) weeks.

Ingredient (%)	BSFLM	Diet 1 (Control)	Diet 2	Diet 3	Diet 4	Diet 5
Maize germ		60.0	60.0	60.0	60.0	60.0
Soybean meal		21.0	21.0	21.0	21.0	21.0
Fishmeal		10.0	7.5	5.0	2.5	0
BSFL		0.0	2.5	5.0	7.5	10
Vegetable oil		2.0	2.0	2.0	2.0	2.0
Limestone		5.0	5.0	5.0	5.0	5.0
Dicalcium phosphate		1.5	1.5	1.5	1.5	1.5
Iodized salt (NaCl)		0.3	0.3	0.3	0.3	0.3
Layer premix [a]		0.2	0.2	0.2	0.2	0.2
Calculated nutrient composition						
Dry matter (%)	94.9	91.6	91.7	91.5	92.4	92.2
CP (% DM)	46.6	20.4	20.2	20.1	19.9	19.7
Energy (Kcal/kg DM)		3066.8	3078.8	3090.8	3102.8	3114.8
Crude fat (% DM)		5.1	5.2	5.4	5.2	5.6
Crude fibre (% DM)		5.2	5.4	5.6	5.9	5.1
Essential amino acids (% DM)						
Methionine	0.8	0.2	0.3	0.3	0.2	0.3
Met + Cys	1.1	0.5	0.5	0.5	0.5	0.5
Lysine	2.9	0.7	0.9	0.8	0.8	0.9
Threonine	1.7	0.5	0.6	0.6	0.6	0.7
Arginine	2.2	1.0	1.1	1.1	1.0	1.1
Isoleucine	1.8	0.5	0.6	0.6	0.6	0.7
Luecine	2.9	1.1	1.2	1.2	1.1	1.3
Valine	2.6	0.7	0.8	0.8	0.8	0.9
Histidine	1.3	0.4	0.4	0.4	0.4	0.5
Phenylalanine	2.2	0.6	0.7	0.7	0.7	0.8
Non-essential amino acids (% DM)						
Glycine	2.5	0.8	0.9	0.8	0.8	0.9
Cystine	0.4	0.2	0.3	0.3	0.2	0.3
Proline	2.4	0.8	1.0	0.9	0.9	1.0
Alanine	3.0	0.8	0.9	0.9	0.9	1.0
Serine	1.8	0.6	0.8	0.7	0.7	0.8
Aspartic acid	3.9	1.2	1.5	1.5	1.4	1.6
Glutamic acid	4.9	2.3	2.7	2.5	2.4	2.7

BSFLM: Black soldier fly larval meal; [a] Super layer premix contents per 2.5 kg: Vit. (Vitamin) A: 8,000,000 IU/kg, Vit. D3:2,000,000 IU/kg, Vit. E: 3000 mg, Vit. K3: 2000 mg, Vit B2: 3500 mg, Pantothenic Acid: 6600 mg, Niacin: 20,000 mg, Folic Acid: 550 mg, Vit. B12: 6 mg, Choline chloride: 200,000 mg, Lysine: 350 mg, Methionine: 120 mg, Manganese: 63,000 mg, Iron: 23,000 mg, zinc: 63,000 mg, Copper: 14,000 mg, Cobalt: 1000 mg, Iodine: 2000 mg, Selenium: 100 mg and BHT: 120,000 mg. BSFL—Black soldier fly larvae, Ca—calcium, DCP—Dicalcium phosphate, FM—fishmeal, Diet 1—0% BSFLM, Diet 2—25% BSFLM and 75% FM, Diet 3—50% BSFLM and 50% FM, Diet 4—75% BSFLM and 25% FM and Diet 5—100% BSFLM.

Table 2. Ingredients, amino acid content of insect meal and formulated diets fed to the grower for a period of 12 weeks.

Ingredient (%)	Diet Types				
	Diet 1 (Control)	Diet 2	Diet 3	Diet 4	Diet 5
Maize germ	50.0	50.0	50.0	50.0	50.0
Pollard (wheat)	19.0	19.0	19.0	19.0	19.0
Soybean meal	13.0	13.0	13.0	13.0	13.0
Fishmeal	10.0	7.5	5.0	2.5	0.0
BSFL	0.0	2.5	5.0	7.5	10
Limestone	5.5	5.5	5.5	5.5	5.5
Dicalcium Phosphate	2.0	2.0	2.0	2.0	2.0
NaCl	0.3	0.3	0.3	0.3	0.3
Layer premix	0.2	0.2	0.2	0.2	0.2
Calculated nutrient levels					
CP (% DM)	18.5	18.3	18.1	17.9	17.8
Energy (Kcal/kg DM)	2905.4	2917.2	2929.4	2941.4	2953.4
Crude fat (%DM)	5.3	5.1	5.9	5.7	5.6
Crude fibre (% DM)	4.8	5.0	5.2	5.4	5.6
Essential amino acids (% DM)					
Methionine	0.3	0.3	0.3	0.3	0.3
Met + Cys	0.6	0.6	0.6	0.6	0.6
Lysine	1.1	1.1	1.1	1.1	1.1
Threonine	0.7	0.8	0.7	0.7	0.8
Arginine	1.3	1.4	1.3	1.3	1.3
Isoleucine	0.8	0.8	0.8	0.8	0.8
Luecine	1.5	1.6	1.5	1.5	1.5
Valine	0.9	1.0	0.9	0.9	1.0
Histidine	0.5	0.5	0.5	0.5	0.5
Phenylalanine	0.9	1.0	0.9	0.9	0.9
Non-essential amino acids (% DM)					
Cystine	0.3	0.3	0.3	0.3	0.3
Glycine	0.8	0.9	0.8	0.8	0.9
Serine	0.6	0.8	0.7	0.7	0.8
Proline	0.8	1.0	0.9	0.9	1.0
Alanine	0.8	0.9	0.9	0.9	1.0
Aspartic acid	1.2	1.5	1.5	1.4	1.6
Glutamic acid	2.3	2.7	2.5	2.4	2.7

Super layer premix contents per 2.5 kg: Vit. (Vitamin) A: 8,000,000 IU/kg, Vit. D3:2,000,000 IU/kg, Vit. E: 3000 mg, Vit. K3: 2000 mg, Pantothenic Acid: 6600 mg, Vit B2: 3500 mg, Niacin: 20,000 mg, Folic Acid: 550 mg, Manganese: 63,000 mg, Vit. B12: 6 mg, Choline chloride: 200,000 mg, Lysine: 350 mg, Methionine: 120 mg, Iron: 23,000 mg, zinc: 63,000 mg, Copper: 14,000 mg, Cobalt: 1000 mg, Iodine: 2000 mg, Selenium: 100 mg and BHT: 120,000 mg. BSFLM—Black soldier fly larval meal, Ca—calcium, DCP—Dicalcium phosphate; FM-Fishmeal; Diet 1—0% BSFLM, Diet 2—25% BSFLM and 75% FM, Diet 3—50% BSFLM and 50% FM, Diet 4–75% BSFLM and 25% FM and Diet 5—100% BSFLM.

Table 3. The proximate analysis and mineral content of chick diet types.

Mineral	Diet Types				
	Diet 1 (Control)	Diet 2	Diet 3	Diet 4	Diet 5
Boron (ppm)	12.2	13.1	13.8	12.2	12.8
Molybdenum (ppm)	1.4	1.3	1.4	1.5	1.4
Iron (ppm)	666.0	818.0	524.0	574.0	481.0
Copper (ppm)	9.4	11.7	9.2	7.8	26.8
Zinc (ppm)	70.8	70.6	63.1	54.8	67.0
Cobalt (ppm)	0.4	0.8	0.3	0.2	0.3
Manganese (ppm)	62.8	86.8	54.0	40.5	43.5
Sodium (ppm)	1530.0	1550.0	1280.0	1790.0	1690.0
Sulphur (%)	0.2	0.2	0.2	0.2	0.2
Magnesium (%)	0.4	0.5	0.5	0.5	0.5
Potassium (%)	1.1	1.1	1.2	1.1	1.1
Phosphorus (%)	0.8	0.7	0.7	0.6	0.6
Starch (%)	28.2	26.2	26.8	28.1	27.0
Ash (%)	7.0	6.8	6.7	6.4	6.4
CP (%)	19.4	20.6	19.5	19.7	20.0
Oil (%)	5.81	6.11	5.62	5.3	5.51
ADF (%)	12.3	13.9	15.3	12.2	13.5
Calcium (%)	4.5	4.5	3.3	3.5	3.2
NDF (%)	27.7	32.2	34.2	31.3	34.4
Digestibility (NCGD) (%)	75.7	73.1	70.2	73.9	70.6
Metabolizable energy (Kcal/kg)	2904	2875	2871	2845	2872

BSFLM—Black soldier fly larval meal; FM—Fishmeal; Diet 1: 100%FM + 0%BSFLM; Diet 2: 75%FM + 25%BSFLM; Diet 3: 50%BSFLM + 50%FM; Diet 4: 75%BSFLM + 25%FM; Diet 5: 100% BSFLM + 0%FM; ppm = parts per million; NCGD = neutral cellulase gammanase digestibility.

Table 4. The proximate analysis and mineral content of grower diet types.

Parameter	Diet Types				
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5
Boron (ppm)	6.3	7.5	7.2	6.4	6.4
Molybdenum (ppm)	1.4	1.2	1.3	1.0	0.8
Iron (ppm)	667.0	539.0	588.0	554.0	394.0
Copper (ppm)	10.0	17.7	12.0	16.8	11.9
Zinc (ppm)	80.7	70.9	70.3	58.4	71.3
Cobalt (ppm)	1.5	0.9	0.3	0.4	0.5
Manganese (ppm)	90.0	90.8	91.2	70.2	78.3
Sodium (ppm)	1640.0	1600.0	1530.0	1120.0	1140.0
Sulphur (%)	0.2	0.2	0.2	0.2	0.2
Magnesium (%)	0.5	0.5	0.5	0.5	0.5
Potassium (%)	0.9	0.9	1.0	0.9	1.0
Phosphorus (%)	0.9	0.9	0.7	0.6	0.6
Starch (%)	29.7	32.0	29.8	29.6	26.9
Ash (%)	9.8	9.7	8.7	12.9	8.1
CP (%)	17.8	17.8	17.5	17.3	17.9
Oil (%)	6.4	6.1	6.7	5.47	5.6
ADF (%)	11.9	9.53	12.4	12.9	11.7
Calcium (%)	5.4	4.6	4.5	6.6	3.0
NDF (%)	32.5	29.5	34.2	34.7	33.8
Digestibility (NCGD) (%)	75.0	77.9	74.1	72.8	74.3
Metabolizable energy (Kcal/kg)	2900	2900	2902	2904	2905

BSFLM—Black soldier fly larval meal; FM—Fishmeal; Diet 1: 100%FM + 0%BSFLM; Diet 2: 75%FM + 25%BSFLM; Diet 3: 50%BSFLM + 50%FM; Diet 4: 75%BSFLM + 25%FM; Diet 5: 100% BSFLM + 0%FM. ppm = parts per million; NCGD = neutral cellulase gammanase digestibility.

3.2. Performance of the Birds (Chick and Grower) Fed on Various Diet Types

The performance of the layer chicks fed on the various diets is presented in Table 5. In the starter phase of the chick, the regression analyses showed a significant linear decrease in final weight as well as overall weight with increase in substitution of FM with BSFLM ($p < 0.001$). For every percentage increase in BSFLM, the layer chicks lose 1.3 g of final weight and the same amount for overall weight gain. ADG and ADFI linearly decreased with increase in replacement of FM by BSFLM ($p < 0.001$) while FCR was not significantly affected (Table 5).

Table 5. Growth performance of Isa Brown layer chicks (8 weeks) and grower (12 weeks) when fed different experimental diet types.

Parameter	Dietary Treatments					Polynomials		
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Linear	Quadratic	Cubic
Chick stage								
Bird initial weight (g)	96.2	101.3	100.9	102.1	101.3	-	-	-
Bird final weight (g)	476.2 ^{a}	481.5 ^{a}	418.0 ^{b}	414.7 ^{b}	346.7 ^{c}	< 0.001	0.081	0.917
Bird overall weight (g)	380.0 ^{a}	380.2 ^{a}	317.1 ^{b}	312.6 ^{b}	246.3 ^{c}	< 0.001	0.148	0.969
ADG (g)	9.1 ^{a}	9.1 ^{a}	7.6 ^{b}	7.4 ^{b}	5.9 ^{c}	< 0.001	0.148	0.969
ADFI (g)	36.2 ^{a}	33.8 ^{a}	29.8 ^{b}	27.7 ^{b,c}	24.7 ^{c}	< 0.001	0.779	0.726
FCR (g/g)	3.17 ^{a}	2.78 ^{b}	3.09 ^{b}	2.68 ^{b}	3.29 ^{a}	0.754	0.548	0.872
Grower stage								
Bird initial weight (gram)	476.2	481.5	418.0	414.7	346.7	-	-	-
Bird final weight (gram)	1181.6	1264.6	1189.1	1139.6	1049.4	0.002	0.026	0.309
Bird overall weight (gram)	705.4	783.2	771.0	724.9	702.6	0.504	0.057	0.257
ADG (gram)	9.2	10.2	10.0	9.4	9.1	0.491	0.052	0.275
ADFI (gram)	84.6	84.3	84.6	78.3	75.2	0.006	0.245	0.746
FCR	1.64	1.45	1.44	1.52	1.40	0.194	0.253	0.358

ADFI—Average daily feed intake, ADG-Average daily weight gain, FCR—Feed conversion ratio, T—treatment, MSE—mean squared error. BSFLM—Black soldier fly larval meal; FM—Fishmeal; Diet 1: 100%FM + 0%BSFLM; Diet 2: 75%FM + 25%BSFLM; Diet 3: 50%BSFLM + 50%FM; Diet 4: 75%BSFLM + 25%FM; Diet 5: 100% BSFLM + 0%FM. ^{a,b,c} Means in a row with different superscript letters are significantly different at $\alpha = 0.05$, while means in row with similar superscript are not significantly different at $\alpha = 0.05$.

The performance of grower birds is presented in Table 5. The final weight of the birds was observed to show a significant quadratic response to increasing inclusion levels of BSFLM with an estimated maximum of 25.6% BSFLM inclusion. Overall weight gain increased up to a maximum of 32.1%. While ADG and FCR were not significantly affected by increasing inclusion levels of BSFLM. ADFI linearly decreased with inclusion levels of BSFLM ($p = 0.006$) (Table 5).

Both the chicks and growers fed diet 2 had better average weekly weight gain than the others until the 10th week when a sharp decline in weight gain was observed (Figure 1). Remarkable decrease in weekly weight gain of the birds from the 14th week onward toward the onset of egg production was observed (Figure 1). The total weekly live weight per bird significantly varied for both the chicks ($p = 0.002$) and grower pullets ($p = 0.021$) (Figure 2) fed on the various diets, though the trend was similar. There was a consistent live weight increase for both the chicks and growers when fed diet 2 (75%FM + 25%BSFLM), followed by those fed diet 1 (100%FM + 0%BSFLM) (Figure 2). Birds fed diet 5 (0%FM + 100%BSFLM) had the lowest total weekly live weight throughout the chick and grower experimental phases (Figure 2).

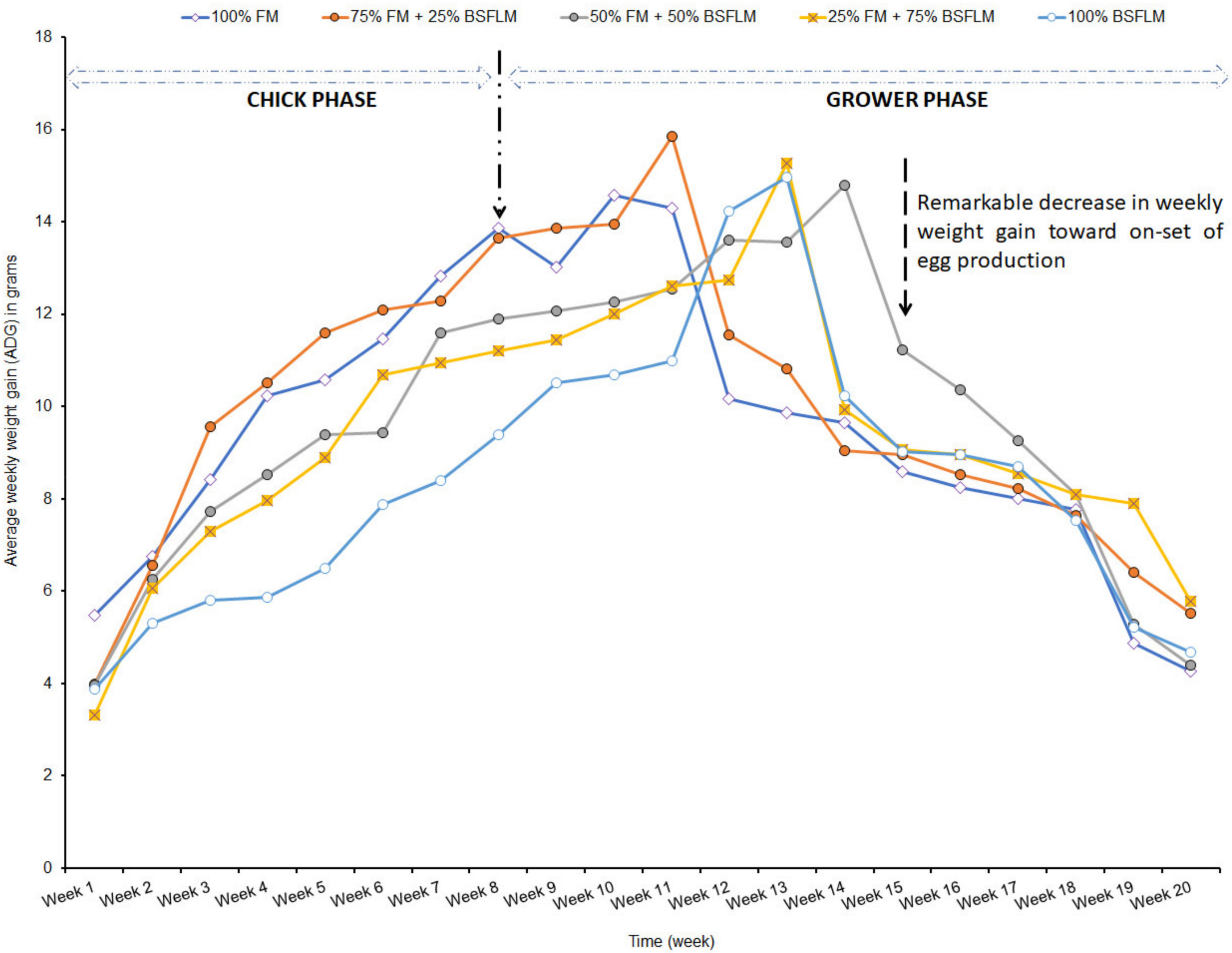

Figure 1. Average weekly weight gain (ADG) in grams of chicks and grower pullets fed on the various diets throughout the experiment. Diet 1: 100%FM + 0%BSFLM; Diet 2: 75%FM + 25%BSFLM; Diet 3: 50%BSFLM + 50%FM; Diet 4: 75%BSFLM + 25%FM and Diet 5: 100% BSFLM + 0%FM.

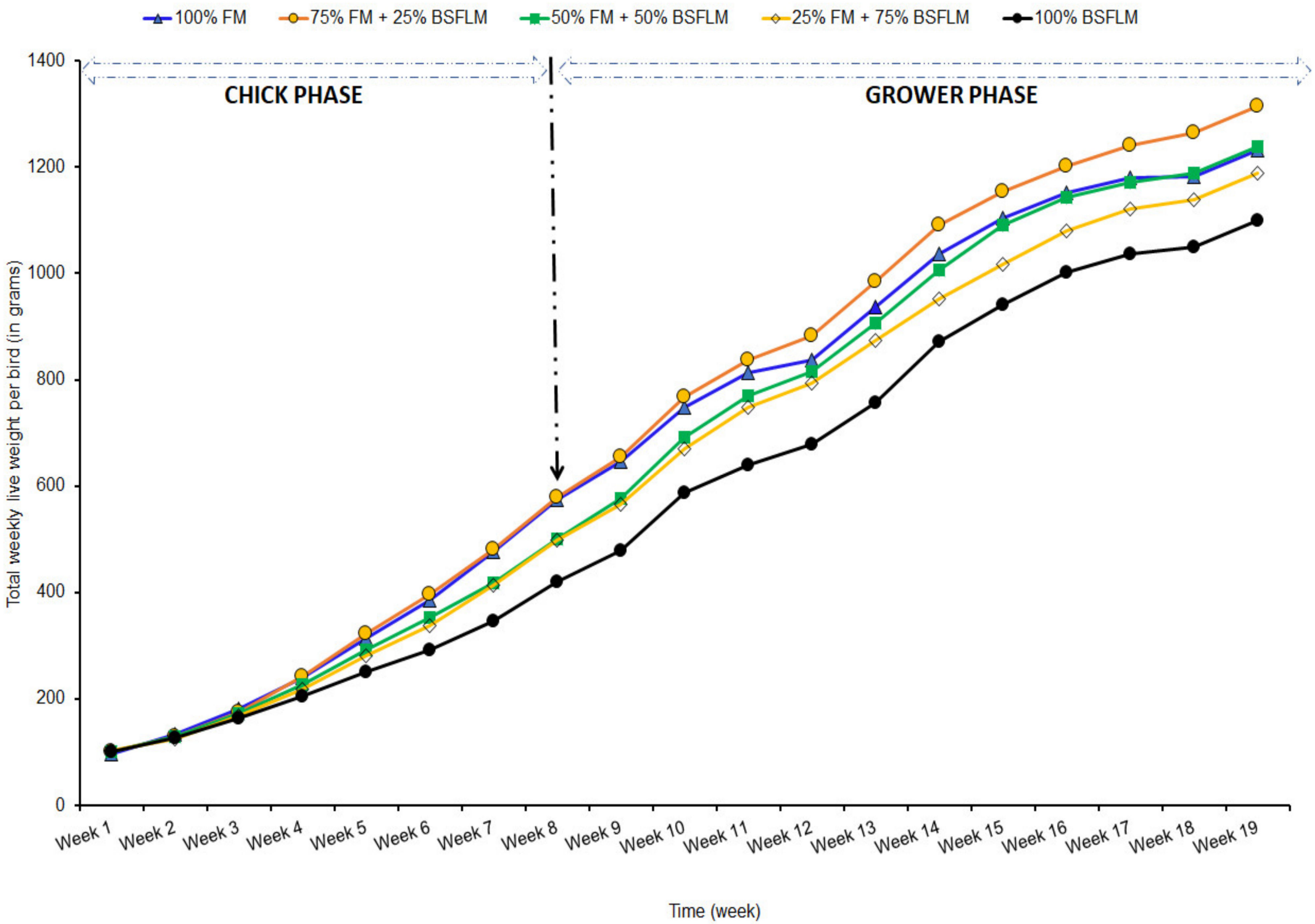

Figure 2. Total weekly live weight per chick and grower pullets fed on the various diets throughout the experiment. Diet 1: 100%FM + 0%BSFLM; Diet 2: 75%FM + 25%BSFLM; Diet 3: 50%BSFLM + 50%FM; Diet 4: 75%BSFLM + 25%FM and Diet 5: 100% BSFLM + 0%FM.

3.3. Evaluation of the Carcass Yield and Organs of Birds Fed on various Diet Types

The dressing percentage (%) or percentage carcass yield of the birds fed on various diet types was similar and ranged between 67–69%. The carcasses weight of chicken provided diet containing 100%BSFLM and 0% FM showed the lowest weight (Table 6). The overall carcass weight demonstrated a significant quadratic response (quadratic effect; $p = 0.021$) following increasing inclusion of BSFLM with maximum weight obtained at 29.3% BSFLM. The weights of carcass cuts namely wing, and drumstick had a comparable trend to the overall carcass weight. Maximum weight for wings was estimated at 32.4% BSFLM while maximum weight for drumsticks was obtained at 33.6% inclusion of BSFLM, which then the weight decreased beyond these estimated percent inclusion. Increasing inclusion of BSFLM did not vary significantly for breast meat weight, liver, gizzard, heart, and kidney ($p > 0.05$) when birds were subjected to various diet types (Table 6).

Table 6. Carcass components weight (grams) and internal organs weight of different parts of grower layer hen fed on various experimental diet types.

Body Parts	Diet Types					Polynomials		
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5	Linear	Quadratic	Cubic
Carcass weight	847.8 ^{a,b}	922.6 ^{a}	900.8 ^{a,b}	840.5 ^{b,c}	806.0 ^{c}	0.030	0.021	0.187
Carcass components weight (g)								
Thighs	122.3 ^{a,b}	131.9 ^{a}	123.9 ^{a,b}	110.8 ^{b,c}	106.8 ^{c}	0.002	0.078	0.083
Wings	112.6 ^{b,c}	126.3 ^{a}	119.9 ^{a,b}	114.9 ^{b,c}	108.1 ^{c}	0.091	0.009	0.131
Drumsticks	107.8	117.9	116.5	110.8	105.6	0.361	0.026	0.332
Breast meat	177.1	195.9	189.6	178.6	175.1	0.342	0.072	0.154
Internal organs weight (g)								
Liver	26.8	26.1	25.7	25.0	24.2	0.080	0.904	0.881
Gizzard	44.3	39.8	42.2	38.4	36.1	0.094	0.889	0.590
Heart	5.5	5.8	5.8	6.1	6.1	0.171	0.505	0.356
Kidney	2.7	3.1	2.9	2.7	2.8	0.771	0.682	0.509

^{a,b,c} Means in a row with different superscript letters are significantly different at $\alpha = 0.05$. Black soldier fly larvae meal (BSFLM); FM—Fishmeal; Diet 1: 100%FM + 0%BSFLM; Diet 2: 75%FM + 25%BSFLM; Diet 3: 50%BSFLM + 50%FM; Diet 4: 75%BSFLM + 25%FM and Diet 5: 100% BSFLM + 0%FM. Birds were 20 weeks old at time of slaughter.

3.4. Economic Analysis of Birds Fed on Various Diet Types

The results of the return on investment (RoI) and Cost benefit ratio (CBR) are shown in Table 7. The cost of feed consumed by the chicks and growers showed considerable variation across the various diet types (Table 7). Live weight of the birds at sales was observed to differ significantly when fed on the different diets formulated with FM and BSFLM. The gross profit margin, CBR and RoI were also observed to vary significantly among the five diet treatments. The control diet (Diet 1) (100%FM + 0%BSFLM) was the most expensive feed formulation for both the chicks and growers while diet 5 (0%FM + 100% BSFLM) was the cheapest in terms of total feed cost and feed intake. There was a positive gain in profit when birds were fed on diet 5 (0%FM + 100BSFLM) and Diet 4 (25%FM + 75%BSFLM) of 0.8 US$ and 0.5 US$, respectively. The calculated cost benefit ratio and RoI were observed to increase with increasing substitution of fish meal with BSFLM (Table 7).

Table 7. Economic analysis of replacing FM with BSFL in Isa Brown chick and grower stages fed on various diet types.

Parameter	Diet Types					MSE	*p* Value
	Diet 1	Diet 2	Diet 3	Diet 4	Diet 5		
Feed cost (USD/kg)							
Chick	0.57	0.56	0.55	0.54	0.53	-	-
Grower	0.48	0.47	0.46	0.45	0.44	-	-
ADI (g/bird)							
Chicks	36.20	33.82	29.81	27.20	24.68	9.1	<0.0001
Grower	84.56	84.31	84.36	78.27	75.20	28.8	0.055
Cumulative feed intake (g/bird)							
Chick (ADI x 42 days)	1520.4	1420.4	1252.0	1142.4	1036.6	-	-
Grower (ADI x 140 days)	11,838.4	11,803.4	11,810.4	10,957.8	10,528.9	-	-
Cost of feed consumed (USD per bird)							
Chick	0.87 [a]	0.79 [b]	0.69 [c]	0.62 [d]	0.55 [e]	0.002	< 0.0001
Grower	5.68 [a]	5.50 [a]	5.40 [a]	4.92 [b]	4.63 [b]	0.266	< 0.0001
Total feed cost	6.42 [a]	6.29 [a]	6.09 [a]	5.54 [b]	5.18 [b]	0.361	< 0.0001
Live weight at sale of birds (g)	1260.4 [a]	1337.5 [a]	1317.5 [a]	1235.7 [a]	1194.3 [b]	14.264	0.033
Sale of birds (US$ per bird)	6.0	6.0	6.0	6.0	6.0		
Gross profit margin	−0.41 [e]	−0.27 [d]	−0.10 [c]	0.48 [b]	0.83 [a]	0.0001	<0.0001
CBR	−0.07 [e]	−0.04 [d]	−0.02 [c]	0.09 [b]	0.16 [a]	0.004	<0.0001
RoI	−6.45 [e]	−4.37 [d]	−1.59 [c]	8.74 [b]	16.05 [a]	0.050	<0.0001

[a,b,c,d,e] Means in a row with different superscript letters are significantly different at $\alpha = 0.05$. Exchange rate was equivalent to 1 USD for 100 Ksh. BSFLM = black soldier fly larval meal. (-) values were not calculated. The protein cost in the diets was calculated in USD $/kg, cost of fishmeal (*Rastrineobola argentae*) = 1.20 USD; BSFLM = 0.9 USD. Each bird was sold at USD 6.0.

4. Discussion

Here, we present the first report globally on the effects of non-defatted BSF meal as a promising and sustainable alternative nutrient-rich protein additive in commercial IB layer chick and grower diets. Protein is an essential component of poultry diet, which accounts for over 70% of total production cost needed for nutrition and growth [7]. However, this protein source is critical because it strongly impacts accessibility and ease of use of the essential amino acids [54]. The composition of protein of BSFLM (47% DM) was higher compared to that documented by De Marco et al. [40], Makkar et al. [11] and Onsongo et al. [7]. These variations in CP composition observed among studies can be largely attributed to the substrate (*brewers' spent grain*) used compared to that reported in previous studies [55]. The methionine content of BSFLM was lower compared to that stated by Onsongo et al. [7] (0.8%), though higher than that presented by Spranghers et al. [56]. The content of lysine of BSFLM was comparable to that published by Onsongo et al. [7]. Similarly, Newton et al. [57] has demonstrated comparable levels of lysine and methionine in poultry diets. However, lysine and methionine content reported in BSFLM is within the recommended quantity (1.00 and 0.38 g/g, respectively), acceptable for chicken diets [23,58]. The considerable variation in the growth and carcass responses to the various diet types might be attributed to deficiency or imbalance of amino acids and other nutrients, which needs further future research exploration. This might be a particular shortcoming due to the method of diet type preparation. Therefore, future research activities should use more advanced methods to effectively formulate poultry diets based on standardized ileal tract digestible (SID) amino acids (AA) for poultry [31]. Moreover, BSFLM has been shown to exhibit low and variable sulphur amino acids (Met and Cys) concentration and these amino acids are the least digestible [32,33].

Growth rate of chicks provided feeds with higher inclusion levels of BSFLM (50, 75 and 100%) was significantly affected. This can be attributed to reduced feed intake observed with the incremental levels of BSFLM as observed in the current study. Besides protein, BSFLM are also known to contain higher levels of chitin than FM (lack chitin), which has been shown to increase the fibre content of the diets [11,19]. Diets rich in fiber (chitin) are beneficial for feed application due the influence imposed on the mucosa lining of the intestine, in respective of the amount used [59], but insoluble fractions such as fibre have also been reported to favor the resulting effects on the intestinal mucus barrier of chickens [60]. It is common knowledge that the addition of fiber in ration in low levels poses a good effect but levels exceeding 30 g/kg have been shown to negatively impact voluntary uptake of feed and nutrient digestibility [61–63], thus poor performance of birds. This explains why formulated poultry diets should not contain more than 3% crude fiber, especially for the younger birds (chicks) to allow for improved feed conversion [64]. However, mixing fiber fractions in different feeds would be more effective if further research is undertaken particularly for the emerging commercial insect-based feeds.

The NDF content of the chick diets increased with incremental levels of BSFLM, which was associated with reduced feed intake and could potentially affect the growth of the birds due to higher substitution level of chitin, which has been well documented to lessen digestibility and micronutrient utilization [65,66]. This effect is especially pronounced for proteins due to poor digestibility of ADF bound nitrogen [66]. The chicks require more protein than the later stages of growth [23] and therefore are more affected when protein intake and digestibility are affected. Other studies have reported similar results when insect meals are included in poultry diets. For instance, Awoniyi et al. [67] reported negative but insignificant body weight gain at 25% to 100% inclusion levels of insects (*Musca domestica* and *Tenebrio molitor)* in broiler chicken diet. The reduction of feed intake by birds has also been reported by Mohammed et al. [68], following the incorporation of various levels of BSFLM in their diets.

The FCR values decreased with increase inclusion levels of BSFLM, though there was no significant difference for chicks and growers fed on the various diet types. Contrarily, Amao et al. [68] reported that replacing fishmeal with BSF larvae meal turn to significant increase the FCR values of experimental hens. Chicks fed diets with lower inclusion levels of BSFLM (25%BSFLM +75%FM and 50%BSFLM + 50%FM) were observed to perform better compared to those fed diet with 100% BSFLM. Previous studies have fed broilers on diets supplemented with *Musca domestica* [69] and *Tenebrio molitor* [67,70,71] and demonstrated that the FCR values did not vary [66,70], which is consistent with the current findings. However, additional studies are warranted to establish the impact of BSFLM on long-term growth rate following the incorporation of higher levels of insect protein in animal feeds.

The incorporation of BSFLM in grower diets did not show any significant effect on the overall weight, ADG, ADFI and FCR of the birds subjected to the various feed regimes. Similarly, no negative dietary effects were observed when soybean meal in poultry feed is replaced by defatted BSFLM [72]. Mwaniki et al. [21] also observed an improved feed intake when birds were offered diets with increased insect meals compared to those provided 0 and 50% inclusion levels of the defatted BSFLM. Marono et al. [20] also reported significant effect of inclusion of BSFLM in laying hens on laying percentage, feed intake, weight gain and egg characteristics. In livestock production including poultry, ADG plays a critical role in growth rate of birds [73]. The effects of diet types did not significantly impact on the ADG of the growing birds, which implies there was adequate supply of nutrients to the birds provided by the various diet types. In this study, the growth rate of growing birds subjected to diets with BSFLM inclusion up to 2.5 and 5.0% (25 and 50% replacement of FM) was comparable [74]. However, the discrepancy observed might be attributed to the different strain of birds used in the two experiments.

The FCR of the growers was similar when exposed to the various diet types. Our findings are consistent to that presented by Maurer et al. [72], whereby the feed consumption and FCR of laying hen (Lohmann Leghorn) were unaffected by the experimental diets with BSFLM replacing soybean cake up to 100%. Contrarily, Mwaniki et al. [21], revealed increased feed consumption by the Shaver White Leghorns provided diets with defatted BSFLM. According to Mwaniki et al. [21] and Liu et al. [75], high feed consumption by birds provided insect-based diet might be due to higher fiber content following increase inclusion levels of BSFLM. This can be attributed to the fact that fibres help to facilitate increased ceca fermentation in birds [76], thus increased nutrients absorption [77] and better growth. Bovera et al. [78] reported, however, that increased intake of chitin through increased inclusion level of BSFLM played a significant probiotic role in enhancing the weight gain in birds.

During the transition phase of the birds from the chicks to the growers (i.e., between week 10 and 12), there was a period of physical adjustment to the new feeds between week 10 and 12. Leeson and Summers [79] and Mwaniki et al. [21] revealed that birds are usually physically challenged before the onset of egg laying with great potential for negative nutrient balances to occur. This explains why young birds must be provided with adequate energy and nutrient-rich feeds for proper body build up before the onset of egg laying. This may be due to the growth of the digestive system of the grower birds, which is capable of handling more fibrous materials that might have originated from the increased inclusion of BSFLM. Mwaniki et al. [21] emphasized that despite the weight gain at the end of the growing phase of the birds, it is imperative that the feed intake of the birds should be increased as the peak egg laying period approaches.

Generally, the weekly average weight gain of the birds subjected to the various feeding regimes declined consistently from week 15 as they approach the egg laying phase. This is a common trend observed in layer birds and have been shown to have associated benefits during the egg laying phase [80]. Gordon et al. [80] demonstrated the influence of body weight on egg size, revealing that lighter weight hens might turn to produce smaller eggs than heavier hens. However, we are also undertaken further research studies with the same clusters of grower hens to establish if weight gain observed at the grower phase would affect the dynamics of total egg mass production and egg size when the hens are subjected to feeding regimes with varying inclusion levels of BSFLM as well as associated profitability [80–83].

No significant dietary effect was observed on carcass traits (all internal organs, breast meat and drumsticks) of grower pullets except for the dressed carcass weight, thighs, and wings. The weight of body parts of the birds was generally higher for birds that were subjected to diets containing 25, 50 and 75% BSFLM inclusion ratio compared to the other diets. Several studies have reported an increase in dressed carcass weight of birds when fed on diets with BSFLM at moderate inclusion levels [7,66], while others have shown that dietary regime of birds with BSFLM does not significantly affect the size of the internal organs [74,84] and broiler chickens fed mealworm [85].

Our findings have proven that the price of feeds for the chicks and grower pullets gradually reduces following increment levels of BSFLM substituting FM. Chick and grower diets with 100% BSFLM inclusion was much cheaper compared to diets with 100% FM. The results also showed that 100% FM diet had the least gross profit margin, CBR and RoI compared to the other diet types thus making BSFLM feed more affordable than the conventional FM feed, that heavily depends on fish importation and overfishing in major waters [86]. The low cost of BSFLM is reflected in the reduced cost of feed, increased profits, CBR and RoI compared to FM, which is coherent with the information provided by Khan et al. [86] and Onsongo et al. [7].

5. Conclusions

Here, we have demonstrated for the first time that the substitution of the expensive fishmeal in poultry feed by BSFLM does not comprise the overall growth and economic performance of the birds. The variation observed among the various diet types can be attributed to nutrient deficiencies or imbalance in the formulated feeds. The best performing diet mixture was 75% FM and 25% BSFLM in terms of the growth performance of the birds but the most cost-effective feed was with 100% BSFLM inclusion rate. Combining evidence obtained in the present study, it can be speculated that poultry feed supplemented with BSFLM would represents a valuable technology for smallholder farmers and the animal feed industry in developing countries. However, future studies should investigate other sustainable solution-oriented approaches such extrusion to increase the nutritional value and digestibility of organic matter and crude protein in BSFLM containing feed blends. Also, future research should formulate poultry diet with BSFLM based on standardized ileal digestibility of amino acids using ideal protein concept as described by Zhang and Adeola [31] to alleviate the effect of protein deficiency during digestibility. A further consideration emerging from this study is the role of BSFLM fat in determining the potential technological quality of the feeds and their impact on poultry growth. Thus, fat content in emerging insect-based poultry feed mixture should be monitored closely to guarantee adequate nutrient supply in the process.

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Informed Consent Statement: Not applicable.

Data Availability Statement: All datasets presented in this study are included in the article and can be availed by the authors upon reasonable request.

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